University of Nottingham

Department of Civil Engineering

Assessment and Design of Emulsion-Aggregate Mixtures for use in Pavements

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ABSTRACT

Emulsion-aggregate mixtures are generally recognised as being of relatively low quality in relation to hot mixtures. This type of mixture exhibits continuously changing properties (stiffness modulus, permanent deformation resistance, resistance to water effects, fatigue resistance, etc.) before reaching a steady state, at a fully cured condition, though it may still contain a low amount of residual water. It has been claimed that it is similar, largely, to unbound aggregate, at very early stages of curing and to hot bituminous mixtures after full curing. Therefore, assessment of the material has to take account of this change in properties. This change of properties also introduces the problem of which laboratory test methods are most suitable for characterising the properties of the material to best enable the evaluation of the relative quality of the material, for mix design and for analysis of a pavement's response to traffic loading. Currently, there is no concensus for characterisation or mix design of this type of slow curing mixture (up to 2 years) or the design of pavement structures with an emulsion-aggregate mixture course, although industry is attempting to produce emulsion-aggregate mixtures with properties equivalent to those of hot bituminous mixtures.

This study attempts to build up a thorough understanding of the factors which affect the properties of an emulsion-aggregate mixture. These factors involve curing time and regime, moisture content, stress level, test temperature, aggregate grading, and emulsion content and type. To characterise bitumen emulsion and emulsion-aggregate mixtures, this thesis describes developments to the base plate of the dynamic shear rheometer to enable testing partially cured and recovered bitumen, and a new test assembly in the Nottingham Asphalt Tester to enable testing in the triaxial mode for determination of stiffness modulus (unsoaked and soaked) and for evaluation of permanent deformation resistance, at different test temperatures. The main objectives are to determine appropriate laboratory tests for use in assessing the material properties, to explore the short and long term properties of the material and factors affecting it, to obtain information on the material performance in a pilot scale wheel

tracking test, investigation of the material's failure characteristics and, finally, to outline proposals for both mix and pavement structure designs.

This thesis describes a two phase study which has been carried out on the characterisation of mixtures at early and later stages of curing. The first phase was a study of the mechanical properties, the stiffness modulus of unsoaked and soaked specimens, measured in the Nottingham Asphalt Tester, both in indirect tensile and triaxial modes of testing, and the permanent deformation of both confined and unconfined specimens. The second phase of the study was of performance in a pilot scale wheel tracking facility, for verification of the results from the first phase. Slabs of emulsion mixtures were laid-down on a base layer (sand or crushed stone) and/or a sheet of rubber. Measurements taken were surface rutting, vertical stress at the top of the base layer and tensile strain at the bottom of the emulsion mixture layer, by means of installed pressure cells and embedment strain gauges.

It is shown that the behaviour and characteristics of the material are different from those of hot mixtures. The results highlight the following:

- the stress dependency of the material in relation to curing time, emulsion type, residual bitumen content, and aggregate gradation, which is similar to that of unbound materials,
- the importance of stress level on determination of the mechanical properties of the material and its effect on both mix and pavement structural design,
- poor fatigue resistance as measured in the indirect tensile fatigue test,
- higher permanent deformation compared to corresponding hot bituminous mixtures, dominated by the material response at early life,
- poor resistance to the effects of water.

The thesis then proposes procedures for mix design and pavement structure design.

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LIST OF ABBREVIATIONS

AASHTO	American Association State of Highway and Transportation Official
A/D	Analogue/Digital Converter
ASTM	American Society for Testing and Materials
BS	British Standard
CKE	Centrifuge Kerosene Equivalent
DBM	Dense Bitumen Macadam
Dia.	Diameter
DSR	Dynamic Shear Rheometer
ITFT	Indirect Tensile Fatigue Test
ITSM	Indirect Tensile Stiffness Mode
LVDT	Linear Variable Differential Transducer
MS	Medium setting emulsion
NAT	Nottingham Asphalt Tester
NCHRP	National Cooperative Highway Research Program
OFC	Optimum Fluids Content
P.I	Penetration Index
PVN	Penetration-Viscosity Number
RAP	Reclaimed Asphalt Pavement
RBC	Residual Bitumen Content
RLA	Repeated Load Axial
RLT	Repeated Load Triaxial
SABITA	South African Bitumen and Tar Association
SFERB	Syndicat Des Fabricants D'Emulsions Routieres De Bitume
STF	Slab Test Facility
SHRP	Strategic Highway Research Program
SS	Slow setting emulsion
VMA	Voids in Mineral Aggregate

LIST OF SYMBOLS

E	Resilient modulus
E_i^*	Complex stiffness modulus
G*	Complex shear modulus
G'	Storage modulus or the elastic modulus
G"	Loss modulus or the viscous modulus
G_{bulk}	Bulk density
G_{dry}	Density of dry mixture
G_{max}	Maximum (Rice) density
h	Layer thickness
Δh	Measured horizontal deformation in the indirect tensile test
hr.	Hours
Hz	Hertz
in.	Inch
Kg	Gramme × 10^3
m	Meter
mm	Meter × 10^{-3}
cm	10 mm
μm	Meter × 10^{-6}
με	Strain × 10^{-6}
N	Number of load application
N	Newton
kN	Newton × 10^3
P	Repeated line load in the indirect tensile test
Pa	Pascal
kPa	Pascal × 10^3
MPa	Pascal × 10^6
PSI	Pounds per square inch (1 PSI = 6.895 kPa)
ms	Millisecond
RBC	Residual bitumen content, percent

S_m	Stiffness modulus of mixture
t	Specimen thickness
σ_d	Axial deviator stress in the triaxial test
σ_3	Confinment pressure on triaxial specimen
υ	Poisson's ratio
δ	Phase angle
°C	Degrees Celsius
%	Percent
V_B	Bitumen content, percentage by volume
V_v	Air void content, percentage by volume
V_{voids}	Total voids in mixture (air and water)
W.C	Water content, percent

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CHAPTER

1 INTRODUCTION

1.1 BENEFITS OF USING AN EMULSION-AGGREGATE MIXTURE

A flexible pavement structure comprises three essential components which act together to protect the subgrade from environmental and traffic effects. These are a surfacing, which may be laid in two layers 'wearing course and base course', a road base, and a sub-base, overlaying the subgrade. A typical pavement structure is shown schematically in Figure 1-1.

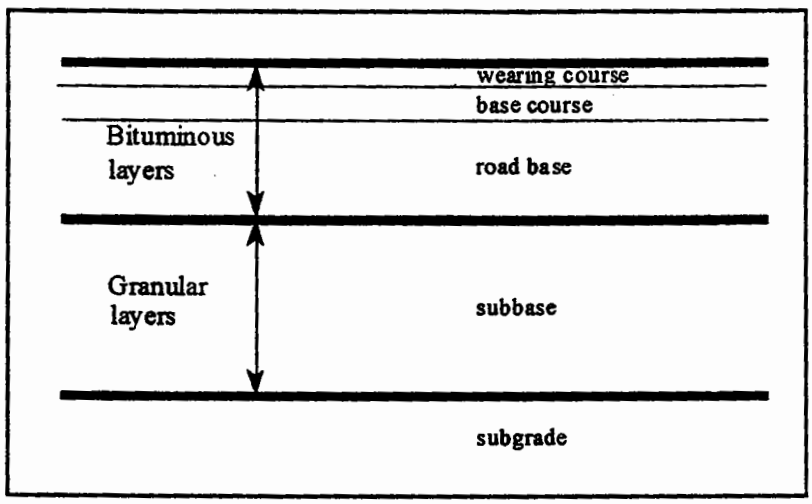


Figure 1-1 Typical flexible pavement structure

The upper layers of the pavement structure are usually constructed with hot bituminous mixtures. To produce this type of mixture, a high temperature, 150-200°C, is required to liquify the bitumen to distribute it between the dried aggregate particles during the mixing process. Storage, transportation, laying and compaction of the mixtures must be performed at controlled temperatures. However, the advantage of this type of mixture is that its strength is rapidly developed on cooling, after the compaction process, allowing the constructed road to be immediately opened to traffic.

In today's climate of environmental and economic constraints, emulsion-aggregate mixtures (a blend of aggregate, water, and bitumen emulsion) provide a feasible alternative to

conventional hot mixtures. A cold process is used for producing this type of mixture. The material therefore offers reduced costs, conservation of energy, and reduction in safety and environmental hazards. However, there are also some disadvantages:

a) The mixtures must be placed in relatively warm, dry weather. Therefore, construction is limited to the summer months.
b) It is susceptible to moisture intrusion and abrasion. Hence, it requires a separate wearing surface, e.g. hot mix overlay or surface dressing.
c) It does not gain its full strength immediately after laying.

1.2 BACKGROUND AND PROBLEM STATEMENT

The composition and preparation of test specimens of emulsion-aggregate mixtures are significant elements in assessing the material behaviour. Proper mixing necessitates using a proper amount of added water in the aggregate. For better compaction, optimum emulsion content and optimum total water content at compaction should be determined. Compaction comparable to that expected in pavement construction must also be achieved; otherwise, actual performance will not be replicated. Thus, mix design for this type of mixtures generally involves the following:

1. Chemical and physical compatibility of binder and aggregate.
2. Optimum mixing water content which maximizes coating to aggregate particles.
3. Optimum total fluids (or water) content at compaction and selection of optimum residual bitumen content which maximize the physical and mechanical properties.
4. Adequacy of structural and durability properties to maximize load distribution and minimize distress (e.g. repetitive cracking of the asphalt layer 'fatigue', permanent deformation and disintegration).

An emulsion-aggregate mixture is generally recognised as being of relatively low quality, although much effort is being devoted, using modern technology for the production of bitumen-emulsion, to enhance the material properties to be equivalent to those of hot bituminous mixtures. The material exhibits continuously changing properties (stiffness modulus, permanent deformation resistance, water sensitivity,

fatigue resistance, etc.) before reaching a steady state, at a fully cured condition, though it may still contain a low amount of residual water. Thus, emulsion mixtures exhibit a composite response over time, being similar, largely, to unbound aggregate in the early stages of curing and to hot bituminous mixtures after full curing.

Stiffness modulus is a significant parameter through which the ability of an emulsion-aggregate mixture to perform as a structural layer in a pavement can be determined. In the UK, many trials have been carried out to investigate material performance. In some of these trials, and in a limited number of commercial applications, trafficking has been allowed either directly on the as-laid materials or after covering with an asphalt layer or surface dressing. A low curing rate and an equilibrium water content of more than 1% have been reported (e.g. Leech 1994, Robinson et al 1996). Nevertheless, stiffness modulus is often determined using the indirect tensile mode of loading, both to evaluate the relative quality of a material and to use as an input parameter for pavement design. However, this change in the material's properties introduces the problem of which laboratory test method is most suitable for characterising the stiffness response of emulsion- aggregate mixtures to best enable the analysis of a pavement response to traffic loading.

Initial shear strength of emulsion-aggregate mixtures for use in a pavement structure is also required to prevent deformation in the layer itself under traffic and under the prevailing environmental conditions. Deformation in the material at early stages of curing will affect the overall material response during the pavement life. However, the deformation potential of the material has often been assessed on fully cured samples, using the Marshall stability, the uniaxial creep test, the uniaxial repeated load test, and the wheel tracking test, all normally used for hot mixtures.

Currently, there is no consensus for dealing with fatigue cracking in this type of slow curing mixture. Some have reported that it is a type of distress which is associated with these materials and therefore should be included in pavement structure design methods. Others, on the other hand, from the point of view of experience, have stressed that emulsion mixtures with a resilient modulus less than 4000 MPa do not fail in fatigue.

Moisture is a damaging factor which leads to durability problems with emulsion aggregate mixtures. Most current test methods applied to bituminous mixtures attempt to simulate the strength loss that may occur in the field, to identify the mixture combinations which are susceptible to water. Using these mixtures in a pavement causes premature distress and ultimately failure before the design life is achieved, due to moisture damage. Since emulsion aggregate mixtures possess varying properties over the curing period, the procedures currently used for assessing bituminous mixtures should not be applied unless the material reaches a fully cured condition and behaves similarly to bituminous mixtures.

The literature thus reveals a lack of information regarding the following:

- Sample preparation in terms of determining optimum water contents for mixing and compaction.
- Establishment of mixture properties for proper performance in the field.
- Testing procedures and criteria to evaluate these properties.
- Relating these properties to the pavement structural response.

Consequently, there is no widely accepted mixture design method or structural design methodology for either virgin emulsion aggregate mixtures or cold recycled materials.

Chapters 2 and 3 review the literature on emulsion-aggregate mixtures and other cold mixtures respectively.

1.3 OBJECTIVES AND RESEARCH APPROACH

Overall, due to the aforementioned problems, the aim of this research is to develop a suitable means for effectively characterising emulsion-aggregate mixtures and to establish suitable design procedures for both the mixture and the pavement structure. More specifically, the following are the elements required to meet the overall objective:

1. Investigate procedures for preparing specimens of emulsion-aggregate mixtures or binder.

2. Develop experimental techniques for use in assessing the material characteristics.
3. Conduct an experimental program to thoroughly evaluate the factors that affect both binder and mixture performance.
4. Examine the material performance in a pilot scale wheel tracking test (scale approximately 1/3) using specially instrumented slabs (dimensions 90 cm × 110 cm).

The study therefore includes two phases. The first phase is a study of the mechanical properties of the material, as follows:

- Evaluation of the elastic properties of this type of mixture using the indirect tensile and triaxial modes of testing, both in the Nottingham Asphalt Tester (NAT). The triaxial mode of loading for testing in the NAT is considered important for routine testing of the material, particularly at early curing stages, when indirect tensile testing is impossible, as the assessment of the material has to take account of the change in its properties. Emphasis is placed on the effect of compaction method, aggregate gradation, emulsion content, water content, test temperature, stress level and curing regime (Chapter 5).
- The permanent deformation of both confined and unconfined specimens as well as wheel tracking on slabs fabricated using the roller compactor (Chapter 6).
- The fatigue resistance of different mixture combinations at two levels of curing, measured in the indirect tensile fatigue test (Chapter 7).
- The resistance of this type of mixture to the effect of water. (Chapter 8).

Since no standard procedure has been established for the sample preparation of such mixtures, Chapter 4 presents a study to develop a suitable mixture preparation procedure to be used for the subsequent investigation. The effect of emulsion mixture composition on the material compactibility is discussed. Variables involved are added water content, total water content at compaction, residual bitumen content, emulsion type, curing time and method, and aggregate gradation. Marshall, vibration, and gyratory compaction methods are examined for use in the compaction of this material.

The second phase of the study is of performance in a pilot scale wheel tracking facility (Chapter 9). The work objectives are the investigation of the material's failure

characteristics and verification of the results from the first phase. Slabs of emulsion mixtures are laid on a base layer (sand or crushed stone) and/or a sheet of rubber. Measurements are surface rutting, vertical stress at the top of the base layer and tensile strain at the bottom of the emulsion mixture layer, by means of installed pressure cells and embedment strain gauges.

Additionally, as discussed in Chapter 10, the effect of water content on the flow characteristics of the binder, and filler content on the flow characteristics of the bitumen-filler mastic are examined in the dynamic shear rheometer 'DSR'. Characterisation of emulsion residue compared to base bitumen is also investigated. Modification to the rheometer base plate to allow testing of emulsion at different curing times is described.

Finally, procedures for both mix and pavement design, based on the evidence from this study, are proposed in Chapter 11. A comparison with available information in both areas of design from the literature is also presented.

CHAPTER

2 EMULSION-AGGREGATE MIXTURES

Emulsion-aggregate mixtures are three component systems containing mineral aggregates, bitumen, and water, excluding any air which may be present. Water in these mixtures may come from three sources; water within the aggregate, water incorporated in the emulsion, and water used for pre-wetting the aggregate prior to the addition of emulsion. Initially, the water content in an emulsion-aggregate mixture needs to be relatively high for uniformity of coating during mixing and for inter-particle 'lubrication' to aid compaction. This chapter describes the components of this type of mixture and their effect on the overall mixture behaviour for mixture design purposes.

2.1 BITUMEN EMULSION

2.1.1 Composition and Classification

Bitumen emulsion is a dispersion of fine bitumen droplets in water. The droplets typically are in the range of 0.1 micron to 5 microns in diameter and are held in suspension and stabilised by an emulsifying agent. As shown in Figure 2-1, bitumen and water exist in separate phases since bitumen does not dissolve in water. The emulsifying agent imparts an electric charge to the surface of the droplets which in turn causes them to repel each other, keeping them in stable suspension and controlling the 'breaking' time according to the requirements of prolonged storage, pumping, and mixing. Breaking is the term used for the bitumen coming out of the emulsified state. Generally, the droplets of bitumen are termed the dispersed phase and the water is the continuous phase. Additives may also be included in the emulsion such as stabilizing agent and flux oils, according to its use.

Emulsions are classified in terms of the surface charge type on the dispersed bitumen droplets, setting time, and base bitumen grade and content in the emulsion. According to the setting time, the start of the breaking process, the emulsions are graded into rapid

setting, medium setting, and slow setting. The commonly used types of bituminous emulsion are:

- Cationic, in which the bitumen droplets exhibit electro-positive charge.
- Anionic, in which the droplets exhibit electro-negative charge.

Currently, emulsion formulations are under the responsibility of the manufacturers. However, the proportion of bitumen in road emulsion is normally in the range of 50-70% by weight for the requirements of storage stability and viscosity (Shell Bitumen, 1995 and Leech, 1994)

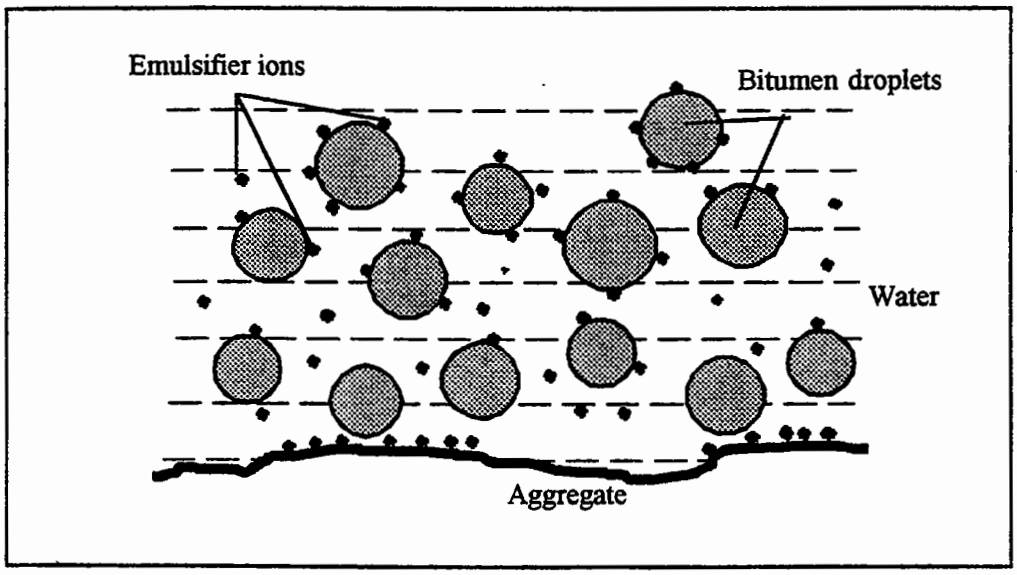


Figure 2-1 Composition of bitumen emulsion

2.1.2 Properties of Bitumen Emulsion

Properties of emulsion may be divided into two general categories: those related to the physical characteristics such as viscosity and storage stability, and those related to its behaviour such as adhesion with the aggregate particles and breaking speed.

Viscosity

Factors governing viscosity of an emulsion include:

1. Concentration of the dispersed phase as depicted in Figure 2-2a.

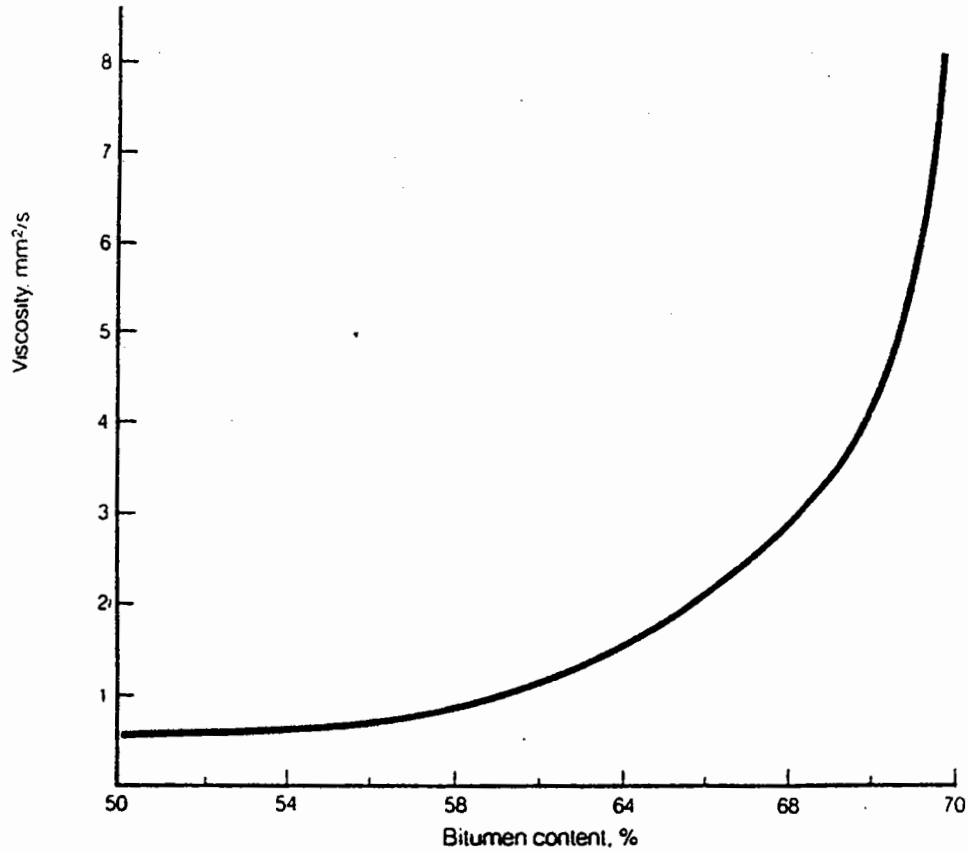


Figure 2-2a Emulsion viscosity as a function of bitumen content (after Shell Bitumen, 1990)

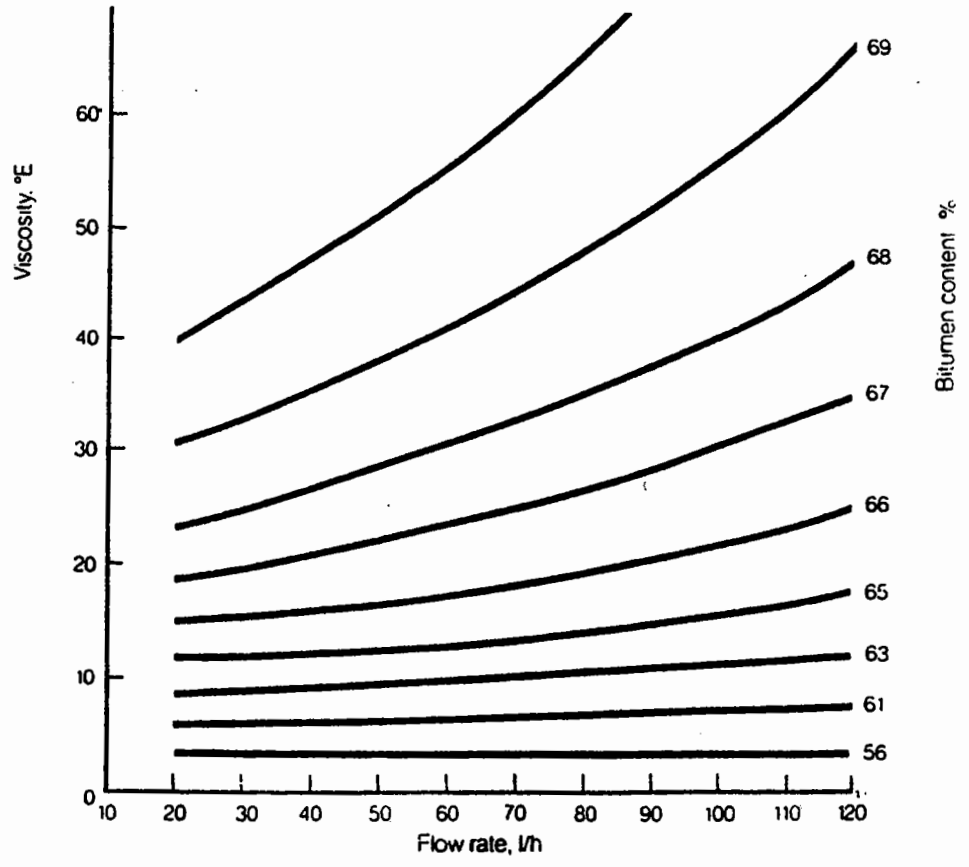


Figure 2-2b Emulsion viscosity as a function of flow-rate for different bitumen contents (after Shell Bitumen, 1990)

2. Type of dispersed phase, i.e. origin of the base bitumen, bitumen grade, and presence of additives (e.g. flux oil), see Figure 2-2b.
3. Type and quantity of emulsifier distributed between emulsion phases.
4. Particle size distribution of the emulsified phase.

The particle size can be determined using a microscope or by electronic measurements (Kubitshek, 1960). Two parameters, the mean diameter and the median diameter defined in Figure 2-3, are normally considered to describe the particle size distribution of an emulsion (Boussad and Martin, 1996).

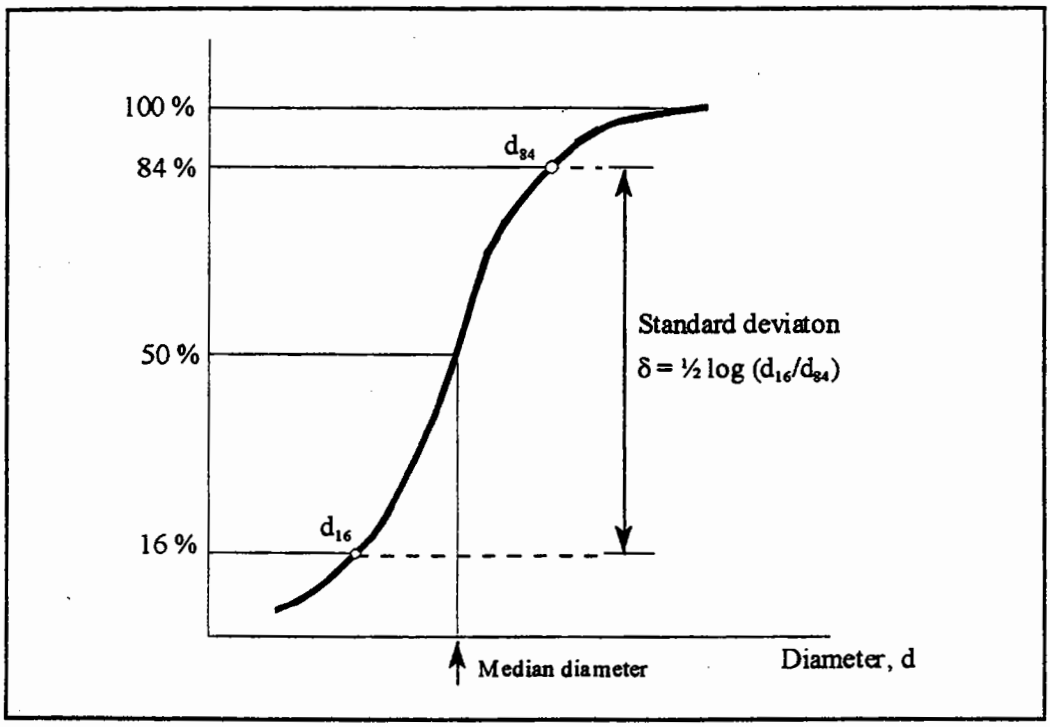


Figure 2-3 The median and the standard deviation describing the particle size distribution of an emulsion (after Boussad and Martin, 1996)

The median diameter of bitumen emulsions is normally between 2 and 20 microns while the standard deviation, representing how wide the distribution is, can be from 0.13 to 0.40 of the mean depending on the manufacturing conditions. However, at a given dispersed phase concentration, the smaller the particle size the higher the emulsion viscosity. For emulsions of same bitumen content, a finer emulsion will coalesce faster than a coarser one (Marchal et al, 1993).

Storage Stability

Bitumen emulsions are a dispersion of two non-miscible phases, thermodynamically unstable liquid dispersions. Over time, surface free energy, the interfacial tension between the bitumen and the emulsifier solution, gradually decreases which eventually leads to the separation of the components into two immiscible phases. Sedimentation, with a concentration of the dispersed phase on the bottom or 'creaming' on the top, is followed by a flocculation. At this stage, agitation of the emulsion leads to recovery of its original condition. However, coagulation of bitumen droplets leads to irreversible condition.

The factors that influence sedimentation of bitumen droplets, the first sign of instability, are given by the parameters in Stokes' law:

$$S_R = 2/9 \times g \times r^2 \times (s_1 - s_2)/n$$

where:

S_R = settlement rate

g = acceleration due to gravity

r = particle radius

s_1 = bitumen specific gravity

s_2 = aqueous phase specific gravity

n = viscosity of the continuous phase

According to Boussad and Martin (1996), storage stability also depends on the bitumen droplets' charge which can be controlled by the emulsifier content: the higher the charge the less easily the emulsion goes from flocculation to the coalescence stage.

Breaking, Setting, and Curing of Emulsion

On adding emulsion to aggregate, breaking commences and then setting occurs. Breaking is the process in which separation first occurs, resulting in either sedimentation or creaming, followed by flocculation of bitumen droplets (the closing up of the dispersed phase droplets). The finely dispersed bitumen droplets flocculate into coarser clumps which then stick together and 'coalesce' to produce a continuous film of bitumen on the aggregate particles. The final stage in the breaking process is the formation of a continuous

mass, the 'coagulation stage'. After breaking, setting of emulsion droplets takes place, in which water is separated from the system .

However, various mechanisms for the emulsion breaking process have been proposed. Marchal et al (1993) proposed that the breaking process greatly depends on the emulsifier remaining in the water phase of the emulsion. Once the emulsion is in contact with the aggregate mineral surface, the free molecules settle onto the aggregate mineral surface. In emulsions containing larger particle sizes (coarse) and, consequently, a higher amount of free emulsifier (in the water phase), the larger particles flocculate onto each other when the free emulsifier is consumed. On the other hand, finer bitumen droplets and less surplus emulsifier result in flocculation on the mineral aggregate, once this quantity is consumed. Many researchers and agencies (e.g. the Asphalt Institute, 1979&1989, and Shell bitumen, 1995) have proposed that cationic emulsion droplets react with the aggregate surface and coalesce under the influence of electro-chemical processes, squeezing out the water between them. However, the evaporation of water is the primary way which finally causes an anionic emulsion to break. During the breaking process, the concentration of droplets at the surface increases and coagulation occurs. Another mechanism which has been proposed as contributing to the breaking is that the pH of a cationic emulsion increases due to the reaction of acid with the aggregate.

Curing is the continuation of the setting phenomenon until the complete separation of the water from the broken emulsion and the loss of any volatile oils contained in the base bitumen. Accordingly, both the adhesion between the bitumen and the aggregate particles and the stiffness of the binder increase. The residual bitumen after the curing process should retain all of the adhesion, durability and water resistance of the base bitumen.

For dense mixtures, bituminous emulsions are formulated for delayed breaking to allow for mixing and laying. After mixing the components of the bituminous emulsion mixtures and laying them, the emulsion should break. According to Finn et al (1968) and the Asphalt Institute (1979 &1989), some of the factors that affect breaking rate of a bitumen emulsion are listed below.

1. The relative absorption characteristics of the aggregate used and the surface area of aggregate.
2. Moisture content of the aggregate prior to mixing.
3. Size distribution and mineral composition of aggregate.
4. Intensity of charge on aggregate versus intensity of emulsifier charge.
5. The type and concentration of the emulsifying agent.
6. Chemical coagulation (the emulsion becomes unstable because of a decreased water content).
7. Mechanical forces brought to bear by rolling and traffic.
8. Atmospheric conditions.

2.1.3 Residual Bitumen

Temperature Susceptibility Measurements

The temperature susceptibility of bitumen is the change in the material consistency (stiffness or viscosity) as a function of temperature. Penetration index 'P.I', penetration-viscosity number 'PVN', and the bitumen test data chart are measurements used to characterise the temperature susceptibility of bitumen.

The penetration index P.I can be determined from the following formula (Pfeiffer and Van Doormaal, 1936):

$$P.I = \frac{20 - 500A}{1 + 50A}$$

$$A = \frac{\log \text{Pen at } T_1 - \log \text{Pen at } T_2}{T_1 - T_2}$$

where:

$\log \text{Pen at } T_1$ = the penetration at temperature T_1 °C, (normally assumed 800 at Ring and ball softening point temperature),

T_2 = the penetration test temperature, usually 25°C.

The lower the P.I value of a bitumen, the higher its temperature susceptibility.

The penetration-viscosity number 'PVN' is based on penetration at 25°C and viscosity either in centistokes at 135°C or in poises at 60°C which are usually specification requirements for paving bitumen. The PVN is then determined from:

$$PVN = \frac{L - X}{L - M}(-1.5)$$

where:

X = the logarithm of viscosity,

L = the logarithm of viscosity for a PVN of 0.0,

M = the logarithm of viscosity for a PVN of -1.5.

The viscosity values of L and M can be determined from the graph developed my McLeod (1976). Alternatively, the following equations can be used:

$\log V = 4.25800 - 0.79670 \log P$ for the line representing a PVN of 0.0.

$\log V = 3.46289 - 0.61094 \log P$ for the line representing a PVN of -1.5.

The bitumen test data chart developed by Heukelom (1969; 1973) is a refinement of the P.I method. The chart enables determination of the temperature/viscosity characteristics of a bitumen from only the penetration and softening point.

Residual Bitumen versus Base Bitumen

By the end of the curing process of emulsion aggregate mixtures, virtually zero water content has been reached and the emulsion residue should retain the properties of the base bitumen. Emulsification of bitumen should not, in theory, influence its original properties.

Jimenez (1971) reported that emulsification causes hardening of the base bitumen in tests on bitumen recovered from the emulsion using a distillation process. Therefore, penetration determination of emulsion residue obtained from distillation is a requirement of specifications .

On the other hand, Agnusdei et al (1990) reported different results. Comparisons were made between rheological parameters of both cationic emulsion residues and base bitumen,

typified by viscosity, complex flow index determined by the sliding plate microviscometer at 25°C, and penetration index. The comparison also involved the temperature susceptibility of both bitumens using the Bitumen Test Data Chart developed by Heukelom (1973). Neither preparation procedures of samples nor description of bitumen recovery method have been reported. However, they noted no noticeable differences between the properties of the two materials. The conclusion then was that asphalt bases are not modified by the emulsification process.

Supporting Agnusdei et al, Needham (1996) found similarity between the dynamic modulus of emulsion residue and base bitumen, measured in the dynamic shear rheometer at 20°C. Emulsion residue was recovered by stirring of the emulsion for a long time during which water was allowed to evaporate. Samples were then brought to a higher temperature to allow them to be squeezed to the rheometer gap height (sample thickness).

It is likely that the method of recovering bitumen from emulsion has a great influence on its properties.

2.1.4 Manufacture of Bitumen Emulsions

Bitumen emulsions are manufactured by the intensive mixing of bitumen and water, dividing up and dispersing the bitumen in the water phase. Normally, the water phase carries the emulsifier in solution in activated form, i.e. acidified or basified.

Factors for Consideration

Dispersion energy:

Emulsion dispersion is achieved by mechanical energy (normally, by means of a high shear mixer known as a colloid mill) to divide the bitumen into fine particles and physical/chemical energy provided by the emulsifier.

Viscosity and temperature of components:

In order to enable the bitumen binder to disperse in the continuous phase properly, it is necessary for its viscosity to be relatively low (normally 200 centipoises); therefore, it needs to be heated; the temperature being dependent upon penetration grade of the bitumen used.

Dosing of the components:

Component dosing must be extremely precise, in particular the emulsifiers and the acid. A slight variation may alter the properties.

The manufacturing procedure for a bitumen emulsion is presented diagrammatically in Figure 2-4.

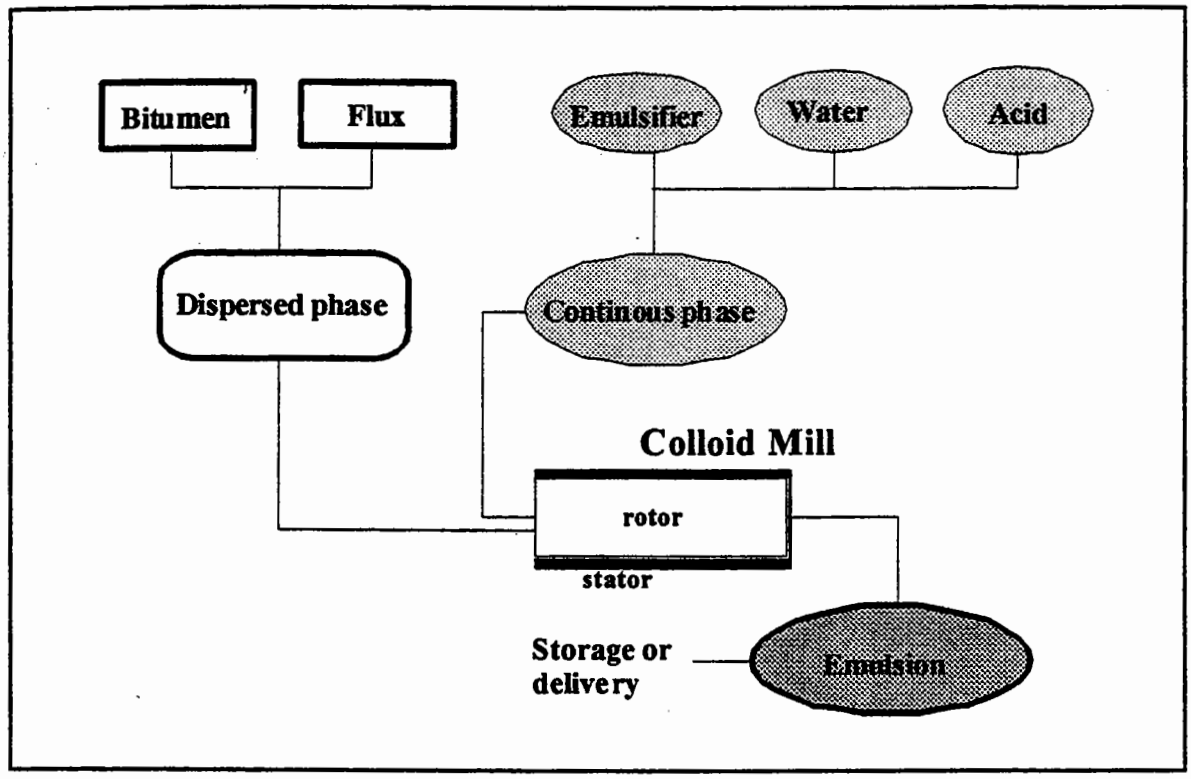


Figure 2-4 Manufacturing procedure of bitumen emulsion

2.1.5 Application of Bitumen Emulsions

As previously mentioned, different setting characteristics of bitumen emulsion can be produced, enabling its use for different applications such as the following:

- surface dressing.
- slurry seal and tack-coating.
- cold bituminous mixtures.
- cold recycled mixtures.
- maintenance and repair of road pavements.

2.2 CONSIDERATIONS FOR EMULSION AGGREGATE MIXTURES

Below are factors that must be taken into account during the preparation and testing of emulsion mixtures.

2.2.1 Compatibility of Emulsion and Aggregate

As previously stated, the breaking and coalescence of emulsion droplets onto the aggregate are heavily influenced by aggregate electro-charge relative to emulsion charge. Mineral aggregates bearing a positive charge on the surface, such as sandstone, siliceous gravel and granite are highly compatible with a positively charged emulsion (cationic). On the other hand, mineral aggregates such as limestone bear a positive surface charge are therefore compatible with negatively charged emulsion (anionic).

2.2.2 Mixing Consideration

During mixing, a sufficient uniform dispersal of emulsion throughout the mixture is required. This depends on:

1. The emulsion-aggregate combination being considered.
2. The amount of premixing water used.
3. Mixing time.

Some of the general aspects of the coating and mixing of bituminous emulsion mixtures which are conceptual in nature are reported by Waller (1980) and Coyne and Ripple (1975). Mixing water is needed to moisten the aggregate used in the mixture so that any agglomerations can be broken up and channels between fine particles can be created through which the emulsion can penetrate. The amount of added mixing water needed for good dispersion is not the same for all emulsions. In fact, cationic emulsions require additional mixing water in order to achieve satisfactory coating. As can be seen from figure 2-5, in the case of medium setting emulsions (MS), coating is not necessarily improved by the presence of excess water. On the other hand, the presence of large amounts of added water in slow setting emulsions (SS) improves the dispersion. Generally, the amount of mixing water must be sufficient and should not be used to the extent that the emulsion drains from the aggregate particles.

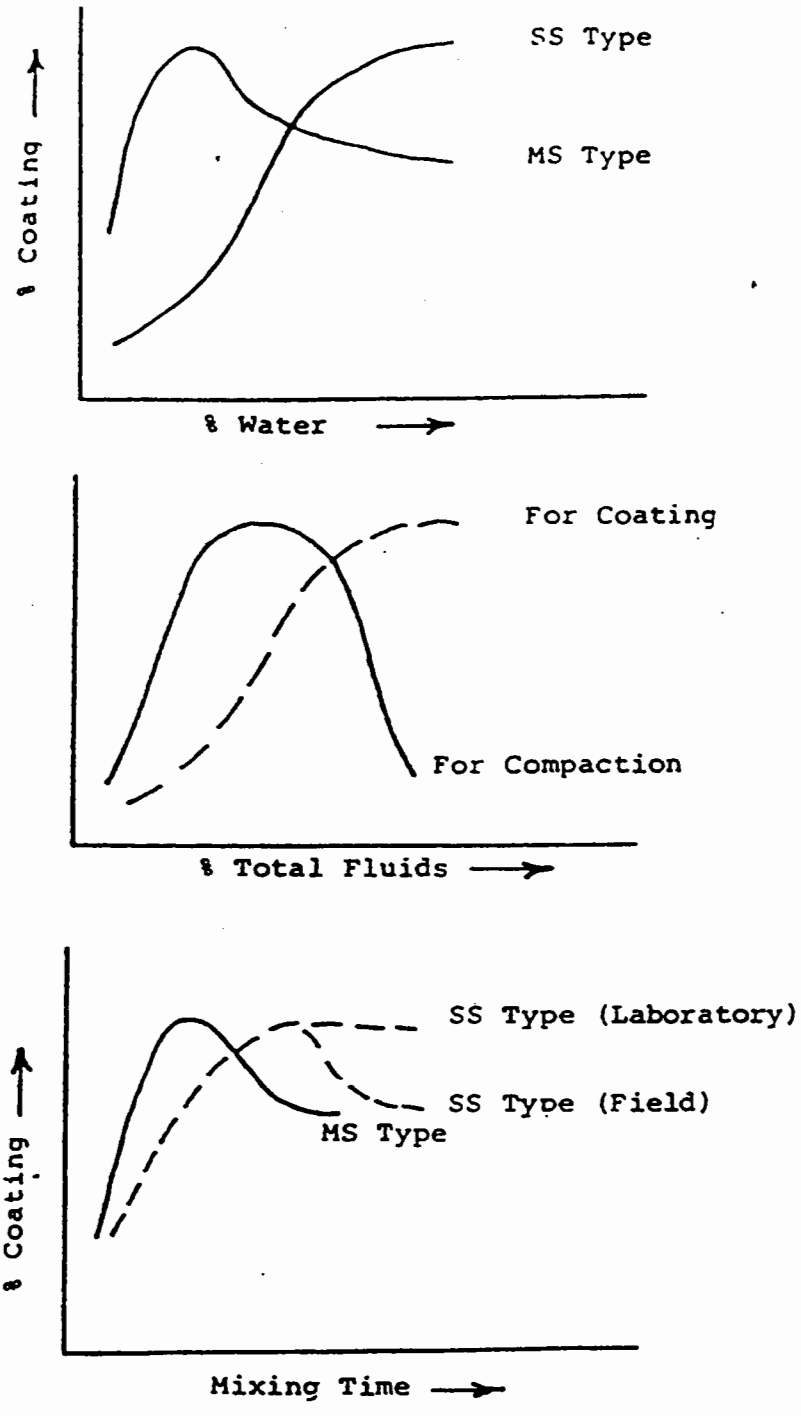


Figure 2-5 Bituminous emulsion mixture characteristics (after Waller, 1980)

In determining the optimum mixing water content, most existing design methods for dense-graded bituminous emulsion mixtures estimate a trial emulsion content using either the Centrifuge Kerosene Equivalent (CKE) procedure, or an empirical equation based on an aggregate gradation (e.g. the Asphalt Institute 1979&1989). In the procedure used by Sabita "South African bitumen and Tar Association" (1993), based on the optimum fluids content (OFC) of a 50/50 blend of emulsion and water with oven-dried aggregate, the water content for mixing can be determined for the emulsion content used as follows:

Water content for mixing = OFC + extra moisture to allow for evaporation and aeration during mixing - the emulsion content used.

Mixing time to a great extent depends on the characteristics of the emulsion-water-aggregate system. Accordingly, no specified mixing time has been reported.

2.2.3 Water Content at Compaction

During the compaction process of bituminous emulsion mixtures, the emulsion acts as a lubricant much as the water in the mixture does. Optimum fluids content (water + emulsion) is usually less than the optimum water content for the aggregate alone. In addition, the maximum density value is often greater with the addition of emulsion (Puzinauskas and Jester, 1983).

Thus, the most favourable combination of residual bitumen and water content at compaction, to maximize dry density, has been the object of several previous studies. Many researchers and agencies have adopted the determination of an optimum combination of emulsion and water content for a predetermined emulsion content. This determines the mixing water content (section 2.2.2); both emulsion content and water content are then varied keeping that optimum content constant.

2.2.4 Compaction

Compaction is one of the most significant factors affecting emulsion-aggregate mixture behaviour. It is recognized that the level of compactive effort for a given compaction method influences a laboratory specimen's density. Besides, compaction is recognized as another source contributing to emulsion breaking and bitumen droplets' coalescence onto aggregate particles.

Various compaction methods have been used to fabricate cold mixture specimens in previous studies. These methods included the following:

1. *Marshall hammer (impact compaction)*:

The mixture is compacted in a mould by repetitive applications of impact load, using a 4.5 kg hammer which is allowed to free-fall a height of 457 mm. 50 blows of compaction per face has been recommended by many researchers (e.g. The Asphalt Institute, 1989 and Gadallah et al, 1977). The aim is to limit aggregate degradation and to match the compaction effort for hot mixtures. However, Darter et al (1978 & 1980) found that 75 blows gives densities comparable to the field density after approximately two years trafficking.

2. *Static compaction*:

The mixture is normally compressed under a gradual application of a static load. Generally, the mixture is rodded prior to compaction and a "double plunger" arrangement is used to promote homogeneity (The Asphalt Institute, 1989).

The Duriez method is also employed for compaction of emulsion-aggregate mixtures. Samples in 80 mm diameter moulds are subjected to a static load of 12 tonnes for 5 minutes. Similarly, Fordyce et al (1993) used a modified Duriez method, by means of a compaction-consolidation technique (loading and unloading of 100 mm diameter samples). High applied loads, 10 kN followed by 30 kN, were used to allow drainage of most of the water contained in the mixtures. Similar dry densities of laboratory compacted 6 mm moulded macadam mixtures and cores, in the order of 2.139 and 2.130 kg/m^3 respectively, have been reported by Robinson et al (1996). However, nothing in the comparison was

reported on the water contents produced in the mixtures after compaction or on the mechanical properties. Water content after compaction and the cohesion built up in the mixtures due to the compaction procedure will have a great influence on the material performance. Khalid and Eta (1996) also used a static load of 85 kN for 5 minutes/side, on Marshall size specimens confined in a split mould with a perforated base plate.

3. *Gyratory compaction*:

The mixture is subjected to a torsional shear force by applying a gyratory motion to the specimen while pressure is maintained on the specimen faces by means of a compaction ram (Tia and Wood, 1985[b]).

4. *Vibratory compactor*:

Hickes et al (1979) studied the effect of compaction methods namely, Marshall hammer and vibratory air hammer on the stress-strain behaviour of open-graded emulsion specimens (4×8 inch and 1.77-1.85 g/cm^3) through the repeated load triaxial test. They have reported that samples compacted by the Marshall hammer showed higher stiffness at an early curing stage because of some crushing of the aggregate. As specimens cured, modulus values increased due to the effects of bitumen and the resulting modulus values of the both methods were similar - see Figure 2-6. In addition, Hickes et al noted that the vibratory hammer can produce the necessary densities without the high contact pressures that result in aggregate degradation.

However, nothing in the literature has been found about the use of roller compaction in the laboratory, even though it can closely simulate field compaction conditions in terms of the orientation of aggregate particles and density of the mixture. The reason might be because of the difficulty of coring or sawing from rolled slabs for such types of mixture at an early curing stage.

2.2.5 Curing

Once a bituminous emulsion mixture has been compacted, curing and strength increase occur. Previous studies have indicated that curing time, environmental conditions such as temperature and humidity, and mixture voids are factors affecting the rate of moisture loss.

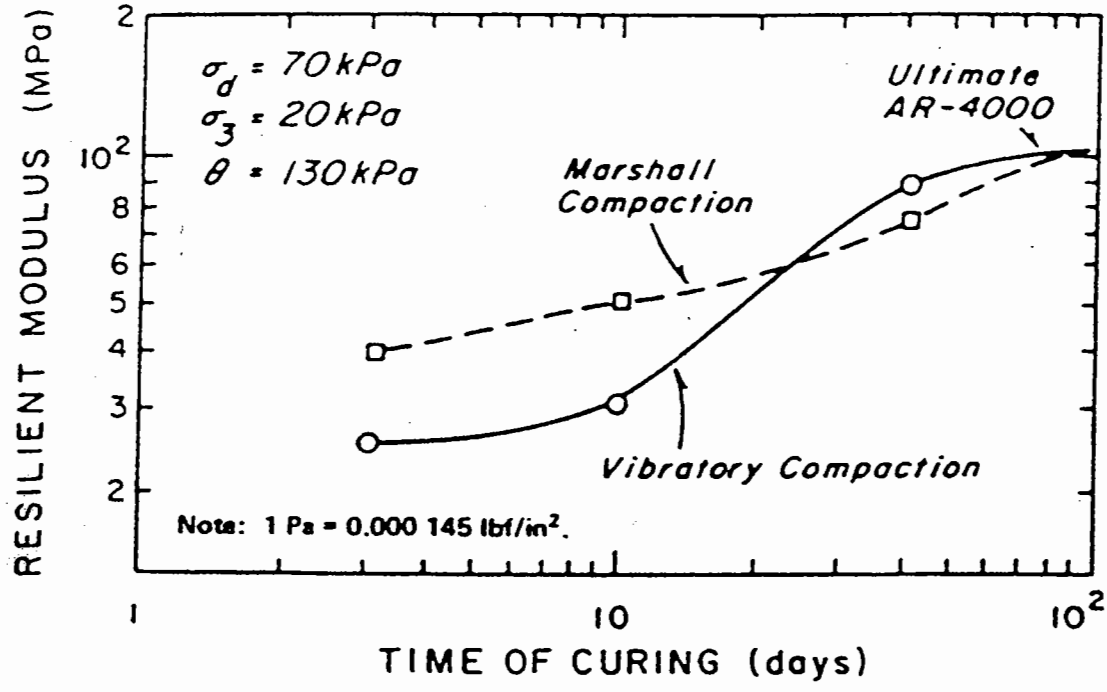
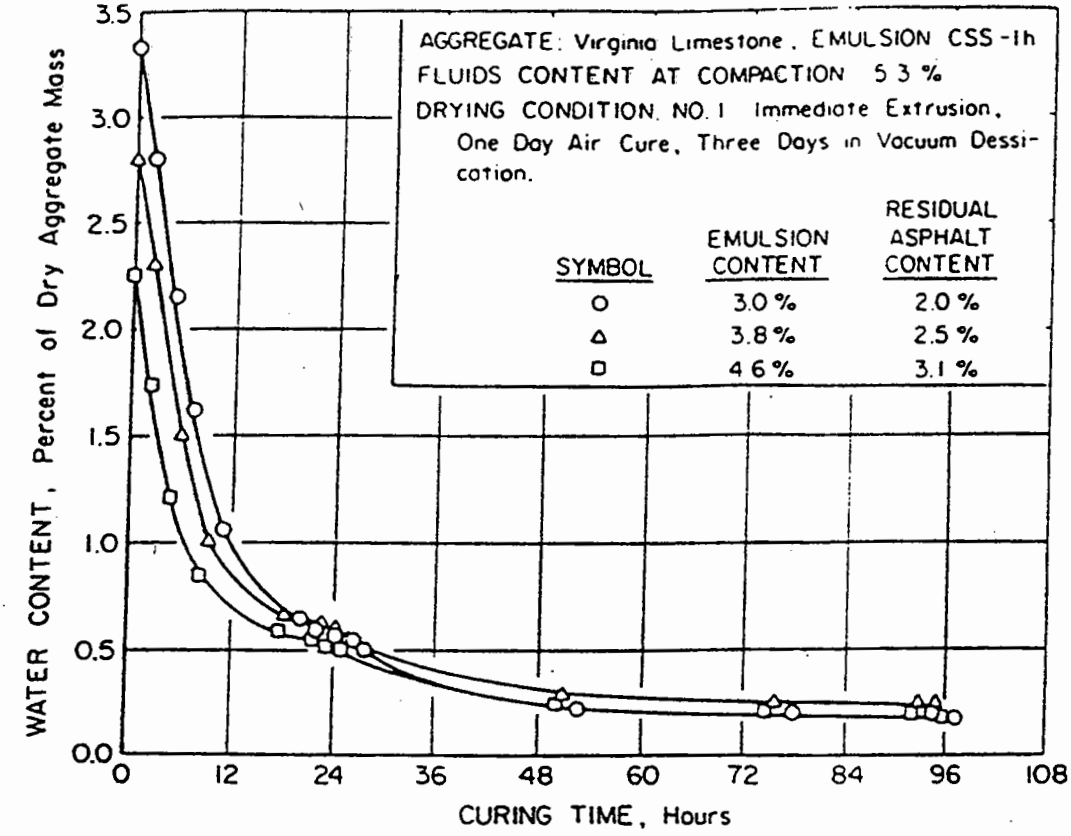


Figure 2.6 Resilient modulus versus curing time for open-graded emulsion mixture specimens prepared using Marshall and vibratory compaction procedures (after Hickes et al, 1979)

Initially, the rate at which emulsion mixtures gain strength is much more rapid than towards the final cured state. According to Finn (1968), Santucci (1977), and Marrais and Tait (1989), the curing period may be as much as 6 months in dry climatic regions and two years in wet climatic regions. Due to this change of properties with curing time, a laboratory curing regime must be able to produce specimens that will in a short time exhibit behaviour representing that in the field. Various laboratory curing methods have been established. These methods have included oven curing (e.g. Gadallah et al, 1977, Mamlouk et al, 1980, and Marais and Tait, 1989) and vacuum desiccation (e.g. Darter et al, 1980, and the Asphalt Institute, 1979) of the specimens both in and out the mould for a range of temperatures and times.

Puzinauskas and Jester (1983) investigated the effect of different curing methods on specimen moisture losses. The curing procedures followed and the results are presented in Figures 2-7 to 2-9. They reported that the majority of water loss occurred during the first two days regardless of the emulsion or the water content used, for all the curing conditions followed, and recommended a two-day curing period to be used.



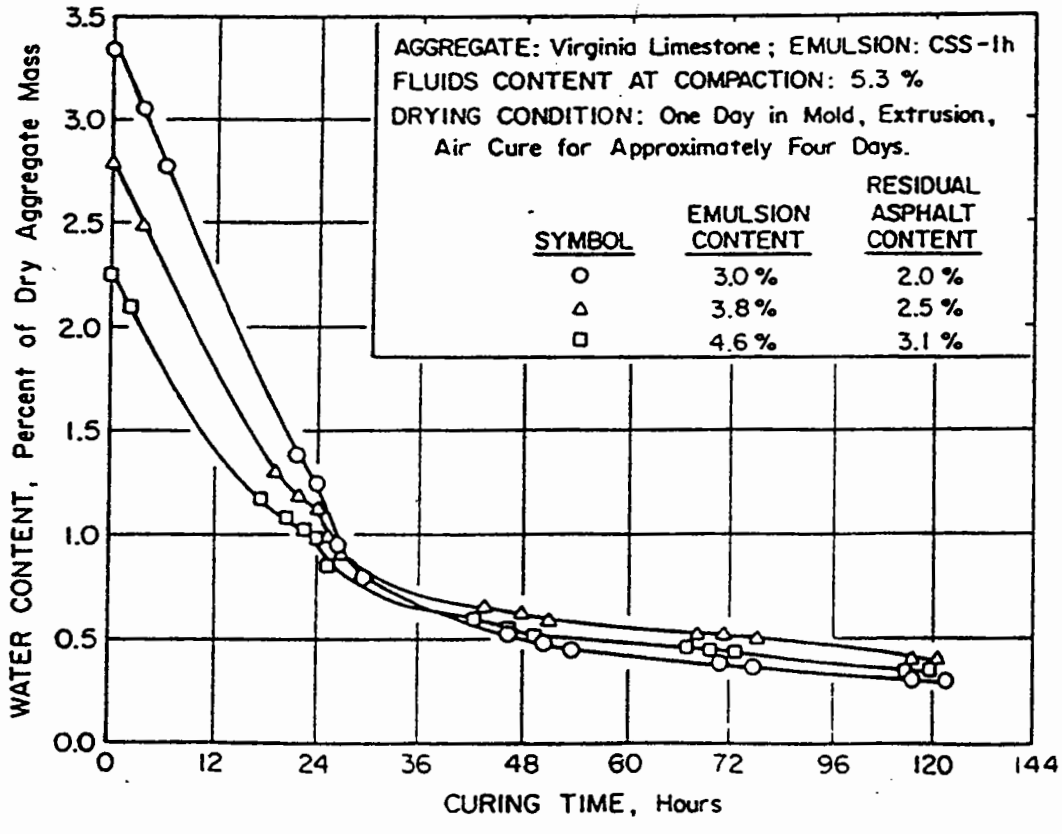
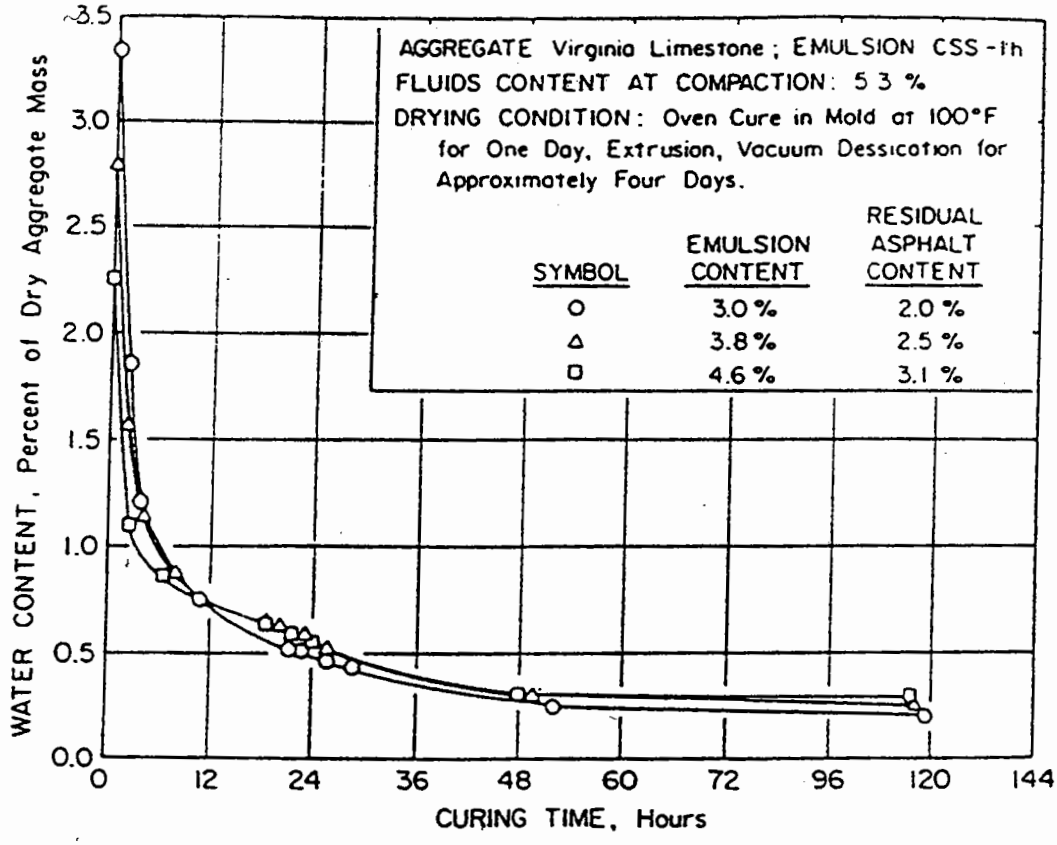


Figure 2-7 Effect of emulsion and water contents on drying of dense-graded emulsion mixes, drying condition No. 1& 2 (after Puzinauskas and Jester, 1983)



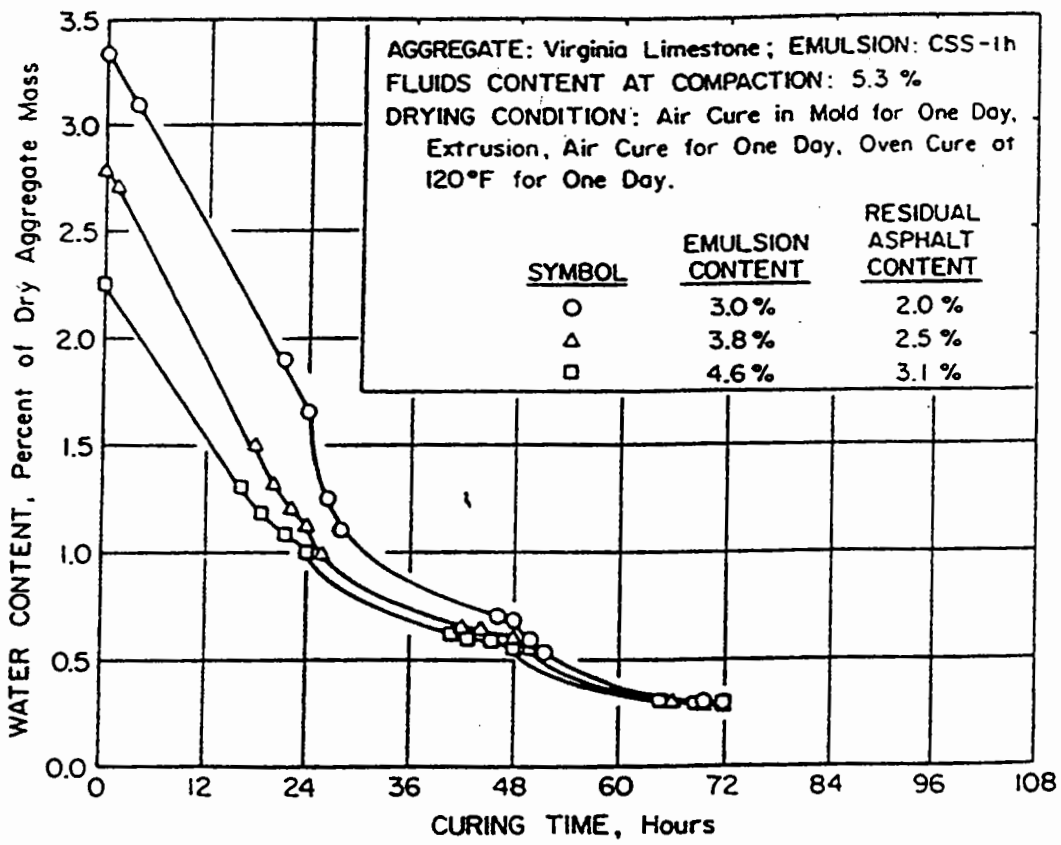


Figure 2-8 Effect of emulsion and water contents on drying of dense-graded emulsion mixes, drying condition No. 3 & 4 (after Puzinauskas and Jester, 1983)

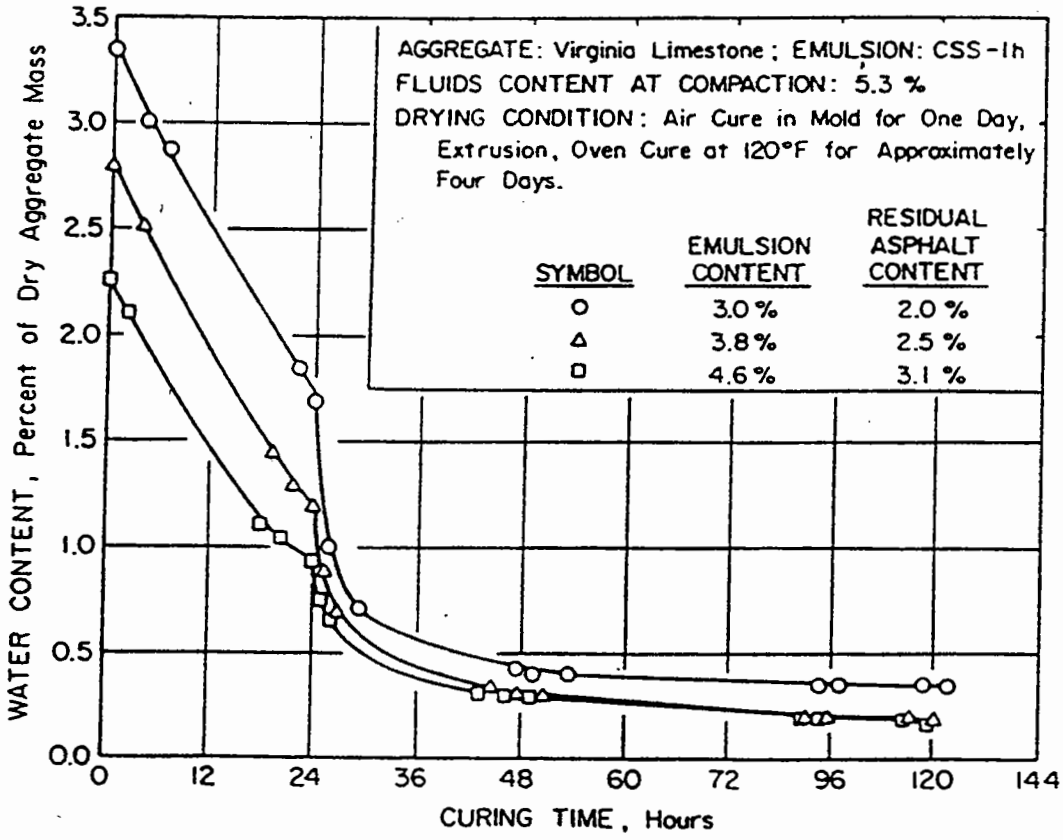


Figure 2-9 Effect of emulsion and water contents on drying of dense-graded emulsion mixes, drying condition No. 5 (after Puzinauskas and Jester, 1983)

2.2.6 Production of Emulsion-Aggregate Mixtures

Manufacturing processes of emulsion-aggregate mixtures include:

- *Stationary or batch mixing plant*:

  This is used for small scale production. The mixtures normally contain fluxed bitumen emulsions to be workable, allowing storing for future use (7 hours to a month).

- *On site manufacture or continuous mixing plant*:

  This plant is for immediate use. The mixtures normally contain non-fluxed emulsions.

The aggregate is fed to a pugmill or rolling drum mixer. Water is added to the naturally wet aggregate without drying. Emulsion is then added in a stream and the aggregate-emulsion combination is mixed at ambient temperature until maximum coating is achieved without breaking of emulsion.

Three type of mixtures can be produced according the material composition:

1. *Open graded mixtures*:

   This type of mixture can be laid using low technology but the material is highly porous and relatively easily deformable. Voids content is normally greater than 15 %.

2. *Semi-dense mixtures*:

   These have greater cohesion and are less permeable.

3. *Dense graded mixtures*:

   No solvent is used with these mixtures for rapid curing. They have high cohesion and good resistance to deformation.

2.2.7 Determination of Optimum Emulsion Content

As there are many methods for determining optimum moisture contents and for curing of laboratory specimens, there are also many methods to determine optimum emulsion content. However, most of the design methods are either modifications to Marshall or Hveem methods for conventional hot-mixtures, or trial and error processes.

A summary of emulsion mixture design procedures from the literature is presented in Chapter 11 for comparison with a design method proposed in this research.

2.3 MECHANICAL PROPERTIES OF EMULSION-AGGREGATE MIXTURES

This type of slow curing mixture (up to 2 years) has often been characterised in the same way as hot bituminous mixtures. Properties of the material include strength characteristics, permanent deformation, fatigue resistance, and water sensitivity. However, many field trials which have been carried out for performance evaluation of this type of mixture under different environmental and/or traffic conditions have revealed that it behaves in a way different from hot mixtures. The following sections present properties of the material from the literature and laboratory tests used to assess them.

2.3.1 Strength of Emulsion-Aggregate Mixtures

Both the Marshall test and the indirect tensile strength test have been used. The Marshall test procedure is performed on cylindrical specimens, positioned between two steel jaws, as shown in Figure 2-10. Load is diametrically applied at a constant rate of deformation (50 mm per minute). The maximum load sustained by the specimen (stability) and the deformation to the maximum load (flow) are then measured.

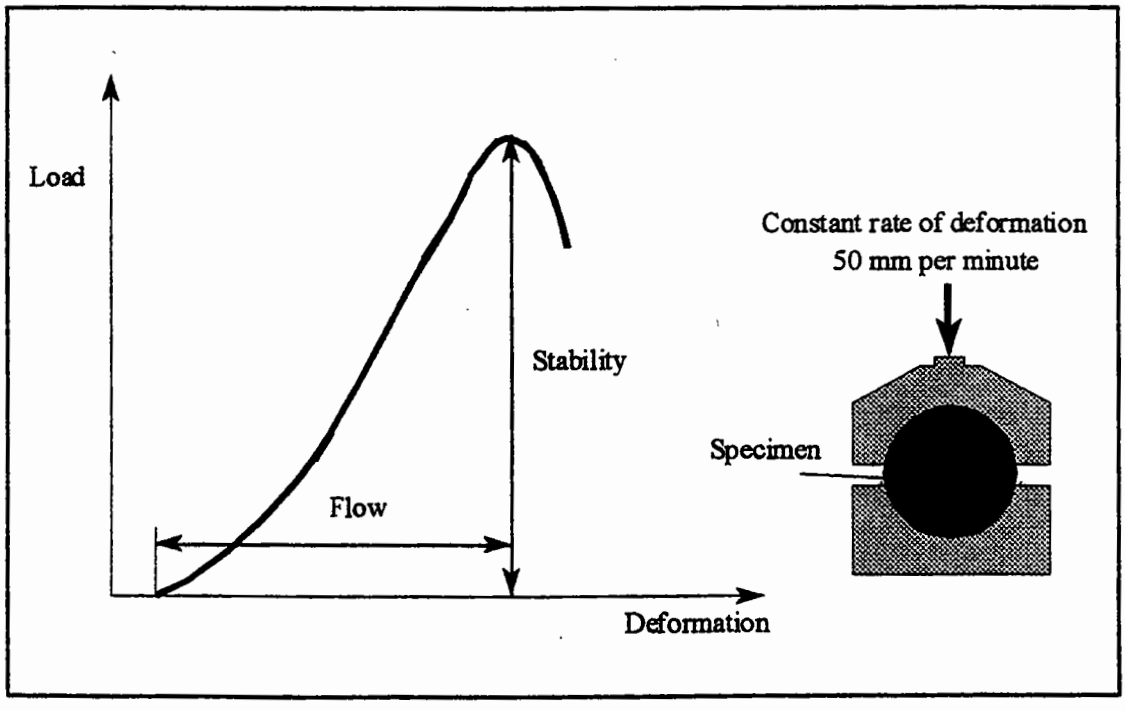


Figure 2-10 Marshall testing and test output

Marshall stability has been used extensively by many researchers on dense graded emulsion-aggregate mixtures (unsoaked and soaked specimens) for mix design purpose (for example: Darter et al, 1980; Gadallah et al, 1977 & 1979; Nikolaides, 1993 & 1994; and Mamlouk, 1980). Marshall stiffness, defined by the ratio of the stability and flow value, and Marshall index, defined by the slope of the linear portion of the load deformation relationship, have also been suggested as potential parameters for controlling properties of emulsion-aggregate mixtures.

Indirect tensile strength is the maximum load the specimen can resist determined by applying a line load diametrically at 50 mm per minute. The concept of this test is similar to that of Marshall.

However, both tests are able to rank the material, as it has been found that test results from both are sensitive to mixture variables indicating similar trends. Generally, Marshall stability and indirect tensile strength values of emulsion-aggregate mixtures are considerably less than those of hot bituminous mixtures, indicating lower cohesion characteristics for the material.

2.3.2 Elastic Response

Resilient or stiffness modulus is often determined using the indirect tensile mode of testing or the repeated load triaxial compression test. Both tests are used to evaluate the relative quality of the material for mix design purposes, and to be used as an input parameter for pavement design.

Indirect tensile stiffness modulus test

This is determined by applying a repeated line load (P) along the diameter of cylindrical specimens (normally Marshall size specimens) and measuring the horizontal deformation (Δh). Stiffness modulus (S_m) can then be calculated from (see also Chapter 5):

$$S_m = \frac{P}{\Delta h \times t}(\upsilon + 0.27)$$

where:

t = specimen thickness, and υ = Poisson's ratio

This test has been identified as an economic and practical means of measuring the stiffness modulus of bituminous mixtures, but is perhaps less satisfactory for investigating properties of material for research purposes. The Nottingham Asphalt Tester (NAT) is one piece of equipment used in performing indirect tensile tests on a routine base (Cooper and Brown, 1989). Since the NAT uses a pulsating load, the instantaneous resilient deformation is difficult to determine and the deformation calculated is close to the maximum deformation induced by the load pulse. According to Nunn and Bowskill (1992), the measurements of this test correlate well with those of the 3-point bending test. The equivalent frequency of a pulsating load with a rise time of 125 ms, defined as the frequency under sinusoidal loading that gives the same stiffness modulus as under the pulsating load of the indirect tensile test, has been reported to be 2.5 Hz, based on empirical correlation between results from both the NAT and 3-point bending tests. Using the rheological model devised by Burger (1935), Nunn (1996) found that the pulse load is equivalent to a sinusoidal load of frequency 1.9 Hz. However, this latter value of equivalent frequency is adopted in this study.

A study of the validity of using the diametral (= indirect tensile) modulus test to determine the resilient modulus of uncured open-graded emulsified bitumen mixtures and interpreting the results in terms of linear elastic theory was carried out by Wallace and Monismith (1980). Theoretical stresses and deformations of the non-linear elastic specimens were calculated using the finite element method and compared with corresponding values for linear elastic behaviour. Figure 2-11 shows the test conditions used. Wallace and Monismith reported that:

1. The deviations from the linear elastic stress distribution were not great; the largest difference was in the tensile stresses in the inner part of the specimen,
2. The results of the diametral modulus test are biased towards the properties of the material in the inner part of the specimen, and
3. Yield of the material within the central region of the specimen would have greatest influence on the test results; therefore, vertical to horizontal stress ratio should be kept low.

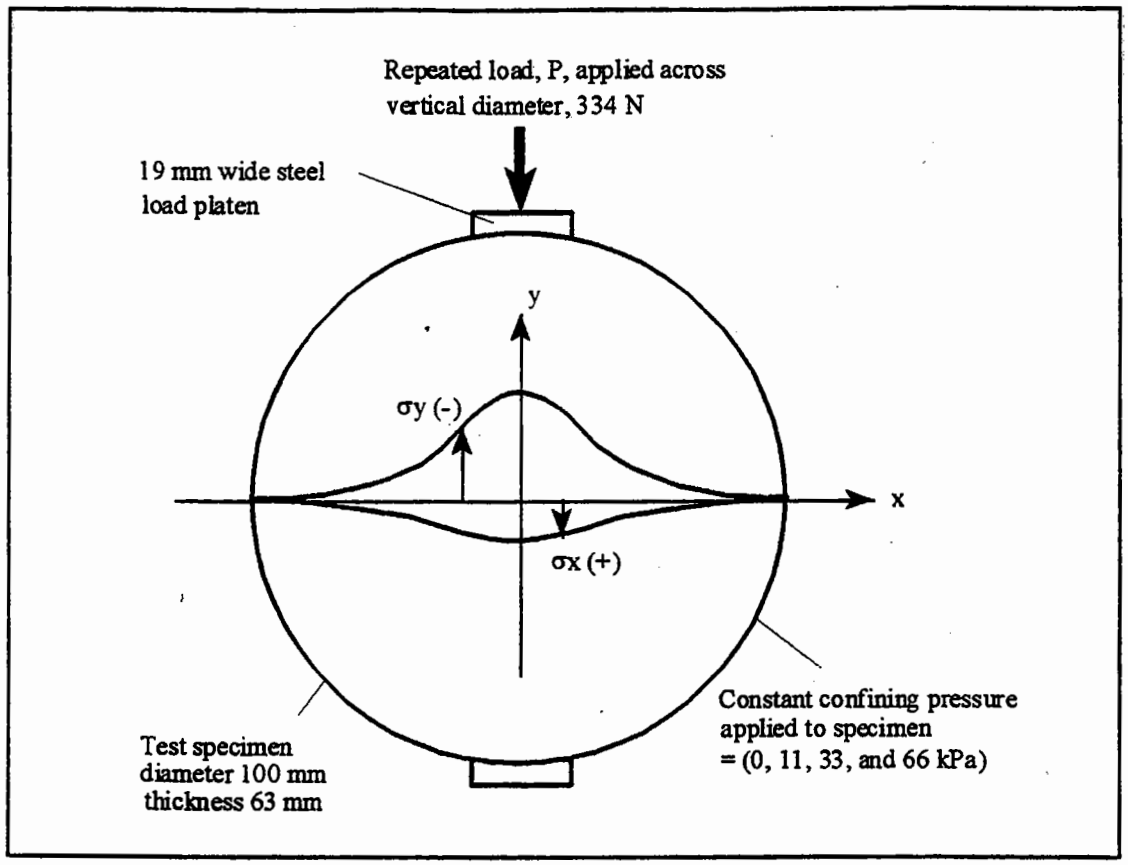


Figure 2-11 Diametral measurement of resilient modulus (after Wallace and Monismith, 1980)

Repeated load triaxial compression test

In this mode, cylindrical specimens are subjected to a confining pressure. Repeated vertical load is then applied and both irrecoverable and recoverable deformation are measured (Transportation Research Board special report 162, 1975). The resilient modulus can then be calculated from:

$$E = \sigma_d / \varepsilon$$

where: E is the resilient modulus

σ_d is the axial deviator stress

ε is the recoverable axial strain

Terrel and Wang (1971) used this mode of testing for evaluation of the effectiveness of using portland cement to increase emulsion-aggregate mixture strength. It has also been used for characterising open graded mixtures and for studying the effect of the compaction method and curing on resilient modulus values (Hickes et al, 1979).

Because of insufficient cohesion in open graded mixtures, they have mainly been characterised by resilient modulus, either from indirect tensile tests or triaxial tests, rather than using Marshall or indirect tensile strength, which are less sensitive to binder content variation.

2.3.3 Fatigue Resistance

Fatigue cracking is the phenomenon of fracture under repeated or fluctuating stress having a maximum value less than the tensile strength of the material. Test methods used in characterising the fatigue resistance of bituminous mixtures are presented in Chapter 7. The literature reveals limited studies on fatigue characteristics of emulsion-aggregate mixtures.

Khalid and Eta (1997[a] & 1997[b]) conducted three point flexural fatigue testing in controlled stress mode at 10°C, on beams dimensioned 240×40×30 mm of 20 mm dense graded base course mixtures and 10 mm close-graded wearing course mixtures, containing 4.9% and 5.6% residual binder content by weight of total mix respectively. The curing regime was 21 days air-curing at 20°C for slabs dimensioned 305×505×50 mm, followed by curing of beams taken from the slabs for 14 days at 20°C using a fan-assisted aerator. Water contents at test have not been reported. However, a lower fatigue resistance for un-modified emulsion-aggregate mixtures was reported compared to hot mixtures.

Santucci (1977), on the other hand, presented fatigue lines as a function of stiffness modulus, applicable to both emulsion-aggregate mixtures and hot bituminous mixtures. That is, both materials have similar fatigue lines for the same modulus. These fatigue lines, however, are applied to mixtures with 5 % air voids and a residual bitumen content of 11 % by volume. To obtain fatigue data for other voids and bitumen contents, Santucci suggested using a formula based on fatigue data from hot mixtures, which will be discussed in Chapter 7.

Marais and Tait (1989) used the fatigue criteria published by Santucci in a pavement design procedure similar to Santucci's method, which was later used by Sabita (1993) because of the lack of fatigue test data on emulsion-aggregate mixtures.

Robinson et al (1996) presented fatigue data for 6 mm macadam mixtures, compacted using Marshall and Duriez methods, from testing in the Nottingham Asphalt Tester in its fatigue mode. The curing regime was 15 days at 40°C. They reported that the static Duriez compactor resulted a fatigue line for the material which matched that of equivalent hot mixtures.

However, Lafon et al (1993) reported that emulsion-aggregate mixtures never fail in fatigue. Snaith et al (1993), in their proposed pavement design method, explained that the material will be damaged in fatigue due to hardening of the binder which occurs with time, as a result of this type of mixture containing high air voids. They therefore expected that the material would behave as an unbound material.

Clearly, there is no agreement on the fatigue response of the material. This may be related to the various material compositions used and the methods of laboratory compaction used, which has to be questioned because of the lack of evidence on correlation between behaviour of field and laboratory compacted specimens.

2.3.4 Permanent Deformation

Most of the emulsion mixture design methods account for deformation by using the Marshall stability or indirect tensile strength of different mixture combinations. The Nottingham Asphalt Tester has also been used, following British Standard DD 185:1994. Khalid and Eta (1996 & 1997[b]) conducted unconfined repeated load axial tests in the Nottingham Asphalt Tester on emulsion mixtures cured for 14 days at 40°C. They reported that dynamic creep values of emulsion mixtures were higher those that of equivalent hot mixtures. This finding supports the conclusions from measurements on trial road sections by some counties in the UK.

However, a noticeable point is that the measurements, either Marshall stability or unconfined repeated load axial have been carried out after a long curing time at high temperatures, to simulate the fully cured state, disregarding the material behaviour during the curing period. The repeated load axial test under unconfined conditions may also

reinforce the difference in the response of the material relative to that of hot mixtures due to the difference in the permanent deformation characteristics of the two mixtures.

2.3.5 Water Sensitivity

Water resistance is incorporated into mixture design procedures, as water is considered one of the main detrimental factors affecting the response of emulsion-aggregate mixtures. The literature reveals many methods of moisture conditioning of the material to simulate environmental effects in the field in a short time. The curing time of the material at which moisture conditioning is carried out is varied from one method to another. In all cases, emulsion aggregate mixtures are recognized as less water resistant compared to hot mixtures.

Methods used in curing specimens before conditioning involved:

- Two to three days curing in or out of the moulds at ambient temperature.
- Oven curing of specimens. Different temperatures have been used.
- Vacuum desiccation of specimens.

In the field, water comes from either surface infiltration or moisture absorption from the underlying layers. The methods published for mix design of emulsion-aggregate mixtures attempt to simulate these field moisture conditions to reflect either the long term performance or the effect of rainfall periods. Laboratory moisture conditioning of specimens has included:

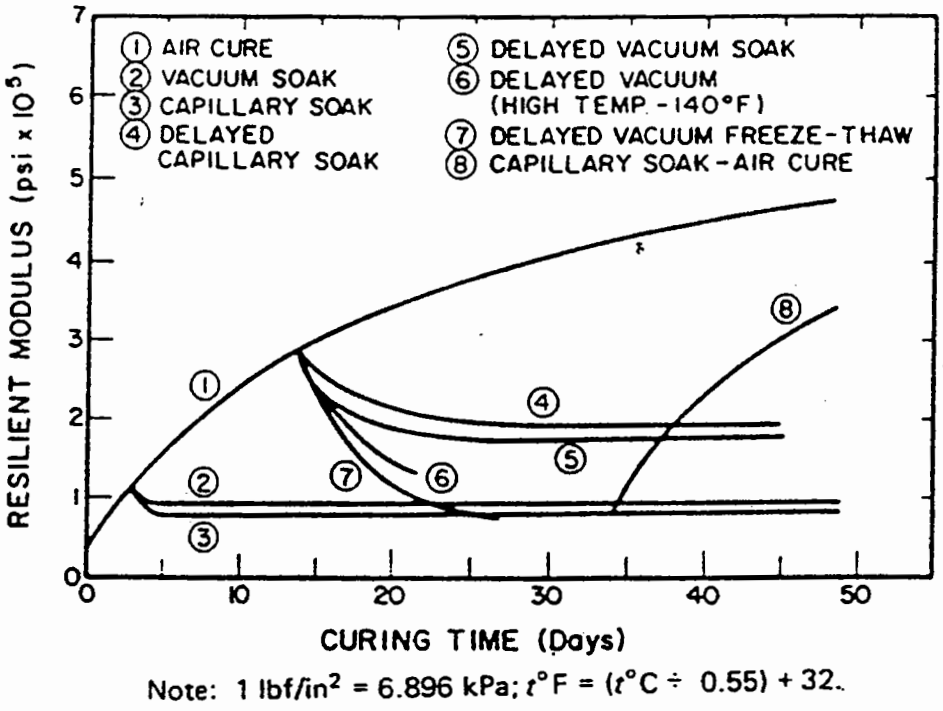
- Vacuum saturation for different periods according to vacuum level (e.g. the Asphalt Institute, 1979 & 1989).
- Capillary soaking (e.g. Darter et al, 1980).
- Immersion of specimens in a water at room temperature (e.g. Tia and Wood, 1985[a]).

Capillary soaking of specimens represents saturation of the material due to ground water. This occurs over a considerable time; therefore, it is realistic to conduct the test on fully cured specimens. The Asphalt Institute method proposes a vacuum saturation at 100 mm Hg for one hour and water immersion for a further one hour at ambient temperature to simulate the effect of prolonged exposure to subsurface water. In the modified Hveem

design method, the Asphalt Institute recommended curing of specimens for 3 days in moulds at room temperature followed by four days of vacuum desiccation after extrusion. On the other hand, in the modified Marshall method the adopted curing regime is curing in the mould for one day and oven curing of extruded specimen at 38°C for another day.

The quantity of fines in a mixture (the percentage passing the 0.075 mm sieve) plays a significant role in the water resistance of the material (Darter et al, 1980). They reported that increasing filler content in emulsion-aggregate mixtures leads to less water resistance and suggested the maximum percentage of filler to be 5 %. They also reported that using a harder base bitumen in emulsion is beneficial for resistance to water.

There is agreement that, upon drying of the soaked mixtures, an increase in the elastic stiffness occurs, corresponding to the value before soaking. That is, the stiffness modulus of the material is reversible. Figure 2-12, taken from Darter et al (1980), shows the effect of various moisture exposure methods as a function of the curing process.



Note: 1 lbf/in^2 = 6.896 kPa; t°F = (t°C ÷ 0.55) + 32.

Figure 2-12 Resilient modulus of emulsion-aggregate mixture as affected by various curing conditions (taken from Darter et al, 1980)

CHAPTER

3 OTHER COLD BITUMINOUS MIXTURES VERSUS EMULSION-AGGREGATE MIXTURES

3.1 FOAMED BITUMEN MIXTURES

Under road conditions, both foamed and cut-back bitumen mixtures are similar in some ways to emulsion mixtures. All three require curing in the field before reaching their ultimate strength. However, cut-backs are not considered further here because their use in cold mixtures is not significant.

Foamed bitumen is produced by injecting water and foaming agent into heated bitumen as they pass under pressure through a specially designed nozzle. Properties of the foamed bitumen reported by many researchers include low apparent viscosity, substantial increase in surface area and a change in surface or interfacial tension. These properties enable foamed bitumen to coat moist aggregate surfaces, in particular, the 'fines' fraction.

Previous studies have revealed that the physical properties of the foam that affect the final mix characteristics are foam ratio (expansion) and half-life stability. Foam ratio is the ratio (in millilitres per gram) of maximum foam volume for a given sample to mass of bitumen in the sample. Half-life stability is the time (in seconds) required after the discharge of the sample is completed for the foam to collapse to half of the maximum volume attained. Bowering and Martin (1976) reported that the most effective foam is that having a foam ratio of 10 to 15 which can be produced by injection of between 1 and 2 percent water. Satisfactory foam at this expansion level typically takes between two and three minutes to deflate to half its original volume. According to Ruckel et al (1983), 8-15 and at least 20 sec for foam ratio and half-life respectively are recommended limits. However, foam ratio and half-life, as illustrated in Figures 3-1 and 3-2, are affected by a) the amount of water in the foam, b) the foaming temperature of the bitumen, and c) the amount of foam produced. In general, increasing the foaming temperature and also

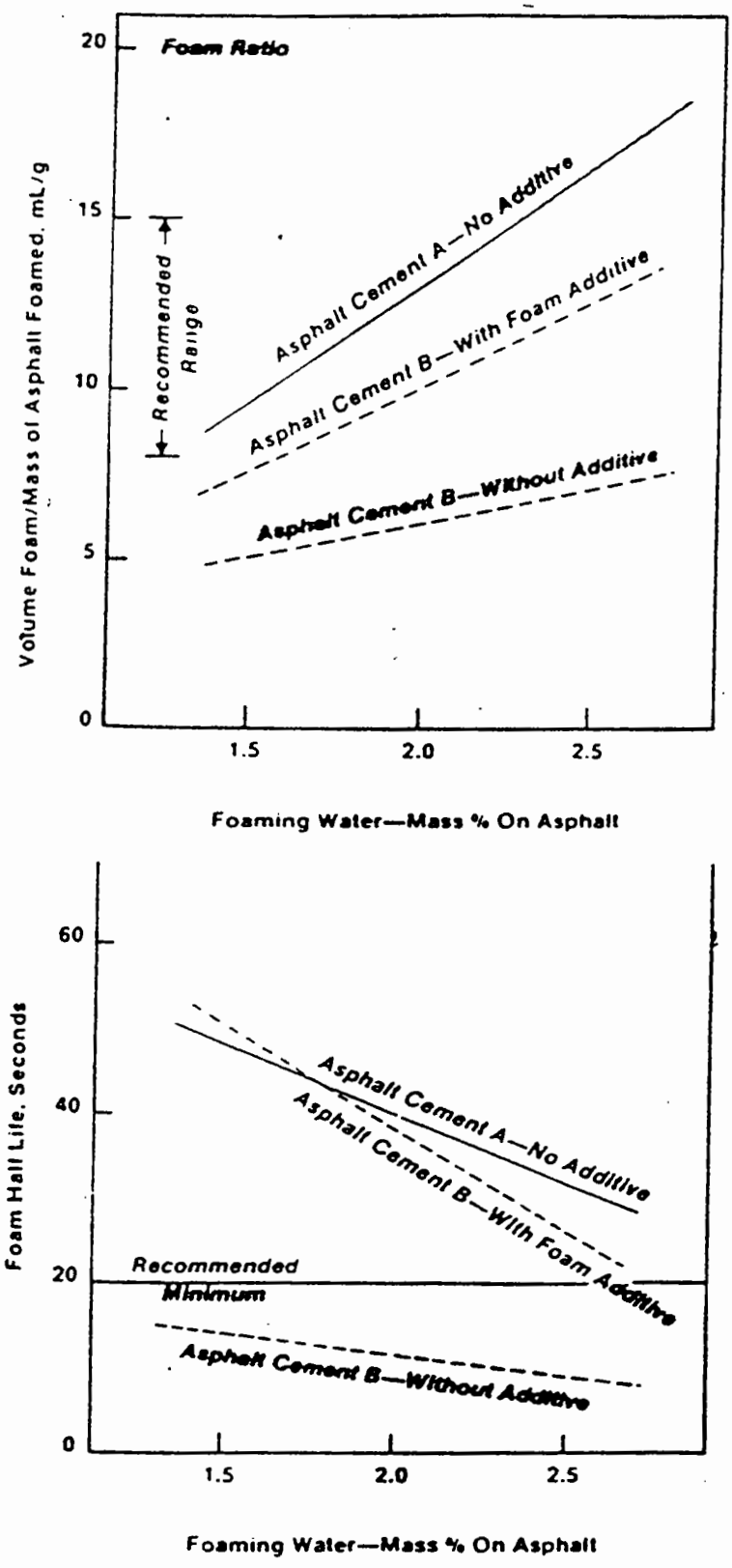


Figure 3-1 Foamed-bitumen quality controls versus foaming water addition ratio (after Ruckel et al, 1983)

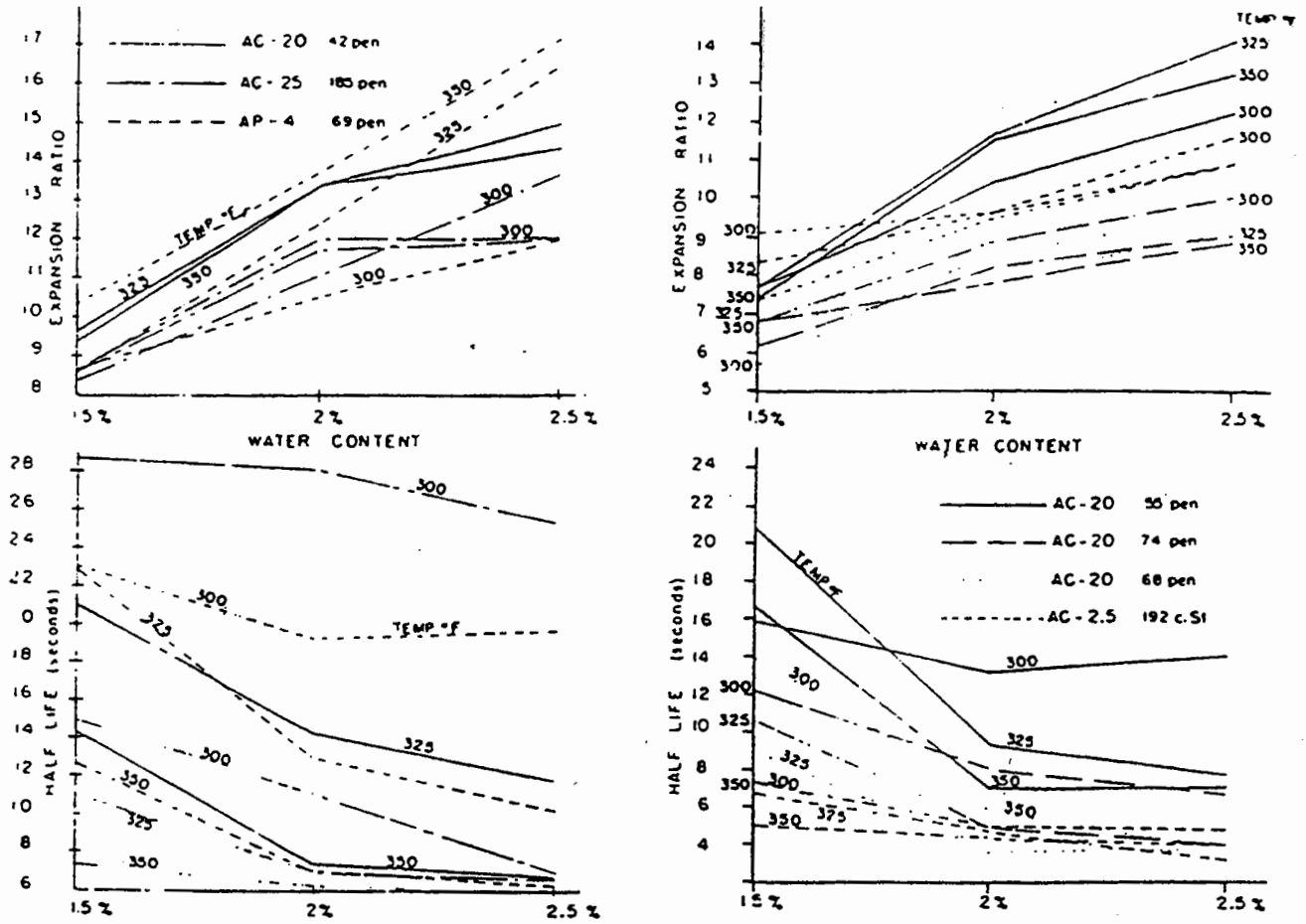


Figure 3-2 Expansion ratios and half lives at various temperatures and water contents (after Brennen et al, 1983)

Table 3-1 Representative data for foamed mixtures (after Bowering and Martin 1976)

Soil Group (Unified-Soil) Classification	Suitability For Use With Foam	Range of Bitumen Contents		Cohesion	Gravel Equivalency of Mix	Remarks
		Full Range	Optimum Range (Best Mix)			
GW	Good	1.5 — 5.0	2.0 — 2.5	300 — 700	1.25 — 1.5	Permeable Mixtures
GW-GC GW-GM	Good	1.5 — 5.5	2.0 — 4.5	300 — 400	1.25 — 1.33	Permeable Mixtures
GP-GC	Good	1.5 — 4.0	2.5 — 3.0	300 — 400	1.25 — 1.33	Low Permeability
GC	Poor	4.0 — 6.0	4.0 — 6.0	300 — 400	1.25 — 1.33	Impermeable Bitumen Content critical Can be improved by adding small percentages lime
SW	Fair	3.5 — 5.0	4.0 — 5.0	100	Nil	Needs addition of -200 mesh filler
SW-SM	Good	1.0 — 6.0	2.5 — 4.0	100 — 400	1.00 — 1.33	
SP-SM	Poor	4.5 — 6.0*	3.0 — 4.5	100	Nil	Needs lower penetration bitumen and addition of -200 mesh filler
SP	Fair	1.0 — 6.0	2.5 — 5.0	100 — 300	1.0 — 1.25	May need addition of -200 mesh filler
SM	Good	1.5 — 6.0	2.5 — 4.5	100 — 400	1.00 — 1.33	
SM-SC	Good	2.5 — 6.0	4.0	400 — 700	1.33 — 1.5	
SC	Alone — Poor (With lime — Good)	3.5 — 6.0* —	4.0 — 6.0 3.0 — 4.0	400 — 700	1.33 — 1.5) 1.33 — 1.5)	Needs addition of small percentage of lime

increasing the water content have the effect of increasing the foam ratios but decreasing the half-life of the foams.

Bowering et al presented a wide range of aggregates which can be improved by foamed bitumen (Table 3-1). Attention was given to the fine fractions of aggregate (materials passing 0.075 mm sieve) in this type of mixture. Fines should be at least 3%, and greater than 5% is preferred.

Like emulsion mixtures, moisture in foam-bitumen mixtures is required to break down aggregate agglomeration and aid bitumen dispersion during mixing as well as to assist compaction. Use of the moisture content at which the loose material has its maximum bulk volume "fluff point" as the mixing water content was recommended by Bernnen et al (1983). Lee (1981) recommended that 65 to 85 percent of the material optimum moisture content, determined by the standard AASHTO test (T99), be used for mixing. Total fluid content (mixing water + foamed bitumen) has also been proposed in determination of water content for mixing and compaction.

It was reported that foam-bitumen mixtures have an advantage over emulsion mixtures in not requiring pre-compaction curing, that is they can be compacted immediately after mixing, without aeration, so that solvent or excess amounts of water are not trapped in the layer. However, Lee concluded: "while no curing is required before compaction, foamed asphalt stabilized mixes do need curing to improve coating and to develop strength".

In a procedure proposed by Ruckel (1983), optimum aggregate moisture content is determined from a moisture content/dry density compaction curve, in which the moisture content is varied keeping an estimated design bitumen content constant. The bitumen contents presented in Table 3-2 have been proposed based on aggregate grading:

Table 3-2 Estimated bitumen contents for use in establishing moisture content/dry density compaction curves (after Ruckel, 1983)

Passing no. 4 sieve, %	Passing no. 200 Sieve, %	Foamed bitumen on dry aggregate, %
less than 50	3.0 to 5.0	3.0
	5.0 to 7.5	3.5
	7.5 to 10.0	4.0
	> 10	4.5
greater than 50	3.0 to 5.0	3.5
	5.0 to 7.5	4.0
	7.5 to 10.0	4.5
	>10	5.0

Generally, it can be concluded that the sequences for preparing foamed-bitumen and bituminous emulsion mixtures are similar. A procedure for preparing such mixtures is presented in Figure 3-3. However, because the bitumen in foamed mixtures is applied in a foamed condition, the quantity of components will be different from those in the emulsion mixtures.

Foamed bitumen mixtures tend to improve with age, traffic and temperature, contributing to the removal of moisture in the mixture. The effect of curing conditions on moisture content and Marshall stability was studied by Lee (1981). The results are presented in Figure 3-4. According to Lee, the gain in strength was accompanied by loss of moisture and, approximately, the same stability resulted when the specimens were cured to the same moisture content.

However, it has been shown that there are significant differences in the performance between foamed bitumen and slow setting bitumen emulsion mixtures. Bowering and Martin (1976), and others have shown that for certain aggregate mixtures, at bitumen contents greater than 1.5 percent, the specimens that incorporated the foamed binder had more desirable engineering properties than those with bitumen emulsion. It was believed

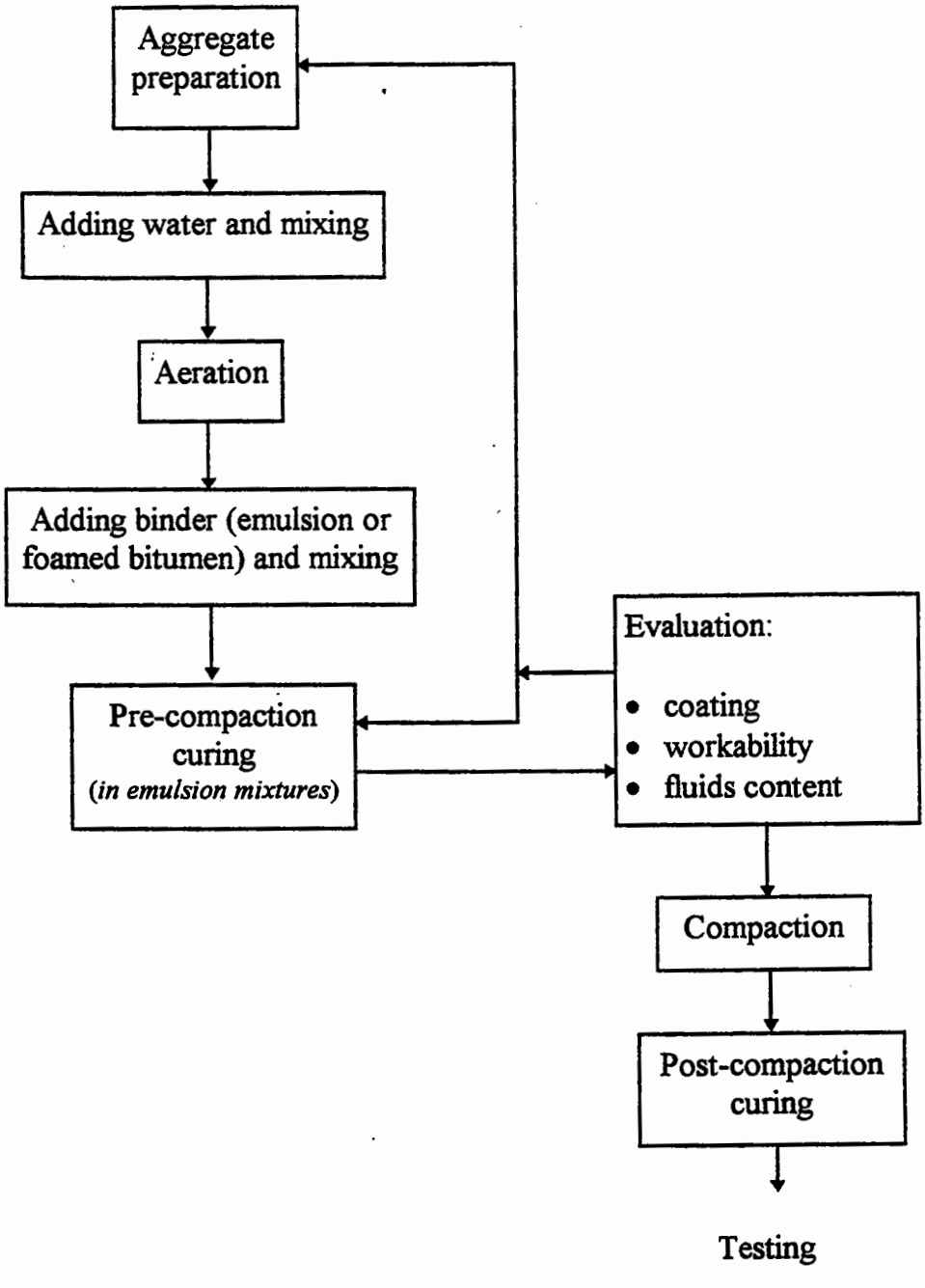


Figure 3-3 Preparation procedure of cold mixtures

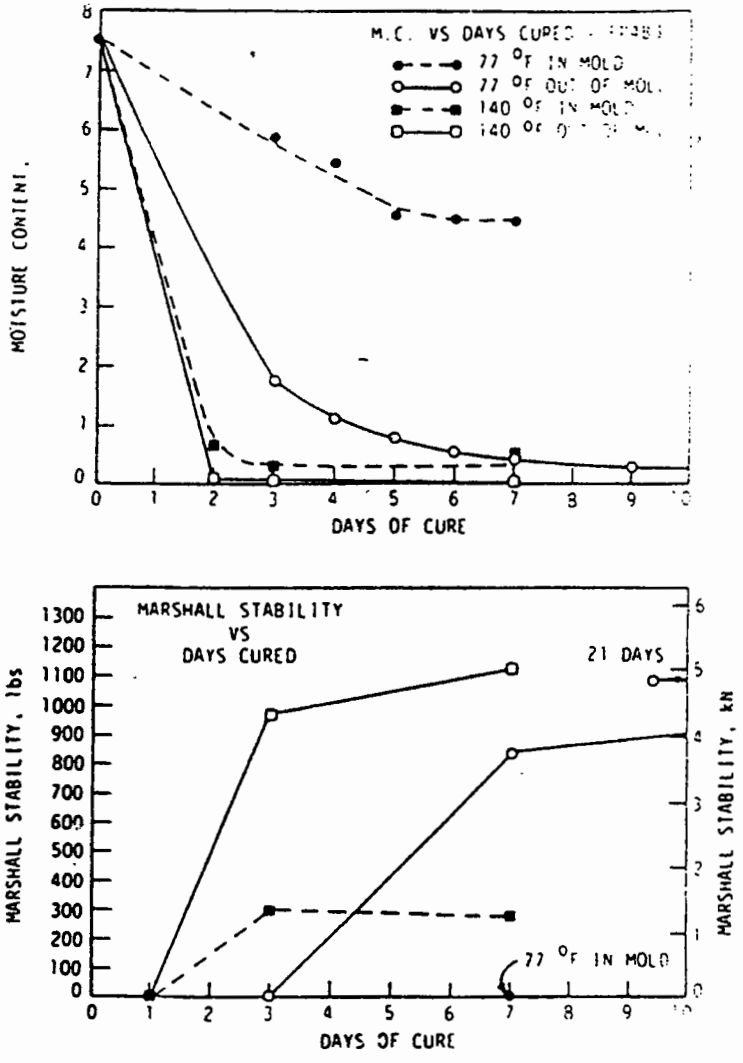


Figure 3-4 Effect of curing conditions on moisture content and Marshall stability (after Lee, 1981)

that the foam system, by concentrating the binder in the fines, results in a stronger mortar fraction.

3.2 COLD MIX RECYCLING

Cold mix recycling is a process in which the reclaimed asphalt pavement is combined with a stabilizing agent (bitumen emulsion, foamed bitumen, or cut-backs), and perhaps new aggregate, without heating in place or at a central plant.

Epps (1990) reported that cold in-place recycling has two forms of construction: full-depth and partial depth. Full-depth cold in-place recycling is a rehabilitation technique in which the full asphalt pavement structure and a predetermined portion of the base material are uniformly crushed, pulverized, and mixed with additional aggregate if required and a stabilizing agent, resulting in a stabilized base course (normal depth is 10-30 cm). Partial-depth cold in place recycling is a rehabilitation technique of a portion of the existing bituminous materials (normally 5-10 cm).

According to Epps (1990) and Roberts et al (1984 & 1991), cold mix recycling is only used to form a base course for low-to-medium traffic volume highways, because cold mixtures are not structurally as strong as hot mixtures.

Problem areas have been cited with cold recycled mixtures, some similar to those with cold mixtures using virgin materials (e.g. Epps, 1990 and Kazmierowski et al, 1992), including:

- construction variation is larger for in-place than central plant operation.
- curing is required for strength gain.
- strength gain and construction are susceptible to climatic conditions.
- cold recycled mixtures do not have adequate resistance to either abrasion by traffic or moisture induced damage.

Design of cold recycled mixtures involves the following basic steps:

- Obtaining representative field samples.
- Evaluation of the recycled materials, where the contained aggregate and bitumen are evaluated independently.
- Selection of the amount and gradation of new aggregate if required to correct the gradation of the reclaimed aggregate material. Its quality should not be less than that of the reclaimed aggregate material.
- Estimation of bitumen demand.
- Selection of the type and amount of stabilizing agent (recycling agent).
- Mixing, compacting, and testing of trial mixtures to determine initial and final cure properties as well as water sensitivity.
- Establishment of job mix formula.
- Adjustment in the field.

In determining optimum binder content, limiting mix design criteria based on cold asphalt mixture technology have been proposed by many researchers (e.g. Santucci and Hayashida, 1983). On the other hand, in the Asphalt Institute method (1983), total binder demand is determined based on the used aggregate gradation; then, according to the reclaimed bitumen content, the required added binder content can be determined.

As for cold mixtures using virgin materials, resilient modulus (M_R) development of recycled mixtures occurs rapidly during the early cure period due to a loss of water from the breaking of the cold binder and/or a loss of solvent from the recycling agent. According to Santucci and Hayashida (1983), some fluxing of the recycling agent and aged bitumen in the RAP may take place during the curing period. As shown in Figure 3-5, after loss of most water where little change in the mixture's weight occurs, the increase in M_R is attributed to the increase of the binder viscosity due to fluxing or blending of the recycling agent residue and aged bitumen.

In a comparison between the performance of two recycled pavement sections built with foamed bitumen and emulsion as binders, Wijk (1983) reported that determined AASHTO structural coefficients of the foamed-bitumen recycled layer during the first 400 days after construction ranged from 0.2 to 0.42 and of the emulsion recycled layer

from 0.17 to 0.41. Accordingly, he concluded that the performances of the two recycled materials are the same and that they consequently have the same service life.

Also, Roberts et al (1984) studied the properties of salvaged materials, recycled using foamed bitumen, and compared the results with those of recycled mixtures using cutbacks and emulsions. Curing conditions were: 1) four days at 140°F followed by either three days at 75°F (dry condition) or submerged in water at 75°F (wet condition), and 2) four days at 75°F and three additional days either dry or submerged in water (wet) at 75°F. They reported that the wet tensile strengths of all mixtures were less than approximately one-half the dry tensile strengths, but the tensile strengths for the specimens prepared with foamed bitumen were higher than those for specimens prepared with either of the other materials (Figure 3-6).

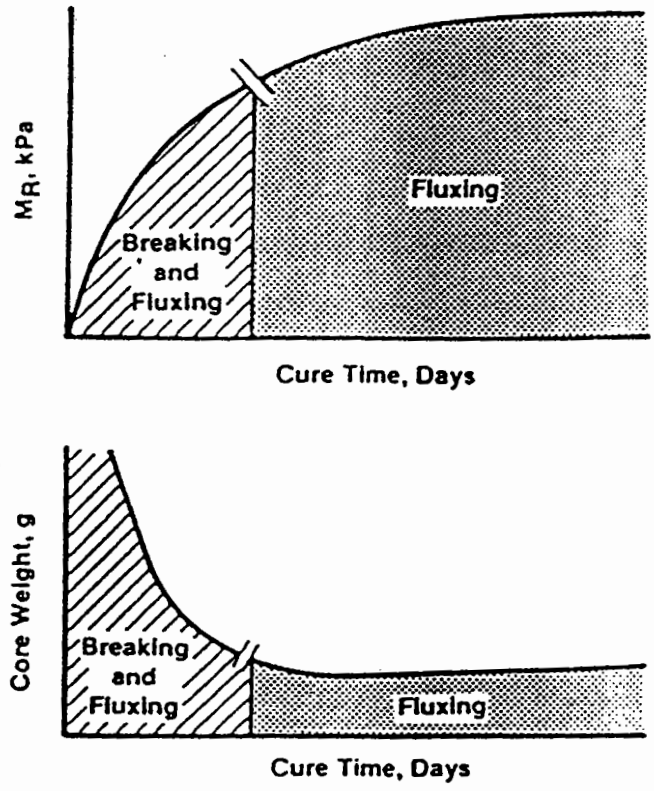


Figure 3-5 Development of modulus with curing time of cold recycled mixtures (after Santucci and Hayashida, 1983)

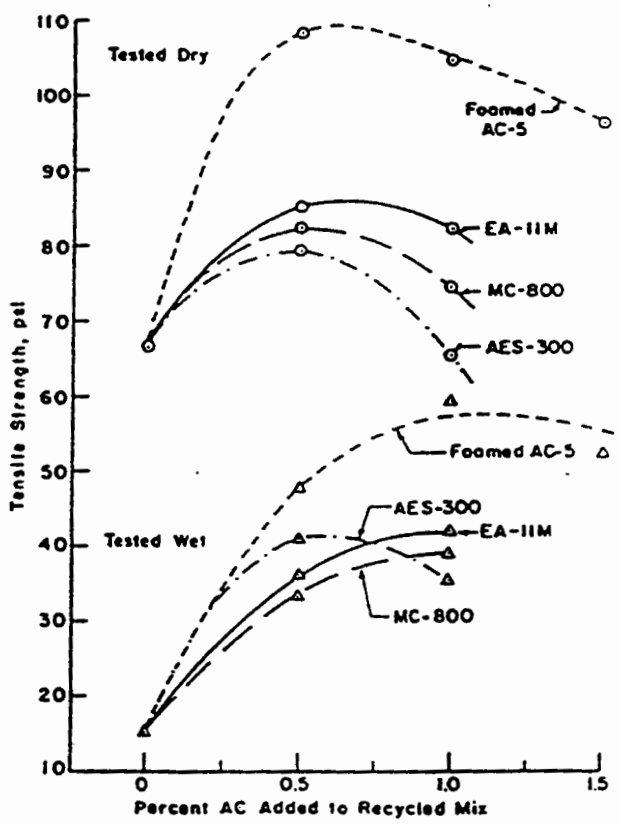


Figure 3-2 Comparison of tensile strength results for foamed, emulsion, and cutback specimens (after Roberts et al, 1984)

3.3 CONCLUDING COMMENT

The behaviour of emulsion-aggregate mixtures and foamed bitumen mixtures are, to a great extent, different. In foamed bitumen mixtures, the bitumen adhesion with the fine fraction of the aggregate plays the major role in the response of the mixture, while the interaction of the emulsifier contained in the emulsion with the aggregate particle surfaces is the dominant factor affecting the behaviour of emulsified asphalt mixtures. Consequently, the design of these mixtures is completely different. In other words, the optimum of the mixture components, i.e. added water content, water content at compaction, and residual bitumen content might be different.

In the literature, comparisons between cold recycled mixtures, using both emulsified and foamed bitumens, have mainly been made on one level of binder content, maintaining the same proportions of reclaimed material. However, it is believed that separate mixture design methods for both types of mixture should first be established and comparisons between the mechanical properties of the materials should be made at their optimums.

CHAPTER

4 PREPARATION AND COMPACTION OF EMULSION-AGGREGATE MIXTURES

Undoubtedly, mixture composition and preparation of test specimens are significant elements affecting material behaviour. Proper mixing necessitates the use of a proper amount of added water to the aggregate. For better compaction, optimum emulsion content and total water content at compaction should be determined. Compaction comparable to that expected during pavement construction must also be achieved; otherwise, actual performance will not be replicated.

In this chapter, the effect of emulsion mixture variables on material compactibility is discussed. Variables involved are added water content, total water content at compaction, residual bitumen content, emulsion type, and aggregate gradation. Marshall, vibration, and gyratory compaction methods are examined for use in compaction of this material. In addition, a specimen preparation procedure for these types of materials is outlined.

4.1 LABORATORY EXPERIMENTATION

4.1.1 Materials

Aggregate

One aggregate type 'a porphyritic andersite' was used. The aggregate gradations used are presented in Figure 4-1. These gradations were selected to study the effect of coarse and fine gradings on the mechanical properties of emulsion aggregate mixtures. C1 and C2 are respectively the coarse and fine limits of the grading used in asphalt concrete mixtures (the Asphalt Institute, 1988), while A and B are fine and coarse gradings within British standard 20 mm DBM, BS 4987: part 1.

Bitumen Emulsion

Four types of bitumen emulsion were used. One of them, designated as 'A' emulsion incorporated 150-200 pen bitumen with 61% residual bitumen content. Two other emulsions are EN998 and Redicote 'K-emulsion'; both based on 100 pen Venezuelan bitumen (62% residual bitumen). Finally, emulsion designated R-emulsion (60% residual bitumen) produced from a blend of two bitumen grades '300 and 35 pen bitumen' in an equal portions was used. All emulsions were cationic. Rheological characteristics of K and R emulsions are presented in Chapter 10.

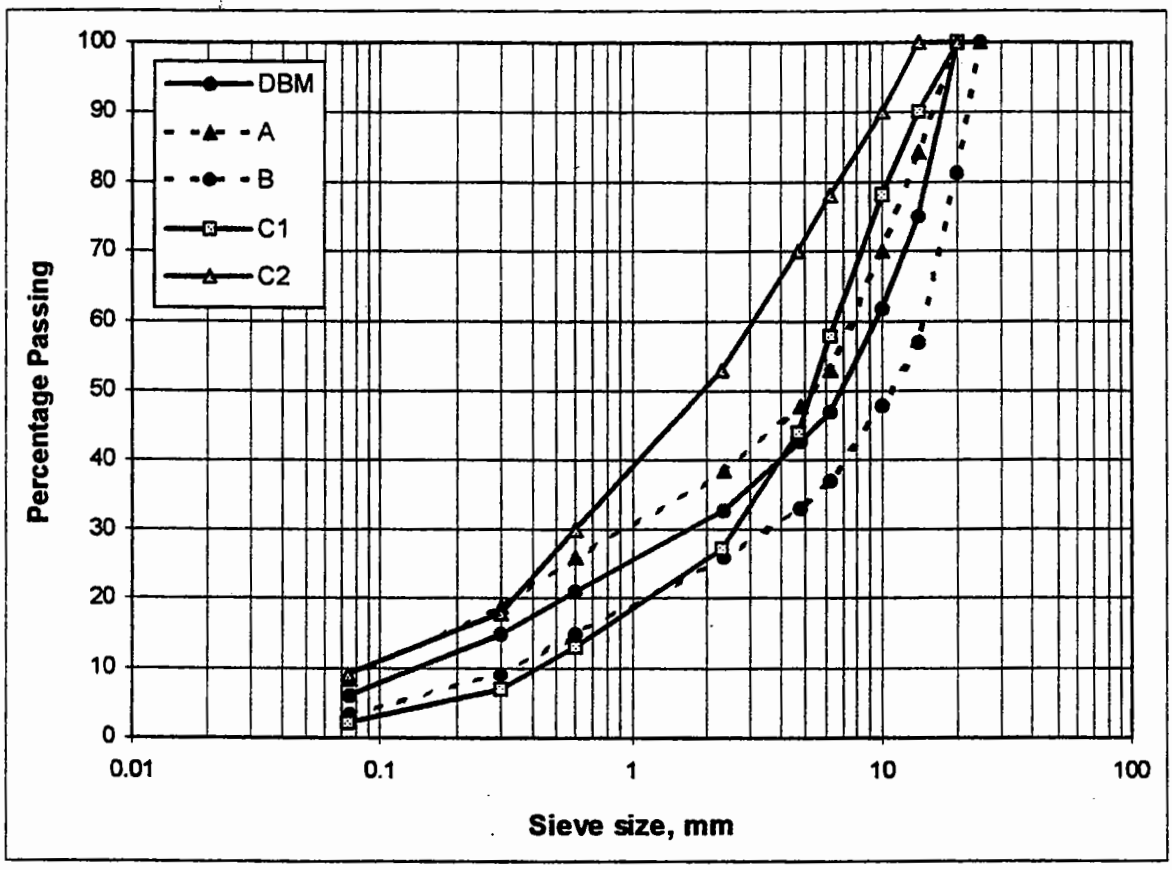


Figure 4-1 Aggregate gradation curves

4.1.2 Mixing and Compacting Moisture Contents

For the determination of minimum water content for mixing and optimum water content at compaction, the flow chart presented in Figure 4-2 was followed. Emulsion mixtures were prepared by first recombining the different aggregate fractions to give the required grading.

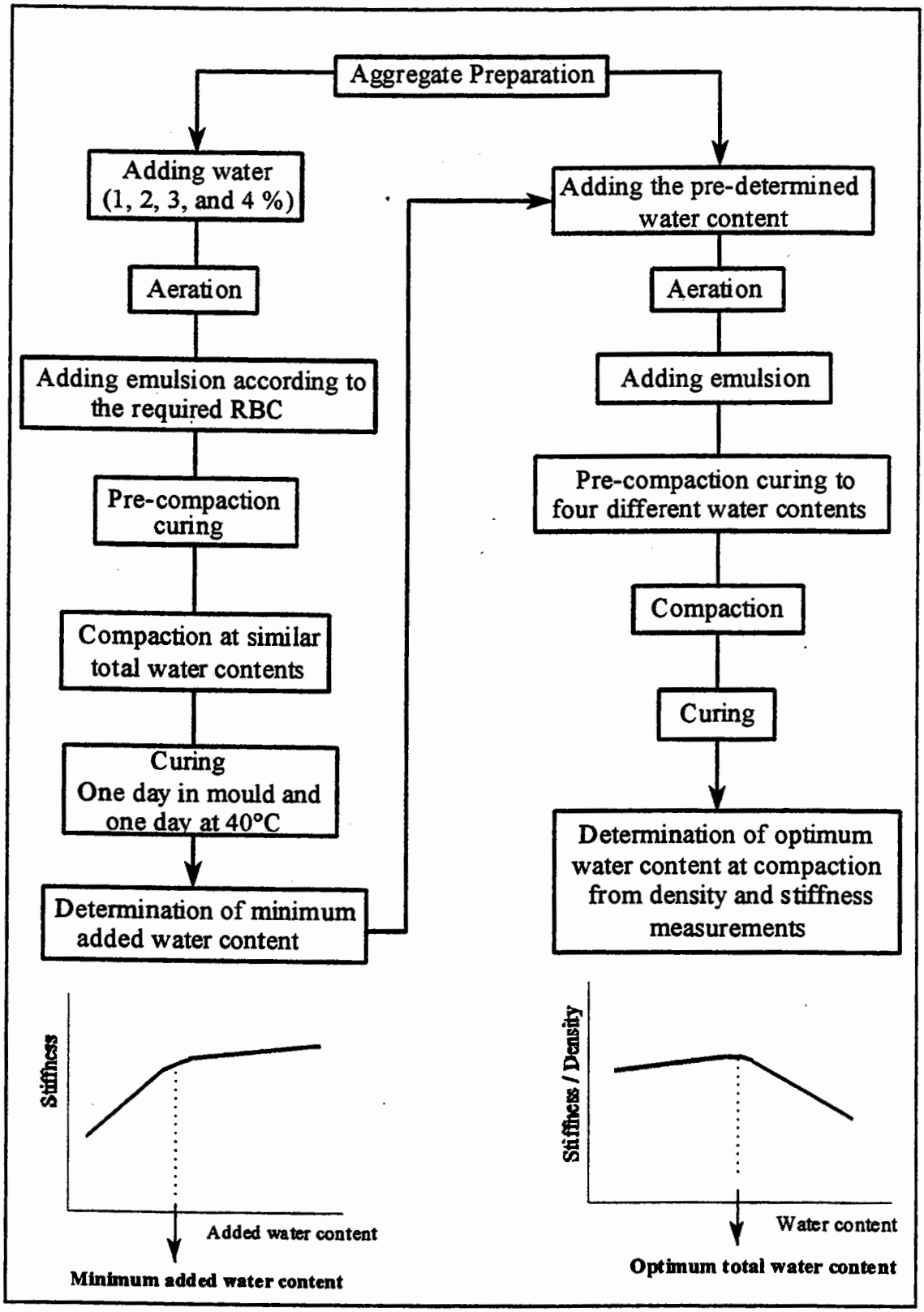


Figure 4-2 Procedure of determining water contents for mixing and compacting emulsion mixtures

The required amount of water was then added to 1200g of dry aggregate and mixed for 90 seconds using a Sun and Planet type mechanical mixer, Figure 4-3. The emulsion, according to the required residual bitumen content 'RBC', was added to the pre-wetted aggregate after an aeration period of 10 minutes and then the materials were mechanically mixed for 2 minutes for emulsions A and EN998 and 1.5 minutes for K and R emulsions, these times having been found suitable from preliminary work. After that, the mixtures were left for water evaporation (pre-compaction curing), to achieve the same total water contents at compaction. Finally, stiffness moduli of the compacted specimens were determined after curing for one day in a mould and one day out of the mould at 40°C, from which the minimum added water content was determined.

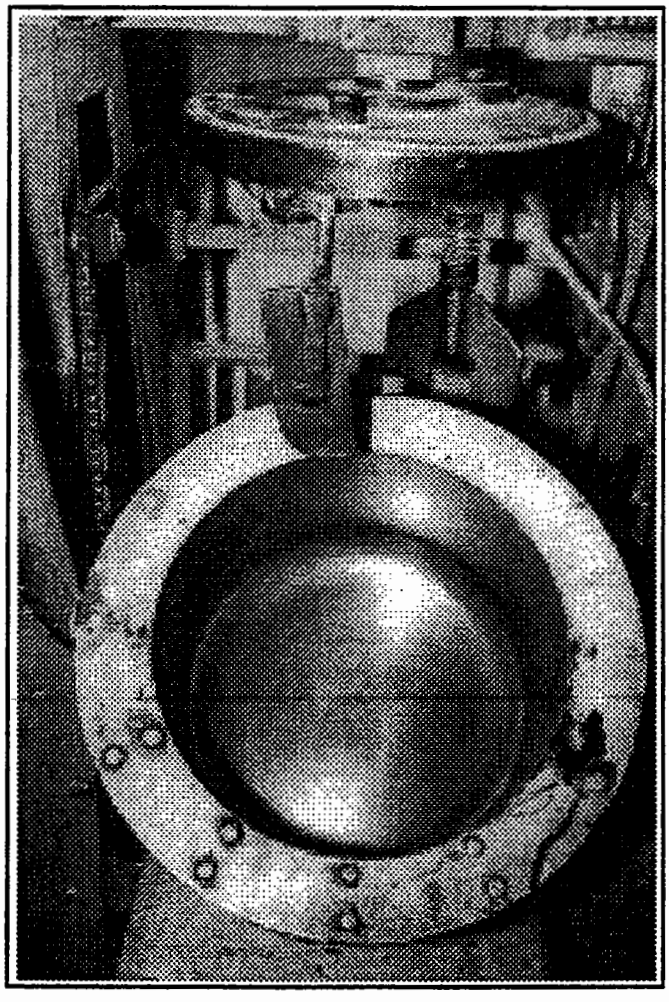


Figure 4-3 Photograph of the mechanical mixer

For the determination of optimum water content at compaction, mixtures were prepared by adding the determined minimum water for mixing (to give uniform coating) followed by the required amount of emulsion. The materials were then mechanically mixed for the times mentioned above. After that, the mixtures were left to stand for different periods of time to obtain a range of different total water contents at compaction.

4.1.3 Compaction

The ability of emulsion-aggregate mixtures to be compacted is sensitive to both the total moisture and residual bitumen contents. For studying the effect of compaction method on the compactibility and mechanical properties of this type of mixture, the mechanical Marshall hammer, Vibrating compactor, and gyratory compactor were used.

Mechanical Marshall Hammer

This is a very common method of compacting bituminous mixture specimens. In this method a hammer weighing 4.5 kg is repeatedly dropped vertically from a height of 457 mm onto the specimen after pouring the mixture into the assembled mould and tamping around the perimeter and over the interior. The mould assembly consists of a base plate, a forming mould, and a collar extension.

For fabricating emulsion mixture specimens, 50 blows were applied to each face of the specimen.

Vibrating Compaction

Compaction was carried out using a vibrating hammer under controlled constant light weight. A diagram of the modified apparatus is shown in Figure 4-4. As shown, the vibrating hammer is hung vertically in a steel frame and the base of the mould is free to move horizontally by means of open crosses. This allows application of a tamping action using a 75 mm tamping foot. To flatten surface irregularities of the specimen faces at the end of the compaction, a larger compaction foot (100 mm) is used.

In the case of Marshall size specimens, the specimens were fabricated in Marshall moulds using a 75 mm tamping foot for 16 tamps - 1.5 sec each per face. The foot was moved

around the surface of the sample in a N, S, E, W pattern, maintaining a tangential contact between the foot and the sample. This compaction procedure was employed to give a unit weight similar to that of specimens prepared using 50 blows of the mechanical Marshall compaction hammer. For the case of 4% residual bitumen of K-emulsion, this method produced specimens about 64 mm height, with approximately 10% voids, using 1200g of aggregate and 4.5% total water content.

In fabricating triaxial specimens, normally 100 mm diameter × 160 mm height, specimens were prepared in a split mould in four layers using a vibrating hammer and 75 mm tamping foot for 16 tamps - 1.5 sec each per layer. For all specimens, a 100 mm foot for 6 sec was used at the end of the compaction so as to level the specimen surfaces.

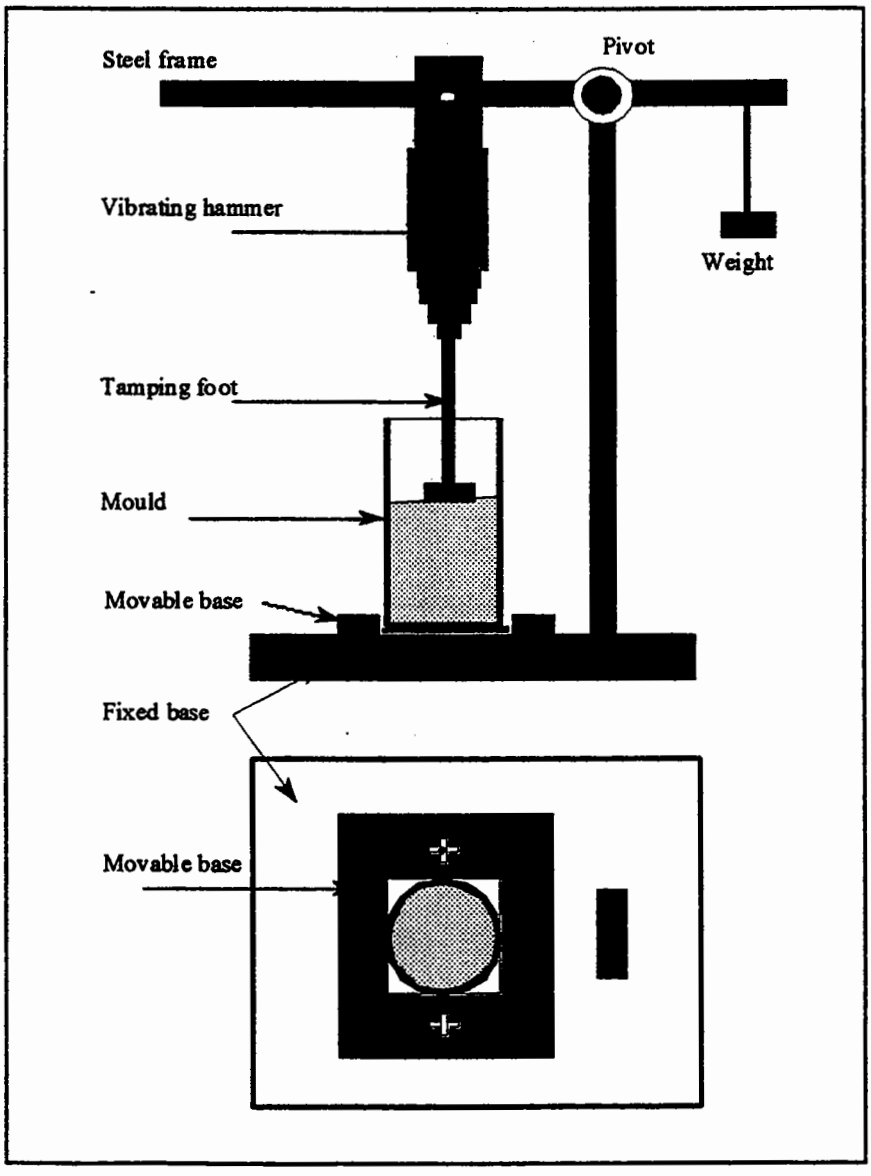


Figure 4-4 Schematic diagram of the vibrating compactor

The reason for using this modified method of compaction was to avoid the aggregate degradation which arises from the Marshall hammer. Another apparent advantage of this method is that it produces specimens which seem to have evenly distributed particles upon inspection. It is also believed that the vibrating hammer improves the coalescence of the bitumen droplets onto the aggregate.

Gyratory Compactor

In this method, a split mould mounted in its cage and clamped at both ends is rotated on an axis eccentric to the vertical with an angle θ. While the mould is rotated, a static compressive vertical load is applied to the material through parallel end plates. This action generates horizontal shear stresses within the material, by which orientation of the aggregate occurs. A view of the apparatus is shown in Figure 4-5.

The apparatus operation is controlled through a computer and an interface unit. The vertical load is applied by a pneumatic actuator which can be maintained at the required level through a voltage/pressure (V/P) converter regulating the pressure of the air supplied. The height of the specimen is monitored during the compaction using a deformation transducer and the applied load is measured using a load cell. Thus, specimen density and number of gyrations are recorded during compaction for compactability analysis.

Compaction of emulsion mixture specimens was performed by applying a static vertical stress of 0.6 MPa and gyrating the mould with an angle θ of 1.25 degrees. The speed of gyration was 30 revolutions per minute.

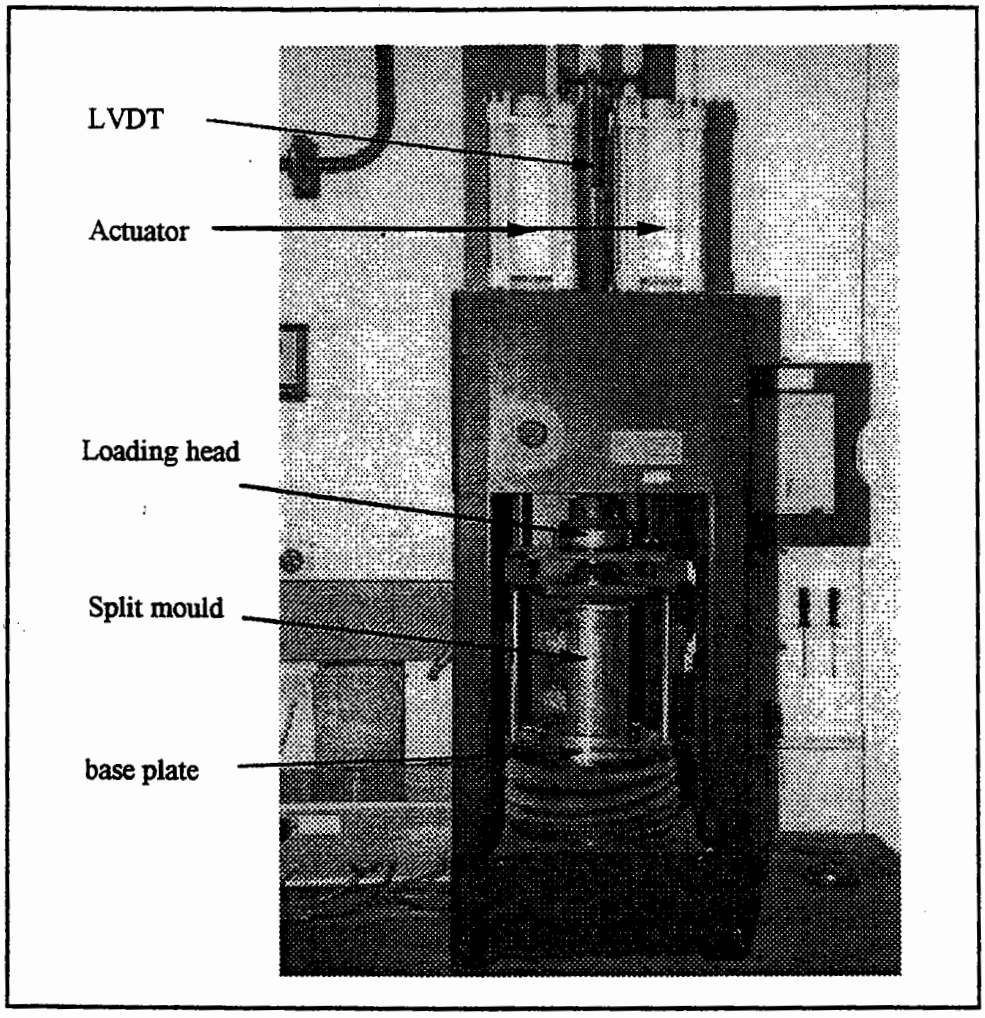


Figure 4-5 View of the gyratory compactor

4.1.4 Post Compaction Curing

According to the findings reported by Puzinauskas and Jester (1983), the major portion of water loss occurs during the first two days regardless of emulsion or water content, or oven curing regime. The curing procedure followed in determining water contents for mixing and at compaction was therefore one day of curing in the mould at room temperature, extrusion, and oven curing at 40°C for two days. For studying the mechanical properties of the material, curing at 20°C for different times was also used.

The stiffness modulus of the prepared specimens was considered significant in determining optimum water contents. Therefore, the Nottingham Asphalt Tester (NAT) was employed

in the indirect Tensile Stiffness Modulus (ITSM) mode for testing specimens at 20°C. A detailed description of the test is presented in Chapter 5.

4.1.5 Density, Water Content, and Voids Measurements

Specimens' weights were monitored before and after compaction and at the time of testing for determination of water contents. Dry weight of specimens was also determined after testing by oven drying at 100°C until obtaining a constant weight from which dry densities were calculated.

In addition, determination of void contents from weight-volume relationships required measurements of the specimens' bulk density and the maximum (Rice) density of loose mixtures (Rice, 1952). These mixtures were prepared by adding the required water to the aggregate, followed by adding the calculated amount of emulsion. Since emulsion mixtures are influenced by the curing temperature, leading to differing amounts of bitumen absorption or loss of light molecular fractions, the mixtures were therefore cured first, realistically, at room temperature for 3 hours, after which the particles of the samples were manually separated, and then cured at 50°C for 24 hours. The rice densities (i.e. the density of the coated aggregate alone) were measured using a pycnometer and a vacuum pump following the abridged form of ASTM D2041(1990) applied to hot bituminous mixtures, described in the Link Bitutest Project by Brown et al (1995)[b]. Simply, after weighing the separated sample in air, 'A', it was placed in the pycnometer and covered with water. The container was then subjected to a partial vacuum, approximately 730 mm Hg measured by a vacuum gauge, for 15 minutes to remove entrapped air. After releasing the vacuum, the container was filled with water and weighed, 'C'. The maximum density was then calculated as follows:

$$G_{max} = \frac{A}{A + B - C} \times 997.1 \qquad 4.1$$

where:

G_{max} = maximum density, kg/m^3.

A = mass of dry sample in air, g

B = mass of pycnometer filled with water at 25°C, g

C = mass of pycnometer filled with water and sample at 25°C, g

Specimens' bulk densities were measured by weighing in air and then in water after sealing with aluminium foil or cling film. The calculations were as in the following equation:

$$G_{bulk} = \frac{S_f \times W_1 \times 1000}{S_f (W_2 - W_3) - (W_2 - W_1)} \quad 4.2$$

where:

G_{bulk} = Bulk density of specimen (kg/m^3).

W_1 = Mass of specimen in air (kg).

W_2 = Mass of coated specimen in air (kg).

W_3 = Mass of coated specimen in water (kg).

S_f = Specific gravity of the film used in sealing specimens (1.65 for aluminium foil and 0.86 for cling film).

Calculations were then made using the following equations:

$$W.C = \frac{W_w}{W_d} \times (100 + RBC) \quad 4.3$$

$$G_{dry} = \frac{G_{bulk}}{1 + \frac{W.C}{100}} \quad 4.4$$

$$V_{voids} = [1 - \frac{G_{bulk}}{G_{max}} \times \frac{100 + RBC}{100 + RBC + W.C}] \times 100 \quad 4.5$$

where:

W.C = water content, percent

W_w = mass of water

W_d = mass of dry mixture

RBC = residual bitumen content, percent

G_{dry} = density of dry mixture

G_{bulk} = bulk density

V_{voids} = total voids in mixture (air and water)

G_{max} = maximum (Rice) density

A point to note is that the water content and residual bitumen content (RBC) are expressed as percentage of the weight of aggregate. It can be seen in equation 4.5, as the water content tends to zero, the bulk density G_{bulk} will be equal to the dry density G_{dry} and V_{voids} will be equal to $V_{air} = (G_{max} - G_{dry})/G_{max} \times 100$, analogue to the equation applied to hot mixtures. As zero water content in emulsion mixtures can never be obtained, the calculations used for hot bituminous mixtures are no longer valid and equation 4.5 should be used in calculation of specimen voids.

4.2 PRESENTATION AND ANALYSIS OF RESULTS

4.2.1 Mixing Water Content

The water content in the bituminous emulsion mixtures during the mixing process plays a significant role in distributing the emulsion and hence achieving a good coating of the aggregate. Also, the amount of water in an emulsion mixture at compaction greatly affects the mechanical properties of this type of mixture, even after the curing process. Increased water content at compaction may lead to a reduction in mass density and material response. Therefore, it is always desirable to keep the water content for mixing at the lowest level which can give uniformly coated aggregate.

As shown in Figures 4-6 and 4-7, it was found that, based on stiffness modulus data from specimens produced using the vibrating compactor and cured one day in the mould and two days at 40°C, the minimum amount of water required to give adequate coating for the mixtures containing type 'A' bitumen emulsion is 2.5% while 3.5% was found to be necessary for the mixtures containing EN998 emulsion. The results were found to be in good agreement with visual appearance during mixing. It can be concluded that bitumen emulsion manufactured using a harder base bitumen requires a higher amount of water for mixing, and hence coating, regardless of the amount of emulsion and the aggregate gradation. This may be attributable to the fact that this type of emulsion (EN998) breaks during mixing somewhat more than the softer emulsion (type A).

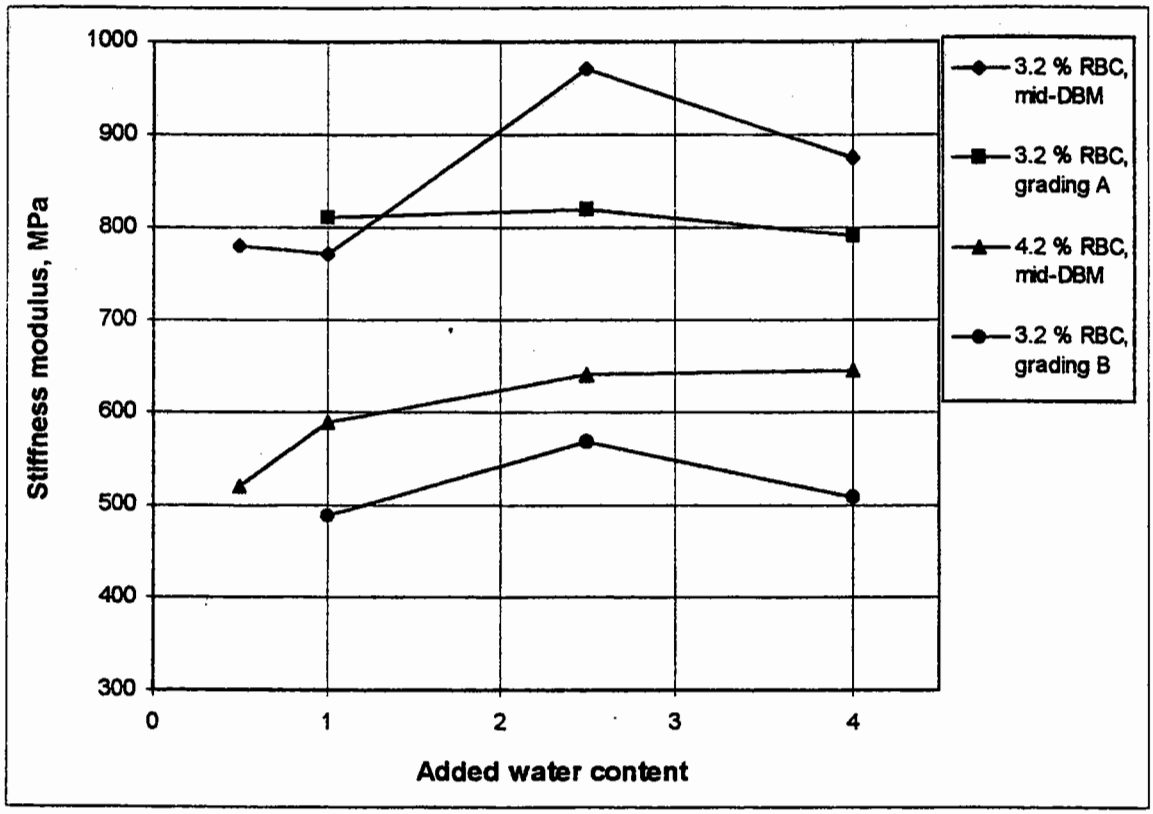


Figure 4-6 Relationship between added water content for mixing and stiffness modulus (4% water content at compaction, A- emulsion, and gradings A, B, mid-DBM)

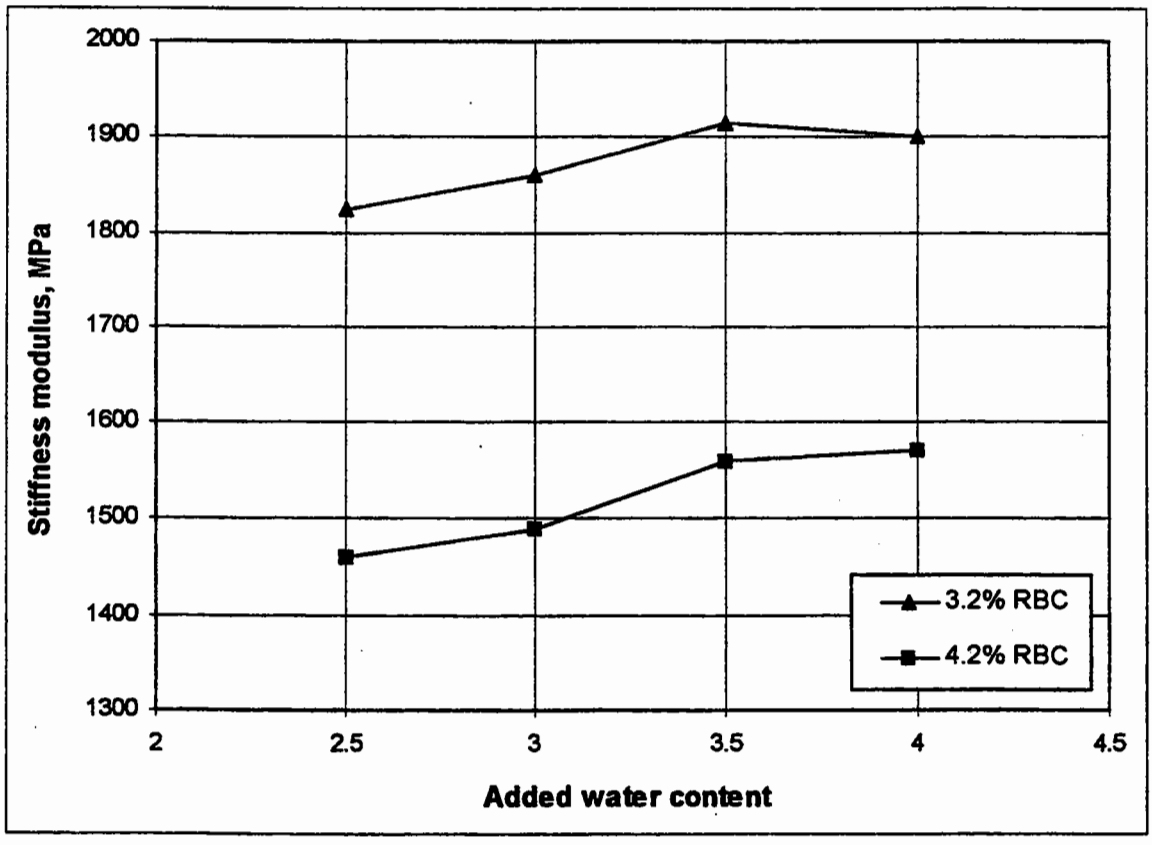


Figure 4-7 Relationship between added water content for mixing and stiffness modulus (4% water content at compaction, EN998- emulsion, and mid-DBM grading)

4.2.2 Effect of Emulsion Type on Compaction

The role of emulsion type (A-emulsion, K-emulsion, and EN998) on the compactibility of mixtures containing mid-DBM grading was examined using the compaction methods previously described (Gyratory, Vibrating hammer, and Marshall hammer). It was found that Marshall specimen densities were greatly influenced by the emulsion used, being very low with emulsion A (softer). This may be due to a high friction between the aggregate particles being created from the lower lubrication effect of this emulsion type (see Figure 4-8). In specimens of EN998 and K-emulsion, densities were approximately the same for all compaction methods used.

Because of this effect, the response of materials was mainly investigated on specimens fabricated using the vibrating hammer or the gyratory compactor.

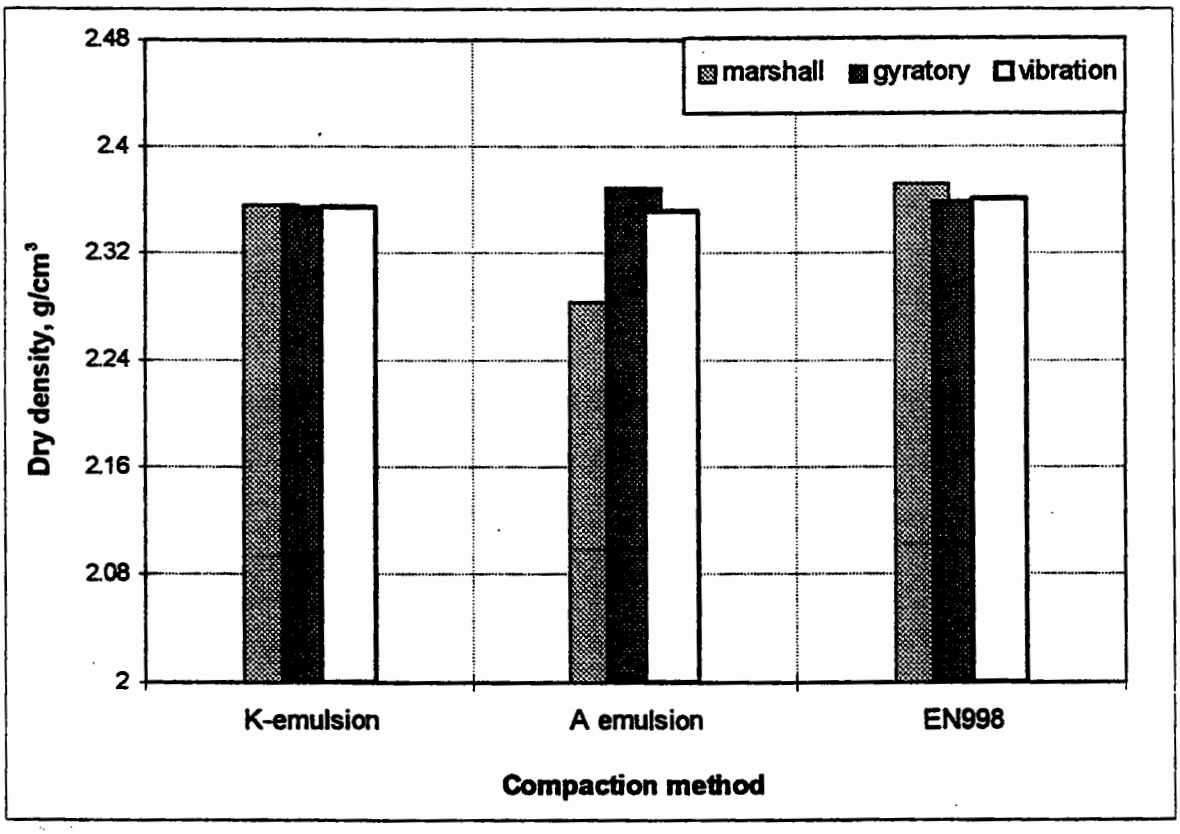


Figure 4-8 Effect of emulsion type on produced densities

4.2.3 Optimum Moisture Content

In a trial to determine the most favourable combination of residual bitumen content and total water content at compaction, to maximise the stiffness of specimens, relationships were plotted between water content and the resulting stiffness modulus and dry density of specimens cured as previously stated. Both the vibrating and the gyratory compactors were used.

Compactibility in the Vibrating Compactor

It has been noted that, for a given amount of emulsion in a mixture, the dry density and consequently stiffness modulus, increases as the total water content increases until reaching a maximum value at the optimum moisture content. Therefore, increasing the water proportion in the emulsion improves a mixture's compactibility. In this study, as seen in Figures 4-9 to 4-12, with the emulsion contents and levels of compaction used, the optimum moisture content of the specimens was always found to be approximately equal to the water content at its saturation condition. However, an increase in the moisture content beyond the optimum leads to a rapid decrease in the specimen density due to the pore water pressure induced in the specimen during compaction. As a result, the stiffness modulus of the specimens rapidly decrease. This lower value of stiffness may also be attributed to an increased water content at testing due to the use of a higher amount of water at compaction. Another point to note is that, over the range of emulsion contents used, the optimum moisture contents at compaction were only slightly different, regardless of the type of emulsion or aggregate gradations.

In the case of type A-emulsion, the optimum moisture contents were found to be approximately 4.1% and 4.55% for mixtures of 3.2% and 4.2% residual bitumen content (RBC) respectively. On the other hand, in the case of EN998 emulsion, the optimum moisture contents were 4.3% and 4.7% respectively. For K-emulsion specimens of different RBC (2.7, 3.85, and 5.00%), the optimum water contents were approximately similar at about 4.5%. As can also be inferred from Figure 4-12, in the mixtures which contain higher emulsion contents, the resulting dry densities do not appear to be much influenced by the total water content at compaction. This matches the hypothesis that emulsion has a

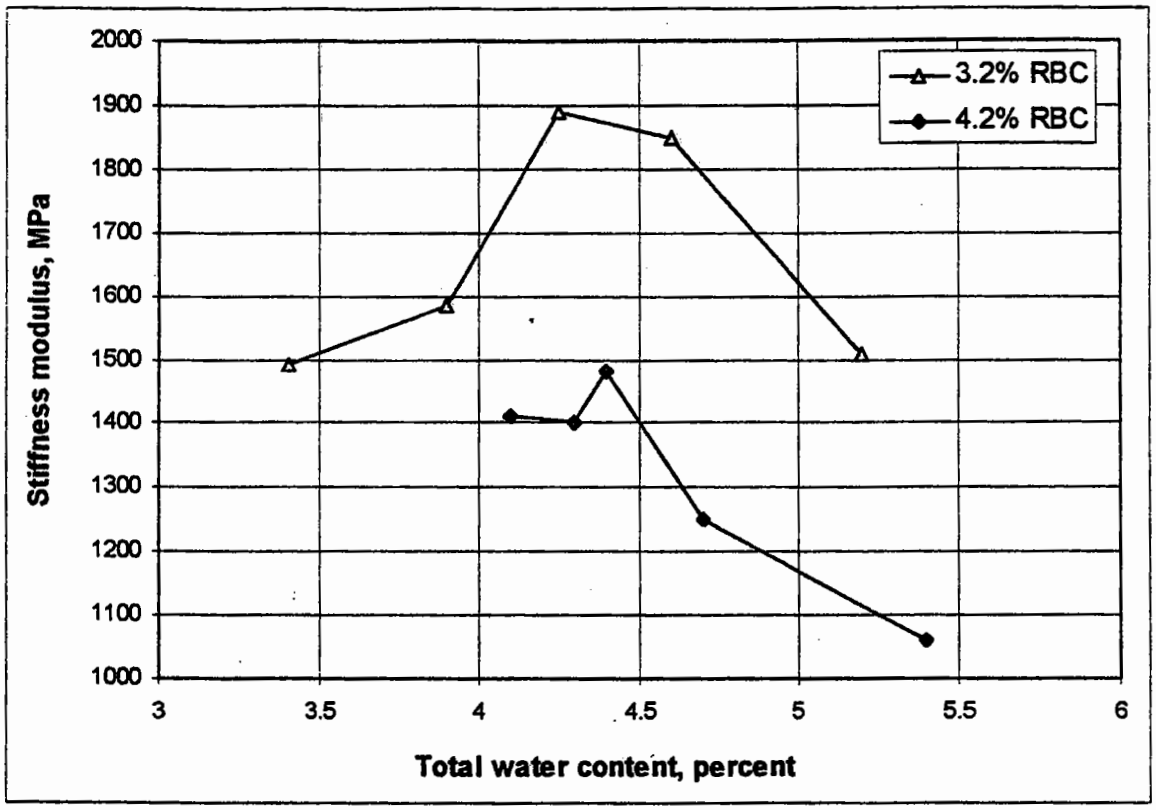


Figure 4-9 Relationship between total water content at compaction and stiffness modulus of specimens containing EN998- emulsion and mid-DBM aggregate grading

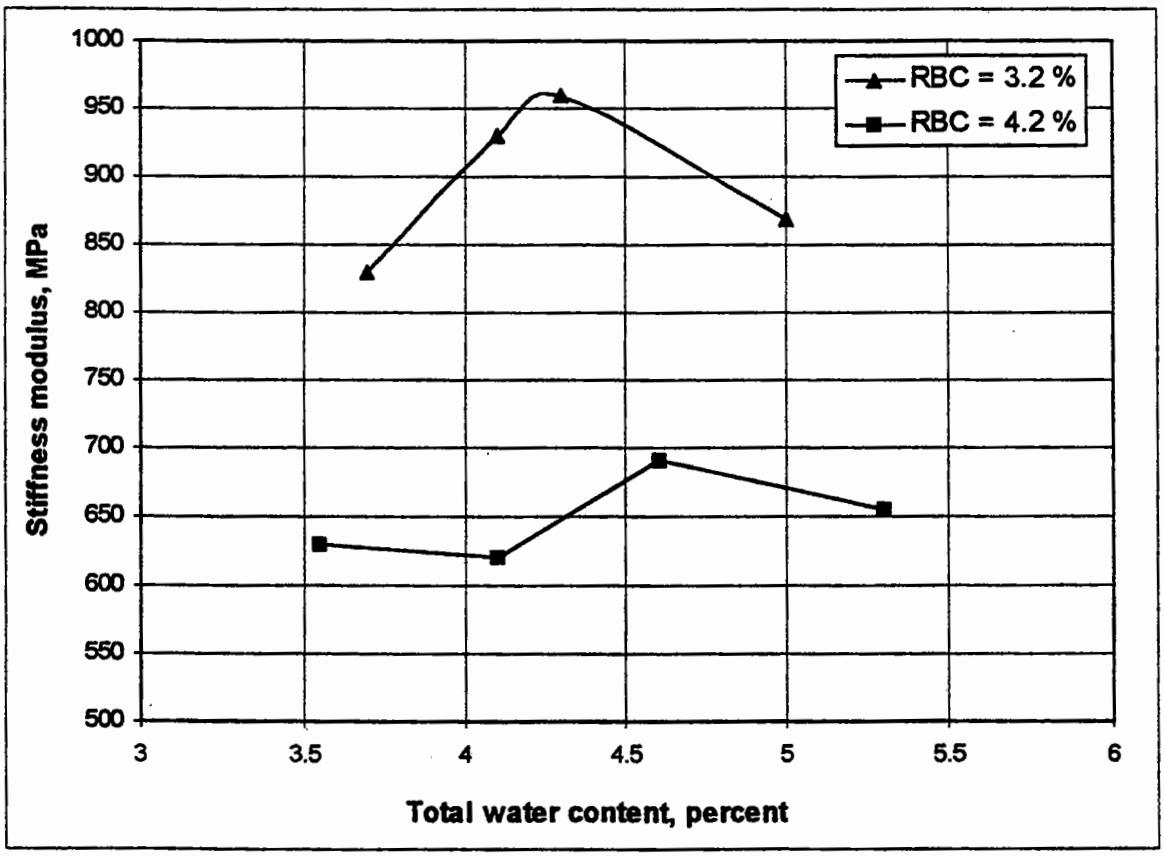


Figure 4-10 Relationship between total water content at compaction and stiffness modulus of specimens containing A-emulsion and mid- DBM aggregate grading

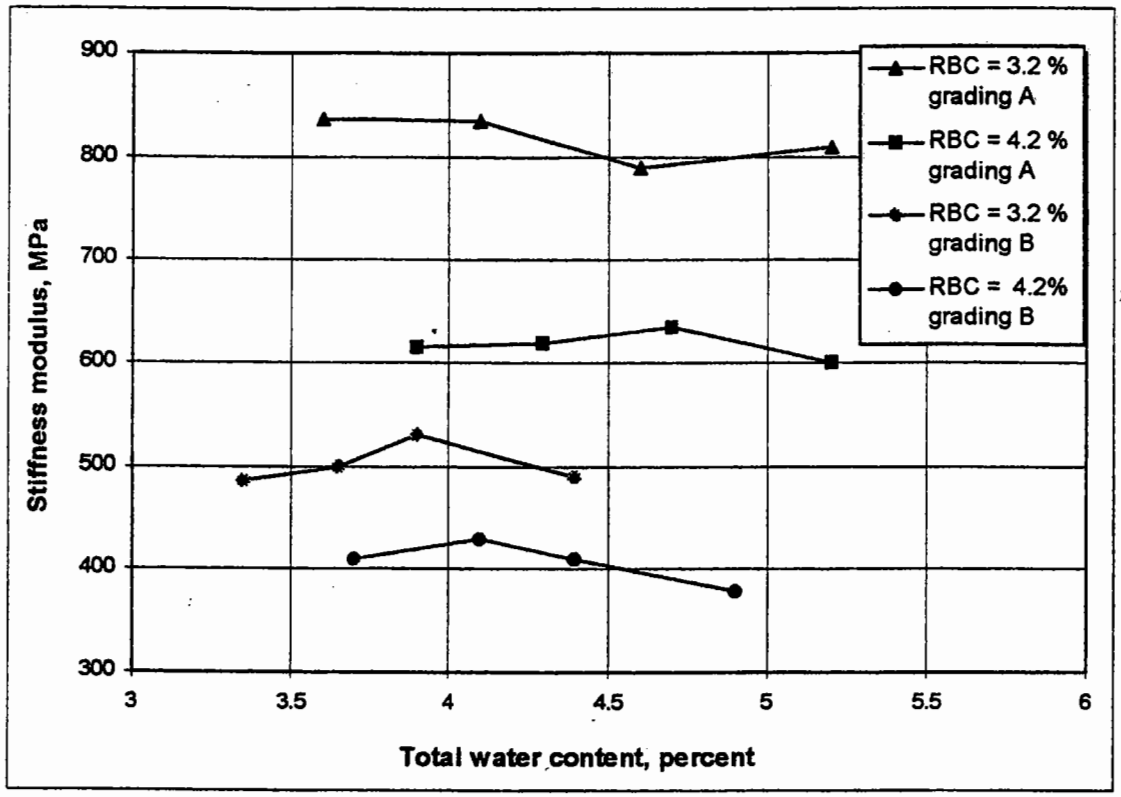


Figure 4-11 Relationship between total water content at compaction and stiffness modulus of specimens containing A-emulsion and aggregate gradings A & B

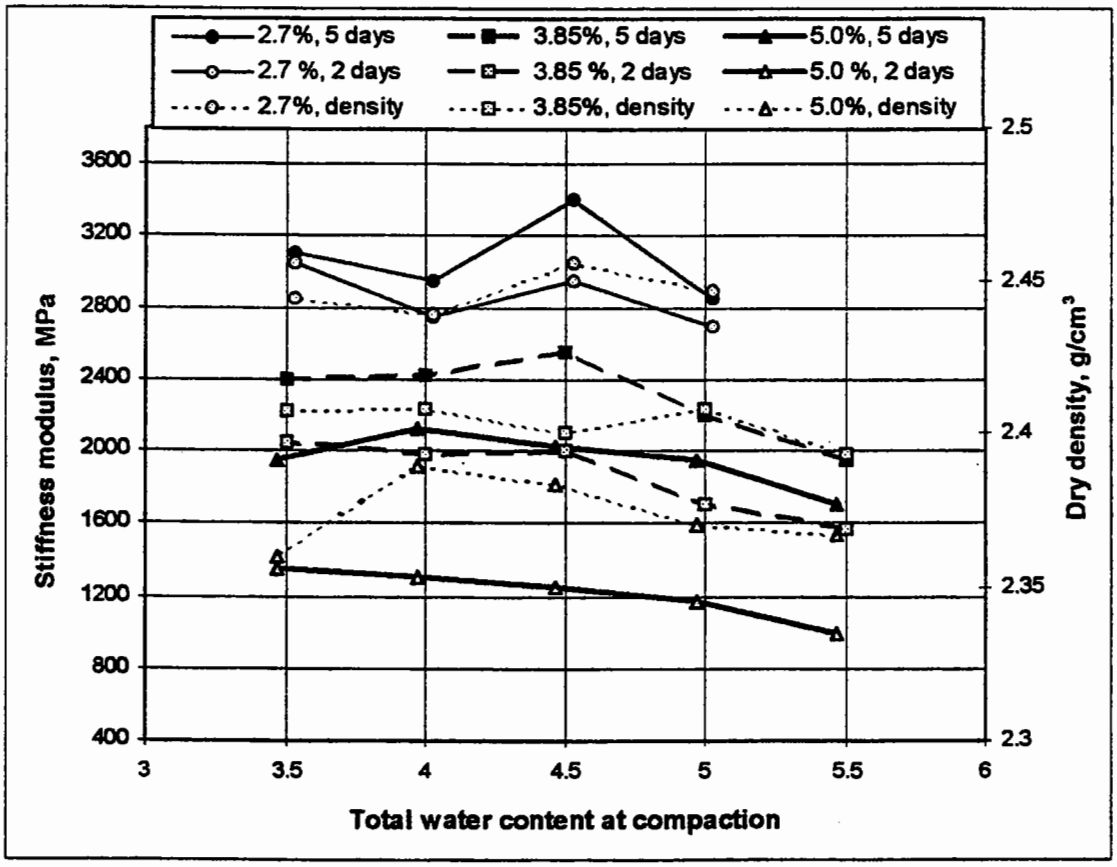


Figure 4-12 Total water content at compaction versus stiffness modulus and dry density of specimens containing K-emulsion and mid- DBM grading

much greater lubricating effect than water. Conversely, there is a definite optimum in mixtures with lower emulsion content.

A similarity in the determined total moisture contents, at early and later stages of curing of mixtures containing 2.7% RBC can be observed in Figure 4-12. The Figure also illustrates that further curing of mixtures containing higher RBC may however lead to a slight increase in the optimum water content due to the accompanied reduction in the contained specimen's water content. A point to note is that a much higher water content in the mixture at the time of compaction greatly reduces the stiffness modulus, even after more curing.

Therefore, and due to the fact that moisture content at compaction affects a specimen's mechanical properties, it is worth keeping the total moisture content constant for mixtures with the same ingredients, using a compaction curve based on a reasonable percentage of residual bitumen (≅ 3.0 to 4%). Following this procedure minimizes the number of specimens required in the mix-design process, without affecting the results.

Compactibility in the Gyratory Compactor

The ability of the material to be compacted under the application of gyration action was studied. The effect of aggregate gradation, emulsion type, emulsion content, and curing on the determined optimum water content were also investigated. Variables used were grading C2 (fine limit of the asphalt concrete specification) and mid DBM of the British standard, K and R type emulsions, residual bitumen contents of 4%, 5%, and 6%, and finally curing for different times at 20°C. Unlike the vibrating compaction in which a little loss of water, together with emulsion, was observed during the compaction process, water loss from the gyratory compaction was high, depending on the total moisture content at compaction.

Compaction of DBM mixtures:

The results showed that the material has various responses. The stiffness modulus and dry density of the mixtures containing K-emulsion and mid DBM aggregate grading as a function of water content at compaction were dependent upon the curing time. As shown in Figure 4-13, at early curing (7 days at 20°C), the optimum water content of mixtures

containing 4% RBC was around 5.2% (although the optimum is not well defined). The mixture containing 5% RBC showed a similar stiffness modulus but slightly different densities for water contents ≥ 4.6%. These results are obviously dependent upon both the specimens' dry density and water content at test. Specimens with higher dry densities had stiffness moduli almost similar to less dense specimens, probably because they contained more water at the time of test.

At a later stage of curing, the optimum water content was 5.7% for the mixtures containing 4% RBC. Clearly, the optimum shifted to be higher than that resulting for the early cured specimens. On the other hand, no optimums could be distinguished for the mixtures containing 5% RBC. It seems that specimens with higher water content at compaction retain much of the stiffness modulus after curing. One may say that 'within the range of water contents tested for specimens containing higher residual bitumen content' the higher the water content at compaction the better the distribution of bitumen, and consequently the higher the stiffness moduli and dry densities. Another possibility is that the increased moduli of the specimens containing higher moisture at compaction resulted from loss of some emulsion, together with water, during the compaction.

The above findings were further investigated by determining the soaked stiffness moduli of the specimens. For this, soaking of specimens was carried out in a water bath under constant head at 20°C for 24 hours. Generally, the reduction in stiffness modulus due to soaking specimens increases as the contained residual bitumen content decreases. However, the durability of emulsion mixtures will be discussed in Chapter 8. Figure 4-14 shows reductions in the stiffness modulus of specimens containing 5% RBC as the water content at compaction increases, indicating a loss of bitumen during compaction. For the specimens containing 4% RBC, little sign of bitumen loss can be seen.

It is expected that bitumen droplets coalesce onto the aggregate particles as a result of the normal and shear stresses induced in the mixture due to the gyration action, coupled with the applied vertical static stress. This interaction between the emulsion and the aggregate is likely to be dependent upon the surface area of the aggregate particle. With increased emulsion content, the non-coalesced bitumen droplets are pushed out by the water pressure

and drain with it. The total moisture content at compaction influences the response of the emulsion during the compaction and hence the resulting mechanical properties of the material, not only behaving as a lubricant for densification of the material. Determination of optimum water content using a dry density criterion is not enough and stiffness modulus of the material at proper curing should also be included. Optimum water content can easily be identified for material with lower RBC, from relationships with stiffness modulus and dry density. Increased water content in mixtures containing higher RBC may affect the way the emulsion behaves during compaction and give misleading results.

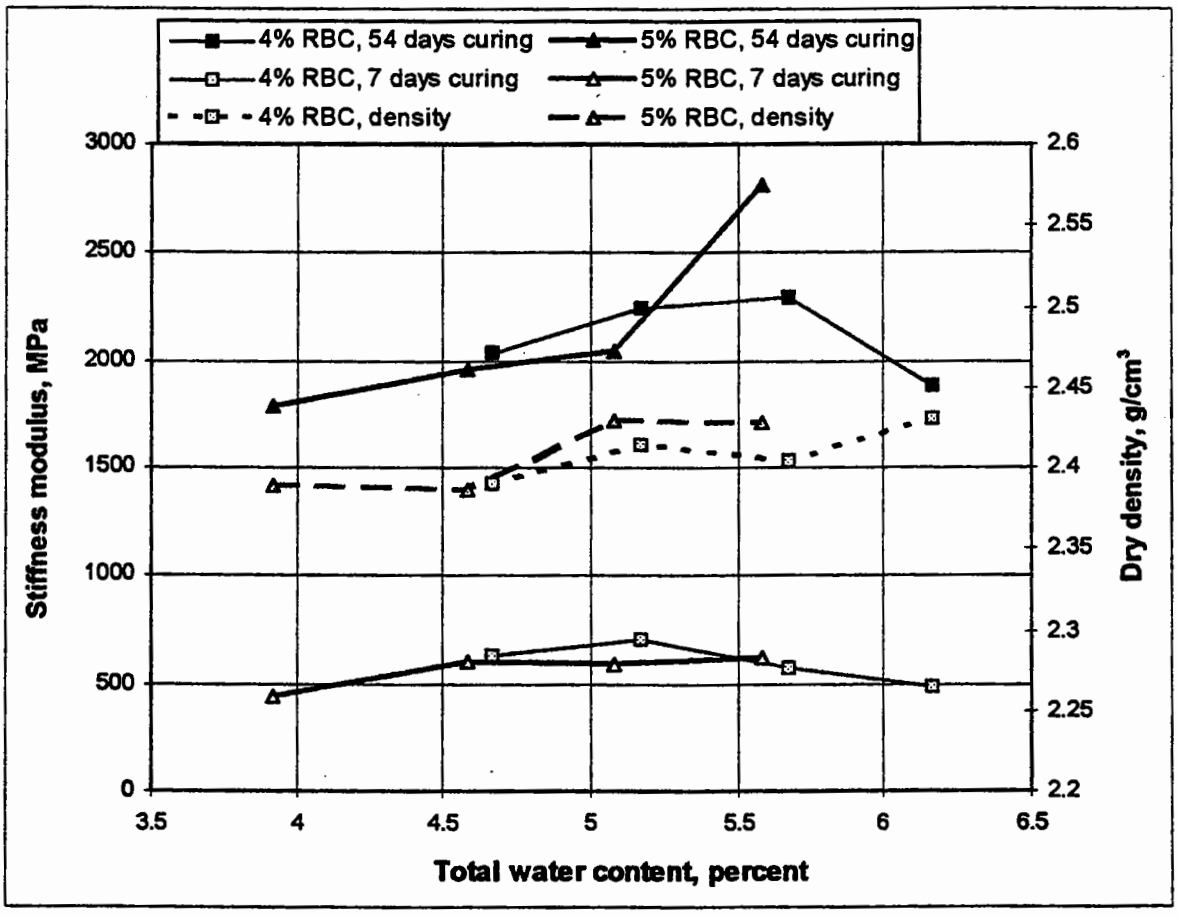


Figure 4-13 Stiffness modulus and dry density of specimens containing K-emulsion and mid-DBM as a function of total moisture content at compaction and curing time

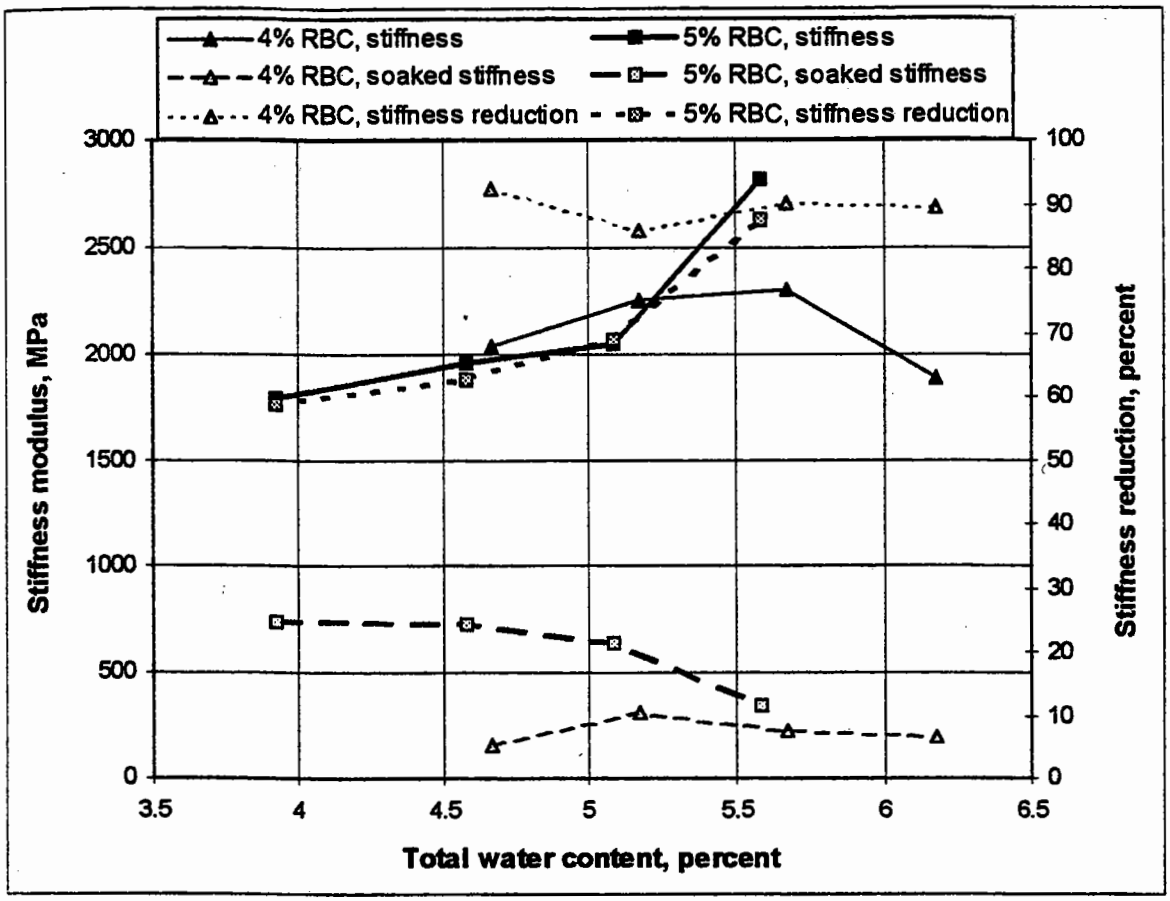


Figure 4-14 Comparison between unsoaked and soaked stiffness modulus of specimens containing 4% and 5% RBC of K-emulsion and mid-DBM

Compactibility of triaxial specimens containing K-emulsion in the gyratory compactor showed different responses depending on the total moisture at compaction. Presented in Figure 4-15 is the dry density as a function of the number of gyrations and the water content at compaction. Normally, the dry density increases very rapidly during the first few gyrations, followed by a gradual decrease in the density increase rate. Generally, the drained water during compaction increases as the total moisture content in a mixture increases. As may be seen, some curves representing mixtures containing higher total water content at compaction and higher RBC showed a rather different response. After a decrease in the density increasing rate during the first 70 gyrations, a rapid increase occurred. It is likely that some fines drained out of this mixture with the water, leaving gaps within the aggregate structure that led to more rapid densification. The use of a higher water content at compaction is therefore not beneficial to this type of mixture, because it may result in reducing the effective RBC or restructuring of the aggregate. Based on the author's

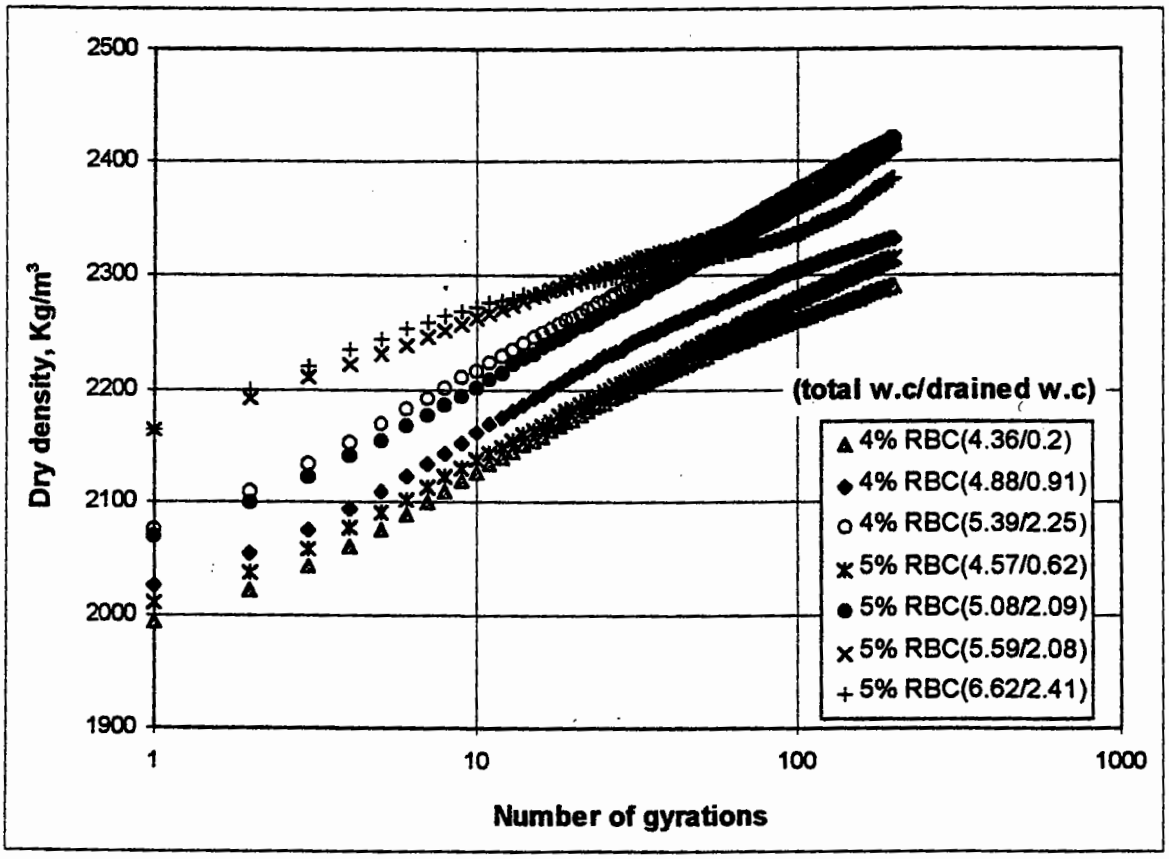


Figure 4-15 Compactability curves of mixtures containing K-emulsion and different water contents at compaction for producing triaxial specimens

experience, a water content that results in a water loss of not more than 1% is recommended.

The mixtures containing R-emulsion were also considered. As seen in Figure 4-16, at early stages of curing, optimum water contents determined from the stiffness modulus and dry density measurements are almost similar, around 5.5%. With curing, the stiffness modulus tends to increase for specimens containing higher water content at compaction. Generally, the optimums are well defined at both curing times. However, the stiffness determination of soaked specimens (Figure 4-17) reveals that increasing water at compaction has a beneficial effect on the mixtures containing 5% RBC in that it reduces the percentage reduction of stiffness after being soaked. This response is attributable to a better distribution of emulsion during the mixing process and to the fact that no emulsion loss was experienced during compaction. Conversely, the mixtures containing 6 % RBC have higher stiffness reduction

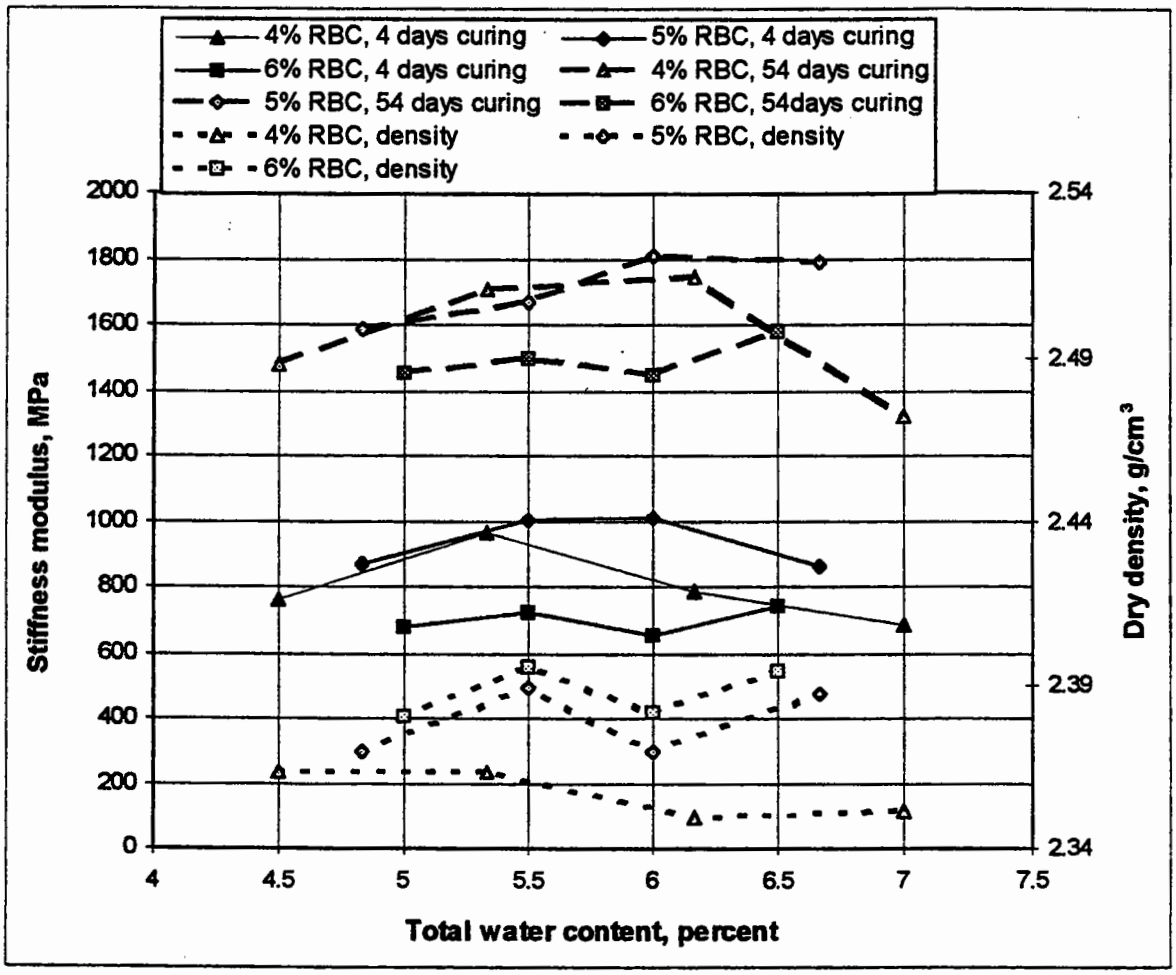


Figure 4-16 Stiffness modulus and dry density of specimens containing R-emulsion and mid-DBM as a function of total moisture content at compaction and curing time

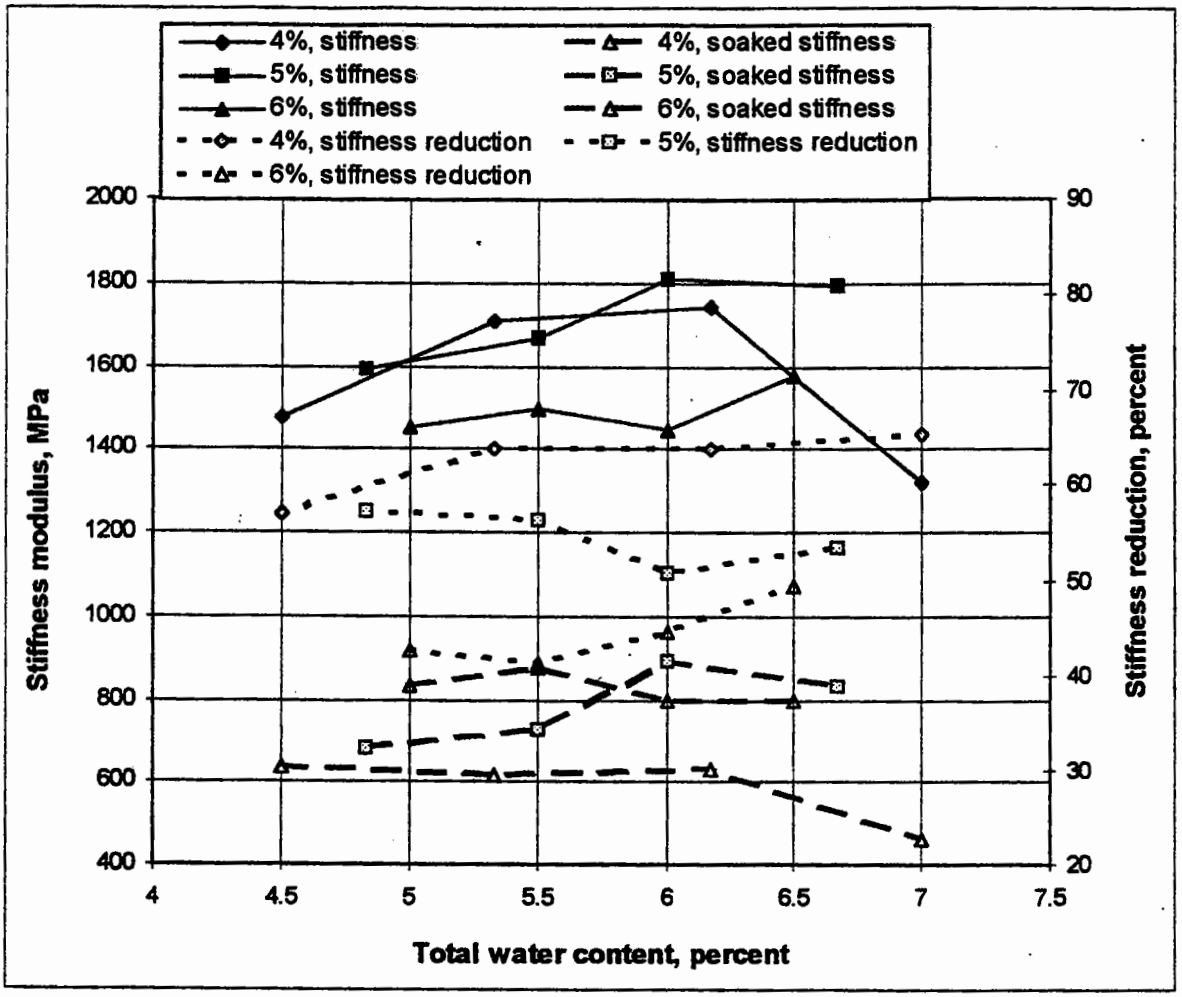


Figure 4-17 Comparison between unsoaked and soaked stiffness modulus of specimens containing 4%, 5%, and 6% RBC of R-emulsion and mid DBM

as the water content at compaction increases. These findings are related to the emulsion type used (being harder emulsion, see Chapter 10) as it may react quickly with the aggregate during compaction. The water thus has an influence on the material response according to the emulsion type and content.

Compaction of fine dense graded mixtures:

A compactibility study of mixtures containing the fine grading aggregate 'C2' involved both K-emulsion and R-emulsion with 5% and 6% RBC. Stiffness moduli were determined for the mixtures which were manufactured using different water contents at compaction, after 4 days and 37 days of curing at 20°C. The results are presented in Figures 4-18 to 4-21.

Similar responses were observed for the K-emulsion and the R-emulsion mixtures. Over the range of water contents used, as water content increases, both the dry density and stiffness modulus values increased whilst stiffness reduction due to specimen soaking decreased (see Chapter 8). Fine dense graded mixtures appear to require more water for better distribution of the emulsion during mixing and better reaction with the aggregate particles during compaction.

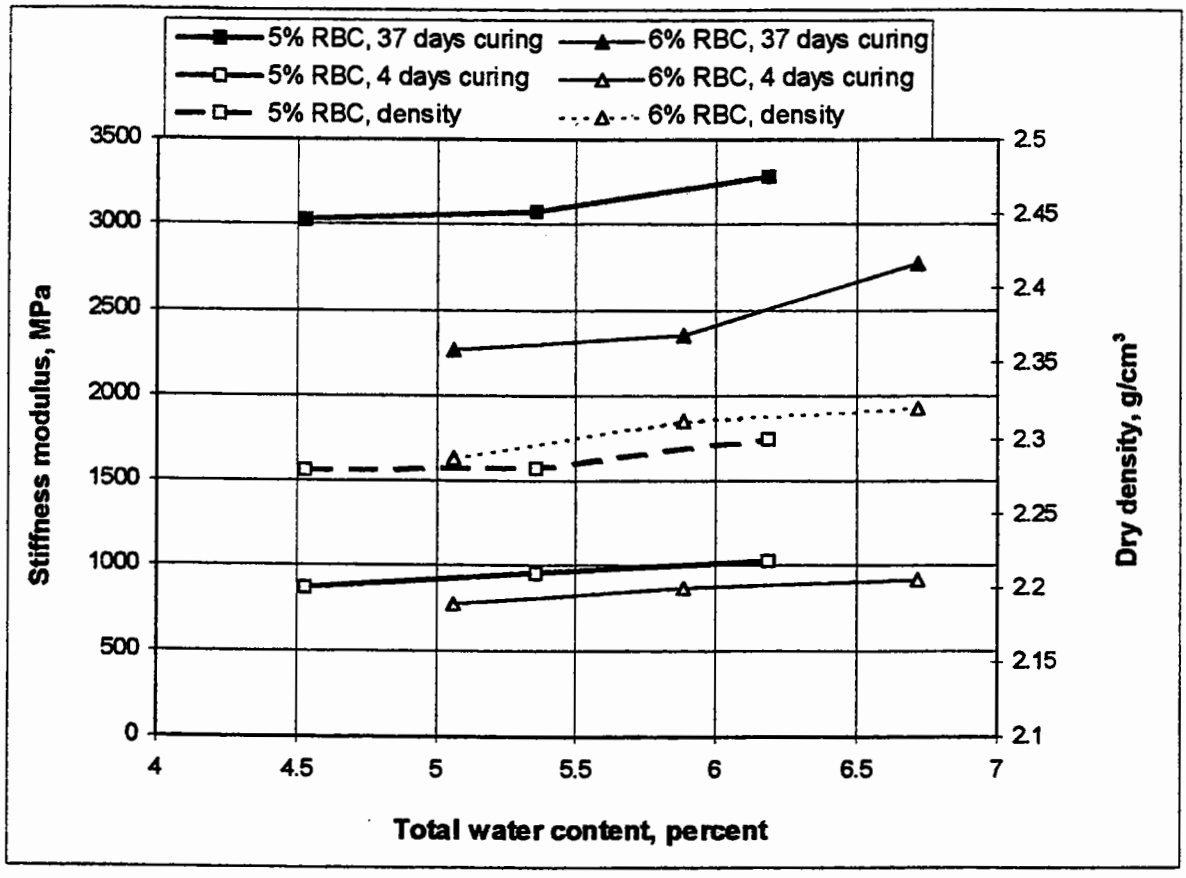


Figure 4-18 Stiffness modulus and dry density of specimens containing K-emulsion and C2 grading as a function of total moisture content at compaction and curing time

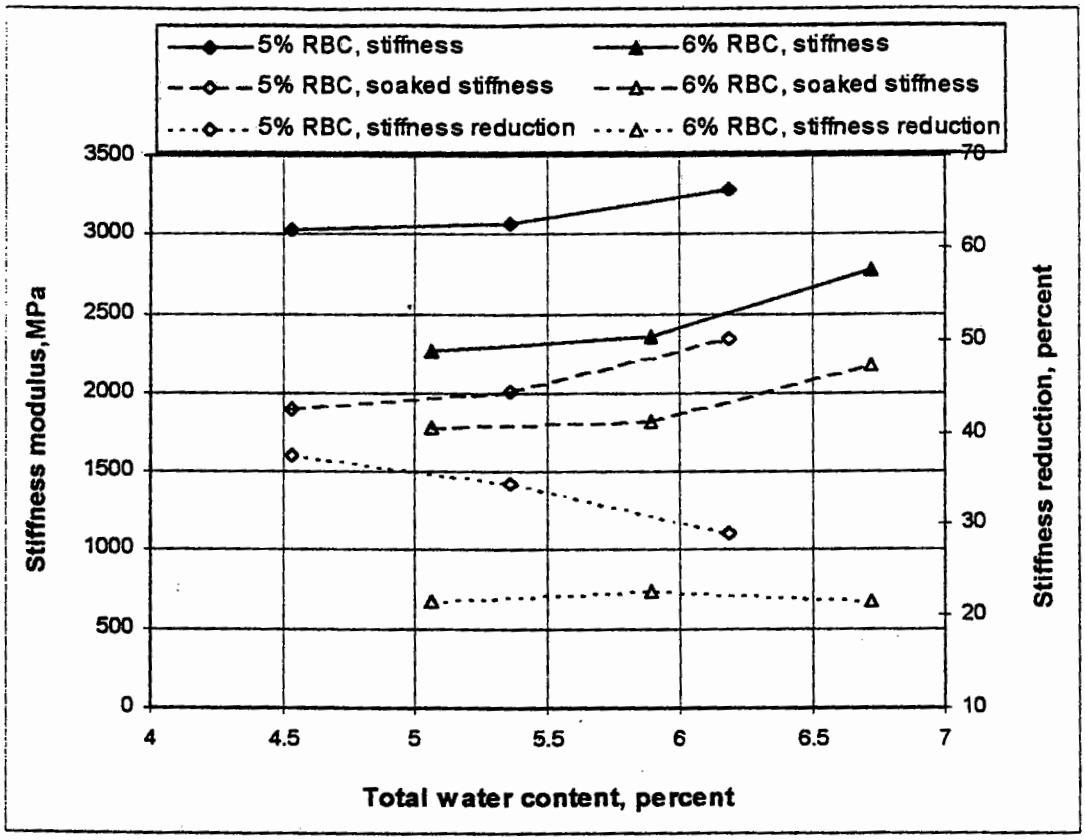


Figure 4-19 Comparison between unsoaked and soaked stiffness modulus of specimens containing 5% and 6% RBC of K-emulsion and C2 grading

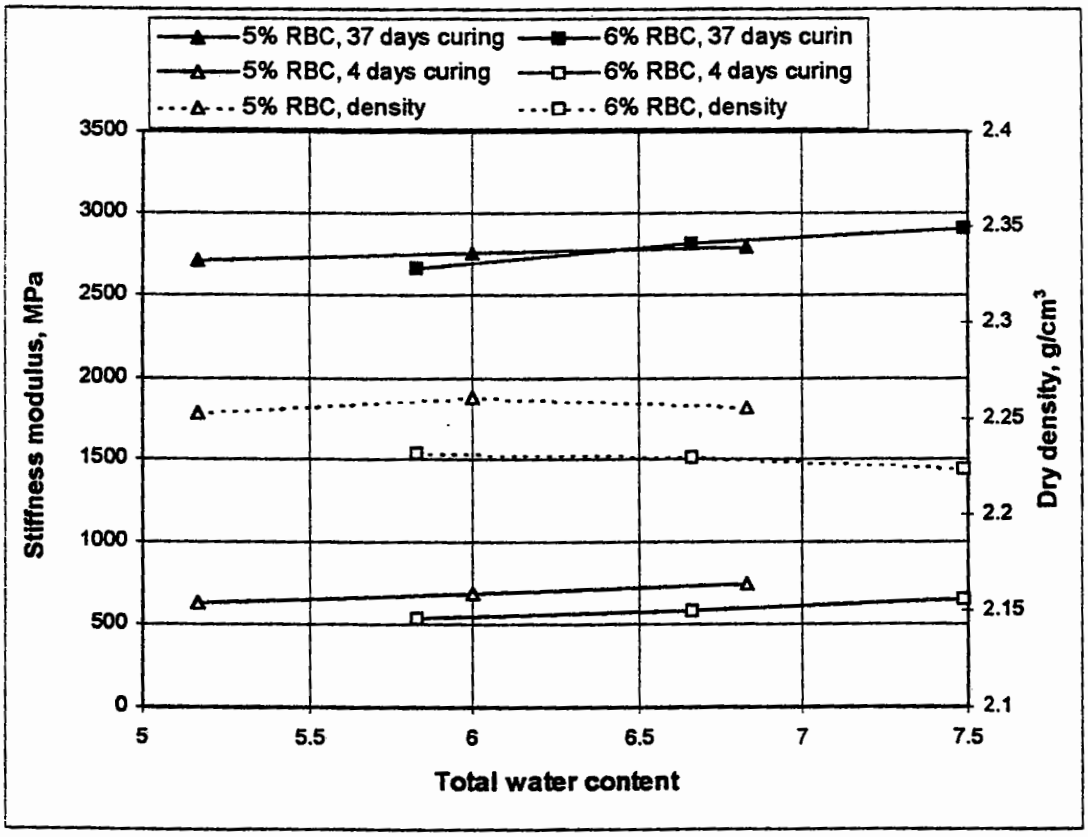


Figure 4-20 Stiffness modulus and dry density of specimens containing R-emulsion and C2 grading as a function of total moisture content at compaction and curing time

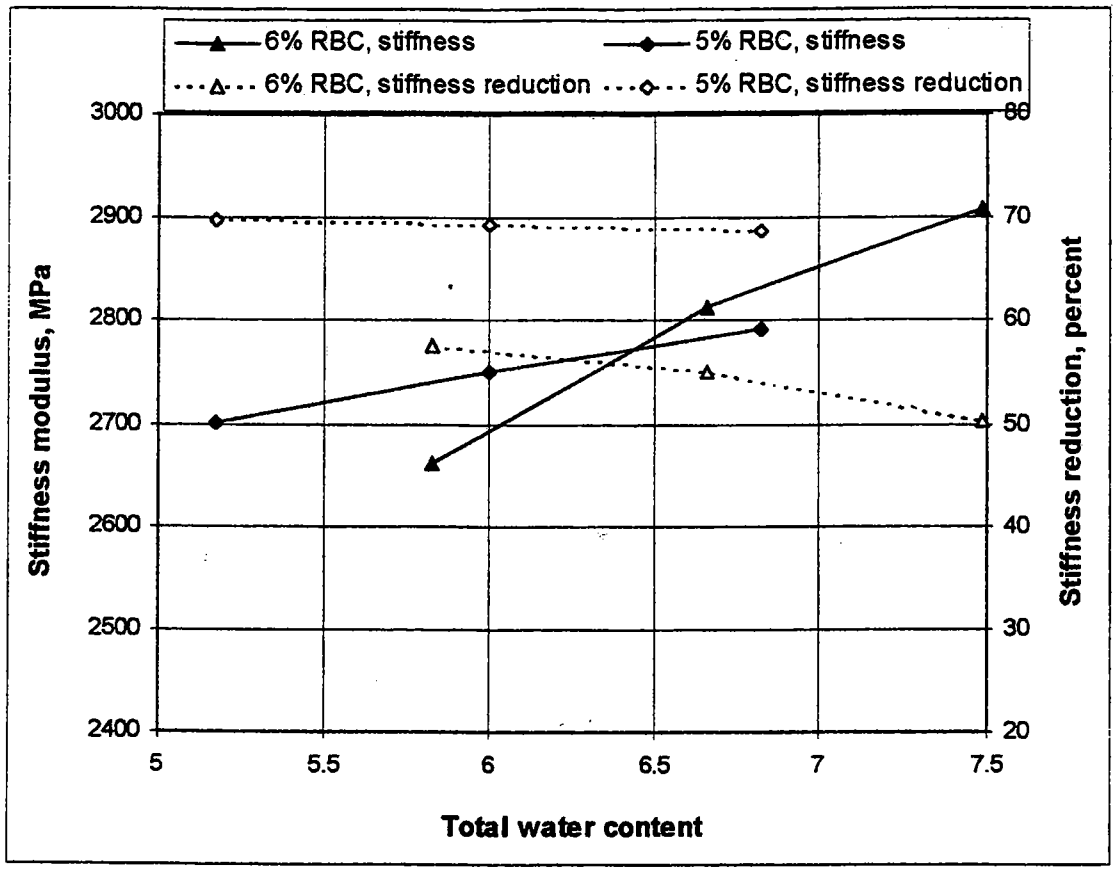


Figure 4-21 Comparison between unsoaked and soaked stiffness modulus of specimens containing 5% and 6% RBC of R-emulsion and C2 grading

It can be concluded that the optimum water content at compaction for a mixture is dependent upon emulsion type and content as well as aggregate grading. The stiffness modulus of the material at proper curing should be involved in the determination of such an optimum. For DBM mixtures with less viscous emulsion, the total water content at compaction should be carefully determined according to the emulsion content used. On the other hand, fine-grading mixtures with normally used emulsion contents, up to 6% RBC, require a higher total water content regardless of the emulsion type used. An important point to note is that, according to the results presented herein, changes in water content at compaction have less effect on both dry density and stiffness modulus than changes in the residual bitumen content. Bearing in mind that producing specimens in the laboratory should replicate the mixtures produced in the field, the total water content in a mixture should depend on the underlying and overlying pavement materials as well as the compaction equipment.

It should be reported that, for all specimens, the bottom surface was usually rough, while the top surface (the surface in contact with the compacting device) was usually smoother. Additionally, while extruding the specimens fabricated using the gyratory compactor, the large particles were separated from the specimen's lateral surfaces and large surface voids were created. This may be attributed to surface forces on the specimen faces resulting from the torsional shear created by the gyratory action while a rotation constraint occurs at the compaction ram at the top surface.

4.2.4 Proposed Sample Preparation Procedure

Considering the aforementioned findings resulting from the experimental work, the following steps can be used for preparing emulsion mixture specimens:

1) Aggregate preparation (e.g., choice of grading, etc.)
2) Determination of the minimum required mixing water content.
   This can be determined either by visually evaluating coating of specimens according to ASTM D224, or as follows:
   - Preparing specimens using different mixing water contents and a typical content of the emulsion type used (4% RBC is preferable in order to achieve a clear optimum).
   - Compacting the mixtures using either a vibrating hammer or a gyratory compactor at the same total moisture content.
   - Determining specimens' stiffness moduli after a reasonable curing time (24 hr at 48C is adequate).
   - Minimum added water content can then be determined by plotting the relationship between added water content and stiffness modulus.
3) Using the pre-determined mixing water content and a reasonable emulsion content (4% RBC is preferable) prepare at least four mixtures.
4) Leave the mixtures in trays for water evaporation to reach various total water contents.
5) Fabricate specimens and determine their stiffness moduli and dry densities after proper curing, from which the optimum total water content at compaction can be determined.

6) Use the determined optimum water content at compaction for all the emulsion contents used in subsequent tests.

4.3 SUMMARY

For preparation of emulsion-aggregate mixture specimens, keeping the mixing water content at as low a level as possible is desirable, provided that uniformly coated aggregate is achieved. This leads to a reduction in the water content at compaction, leading to better properties of the material. Optimum water content at compaction should however be determined using both a dry density criterion and the stiffness modulus of the material after an appropriate curing regime. Over the range of emulsion contents used, a slight difference was observed in the determined water content at compaction. The dry density and stiffness modulus were generally sensitive to the change in residual bitumen content (RBC) more than the change in water content at compaction. It is therefore suggested that the total water content at compaction should be kept constant in determining the optimum residual bitumen content. The optimum water content can be determined using a compaction curve based on assumed RBC, preferably 3-4 % for DBM grading and 5 % for finer grading.

According to aggregate gradation and emulsion type, too high a water content at compaction can lead to more than 1% water loss during compaction and may reduce the effective RBC. Adhesion built up between binder and aggregate particles was found to be significant in fine dense graded, but much less so in DBM graded mixtures, resulting from the compaction process and the drainage of the water during compaction.

Further discussions on the effect of compaction method, aggregate gradation, emulsion type, and curing regime on stiffness modulus of the material, and consequently on the determined RBC, and the effect of aggregate gradation on resistance to water, are presented in Chapters 5 and 8 respectively.

CHAPTER

5 ELASTIC PROPERTIES OF EMULSION-AGGREGATE MIXTURES

Stiffness modulus is an important parameter in deciding the ability of an emulsion-aggregate mixture to perform as a structural layer in a pavement. The transfer of traffic loading to the pavement foundation depends on the horizontal stiffness of the bound layer, or rather the tensile response of the material due to bending under wheel loading. Conversely, the contribution of the unbound materials to the bearing capacity of the pavement is mainly from their compressive response.

As reported in the literature, emulsion mixtures exhibit a composite response over time: being similar, largely, to unbound aggregate, at early stages of curing and to hot bituminous mixtures after full curing. This changing of properties introduces the problem of which laboratory test method is most suitable for characterising the stiffness response of emulsion-aggregate mixtures to best enable the analysis of a pavement response to traffic loading. This chapter therefore evaluates the behaviour of this type of mixture using the indirect tensile and triaxial modes of testing, both in the Nottingham Asphalt Tester (NAT). Emphasis is placed on the effect of compaction method, aggregate gradation, emulsion content, water content, test temperature and curing regime.

5.1 ELASTIC PROPERTIES IN INDIRECT TENSILE MODE

Characterization of cold mixtures for use in pavements concerns those factors which affect the response and damage of the pavement structure. The stiffness of emulsion-aggregate mixtures for use in pavement layers is important in terms of their load-spreading characteristics. This section presents and discusses the behaviour of emulsion mixtures under indirect tensile loading and the effect of mixture variables and compaction method on stiffness modulus.

5.1.1 Theory

In the indirect tensile mode of loading, a line load is applied across the vertical diameter of a cylindrical specimen, by which a biaxial stress distribution in the specimen is produced, as indicated in Figure 5-1. By measuring the linear extension of the horizontal diameter, i.e., the horizontal deformation (Δh), and using both the induced horizontal tensile stress (σ_{hx}) and the vertical compressive stress (σ_{vx}) across the horizontal diameter, the stiffness modulus (S_m) of the material can be determined.

However, in order that the stress conditions in the specimen are given by the closed form solution of the theory of elasticity, the following assumptions have to be made (Hudson et al, 1968):

- the specimen is subjected to plane stress.
- the material is linear elastic.
- the material is homogeneous and isotropic.
- Poisson's ratio (ν) for the material is known.
- the vertical load is applied as a line loading.

Then, the maximum and average stresses on the horizontal diameter are as follows:

$$\sigma_{hx\,(max)} = \frac{2P}{\pi d t} \qquad 5.1$$

$$\sigma_{vx\,(max)} = \frac{-6P}{\pi d t} \qquad 5.2$$

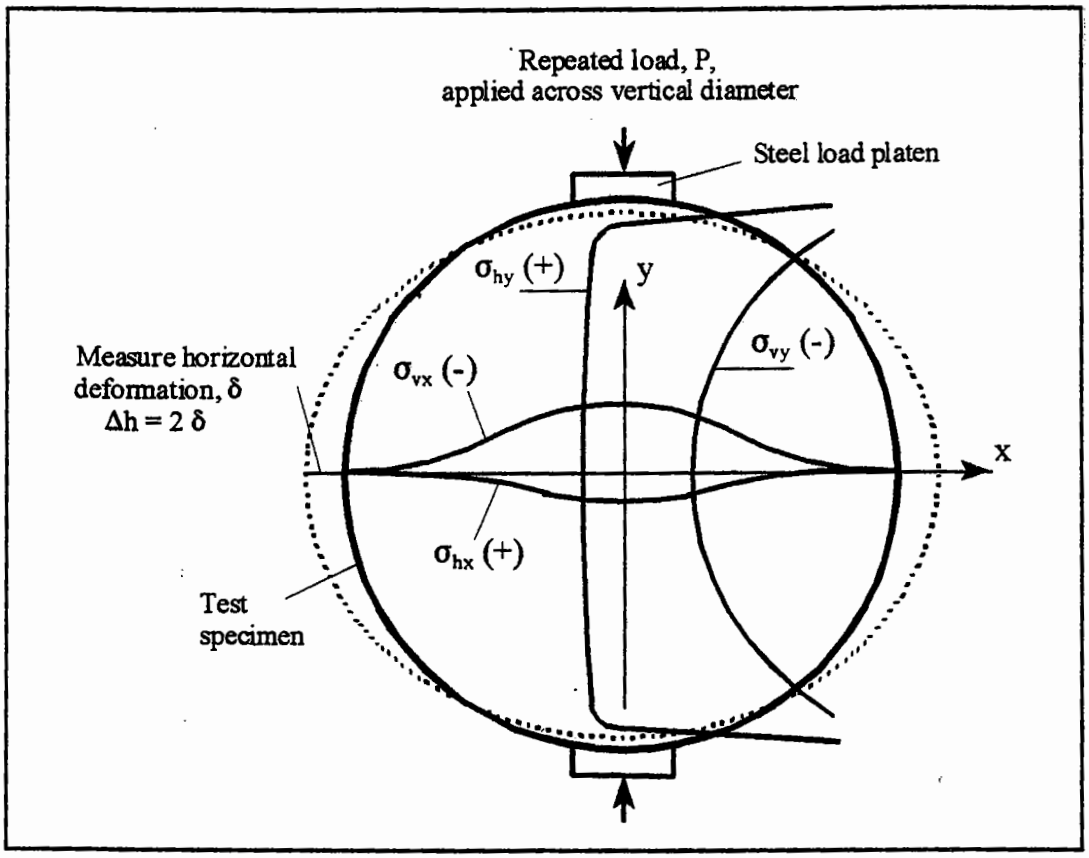
$$\text{average horizontal stress } \bar{\sigma}_{hx} = \frac{0.273P}{dt} \qquad 5.3$$

$$\text{average vertical stress } \bar{\sigma}_{vx} = \frac{-P}{dt} \qquad 5.4$$

where:

d = specimen diameter

t = specimen thickness



Notes: σ_{vx} = vertical stress across x-axis (compressive)

σ_{hx} = horizontal stress across x-axis (tension)

σ_{hy} = horizontal stress across y-axis

σ_{vy} = vertical stress across y-axis (compressive)

Figure 5-1 Stress distribution across horizontal and vertical axes of specimen

Considering the average principal stresses in a small element subjected to biaxial stress conditions, the horizontal strain ($\overline{\varepsilon_{hx}}$) would be:

$$\overline{\varepsilon_{hx}} = \frac{\overline{\sigma_{hx}}}{S_m} - \upsilon \frac{\overline{\sigma_{vx}}}{S_m} \qquad 5.5$$

$$\overline{\varepsilon_{hx}} = \frac{0.273P}{S_m d\, t} + \frac{\upsilon P}{S_m d\, t} \qquad 5.6$$

Horizontal deformation $\Delta h = \overline{\varepsilon_{hx}}\, d$ 5.7

$$\therefore \Delta h = \frac{0.273P}{S_m t} + \frac{\upsilon P}{S_m t} \qquad 5.8$$

The stiffness modulus of the material can then be calculated from:

$$S_m = \frac{P}{\Delta h\, t}(0.273 + \upsilon) \qquad 5.9$$

5.1.2 The Nottingham Asphalt Tester

The Nottingham Asphalt tester (NAT) comprises four units, a main test frame placed in a temperature control cabinet, an interface unit for the acquisition of data and controlling of the test, a pneumatic unit connected with the interface unit and an actuator mounted above the test frame for controlling the applied load. A schematic diagram is shown in Figure 5-2. The computer controls a voltage/pressure (V/P) converter and operates a solenoid valve via the interface unit. Using software, air at a pre-determined pressure is introduced into a reservoir in the pneumatic unit and the solenoid valve is switched to apply a load to a specimen. The load is then measured using a load cell and the V/P converter is adjusted to achieve the required level. The NAT can be configured for testing specimens in the indirect tensile mode, for stiffness determination following the theory previously explained, or for fatigue testing, or in the repeated load axial mode for assessing the permanent deformation of a mixture.

In the indirect tensile mode (DD213: 1993), a pulsating load is applied vertically across the diameter of the cylindrical specimen and the horizontal deformation is measured by means of two linear variable differential transducers (LVDTs), which are mounted diametrically opposite one another in a rigid frame clamped to the test specimen. For the determination of the resilient modulus, since the instantaneous recoverable deformation can not be measured, due to the difficulty in determination of the inflection point on the unloading portion of the deformation curves, the total horizontal deformation is used. Figure 5-3 illustrates the definition of the measured horizontal deformation used for stiffness determination in the NAT, compared to the ASTM definition.

For testing, a target load pulse rise-time (120 ms was used in this research followed the British Standard DD 213: 1993) and a target horizontal deformation are selected, and the software automatically adjusts timing and load to achieve these targets. During the test, the specimen is subjected to five load pulses and stiffness modulus is then determined from the vertical load, the measured horizontal deformation, the Poisson's ratio of the material, and the specimen dimensions.

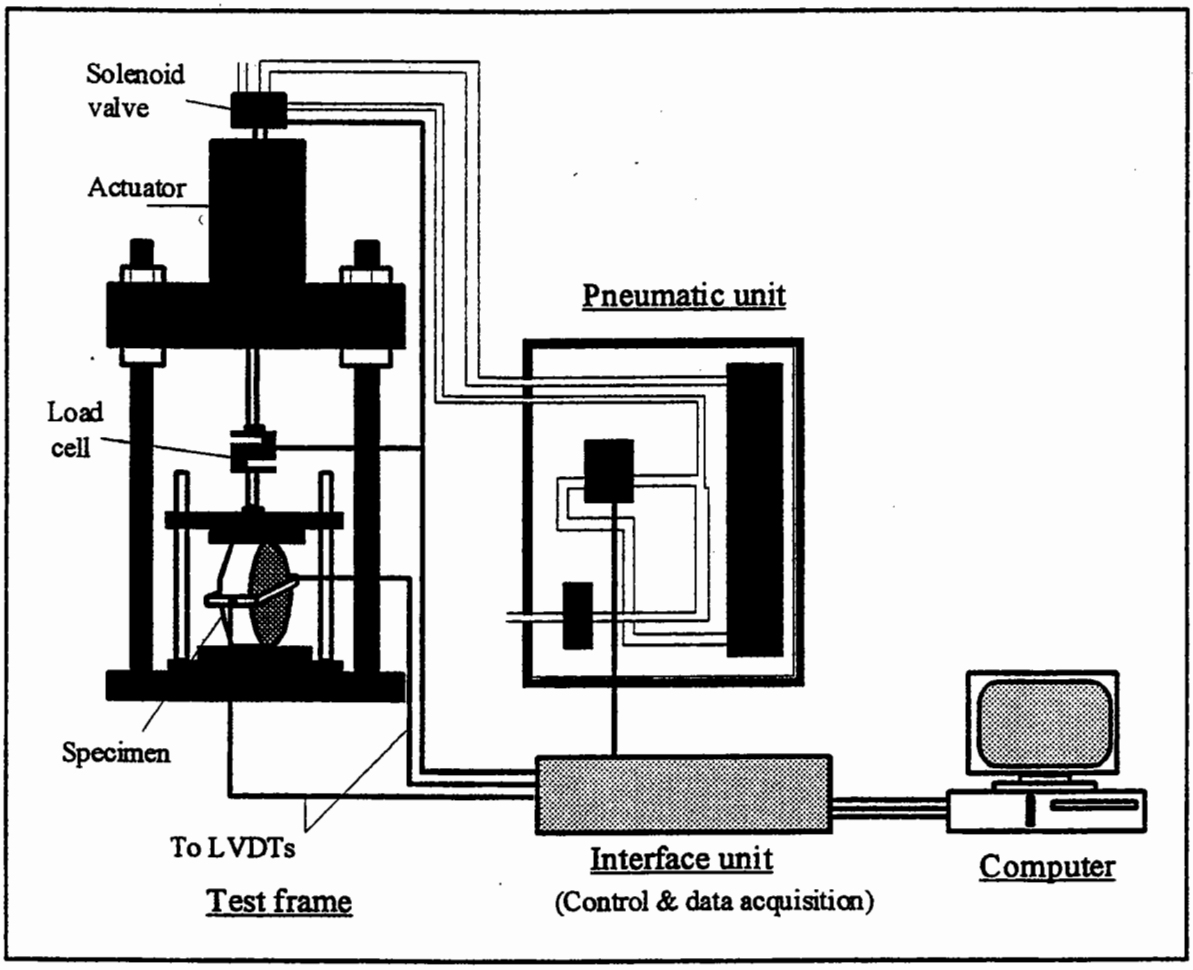


Figure 5-2 The Nottingham Asphalt Tester configured for testing in the indirect tensile mode

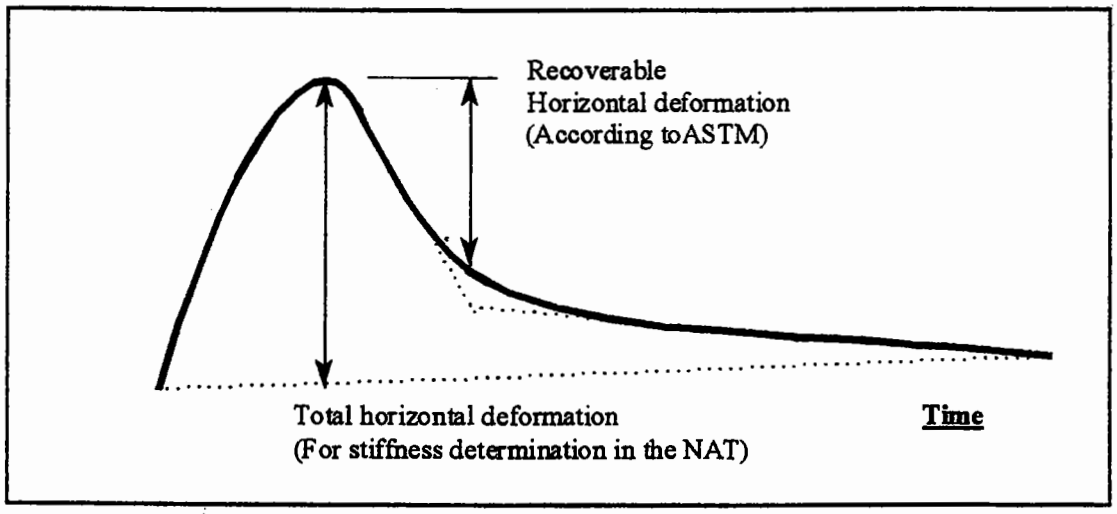


Figure 5-3 Definition of the measured horizontal tensile deformation in the NAT compared to the definition of the ASTM

5.1.3 Study of Factors Affecting Stiffness Modulus

It was stated that the stiffness of emulsified material for use in structural layers of roads is important with respect to the load-spreading characteristics of the pavement structure. Generally, it is influenced by curing time, temperature, aggregate type used, emulsion type and content, and mode of loading. Therefore, these factors should be considered in both mix design and structural design procedures. The stiffness moduli of the prepared specimens used in this study were determined using the Nottingham Asphalt Tester (NAT) in the Indirect Tensile Mode at 20°C according to the British Standard DD213: 1993.

Effect of Compaction Method

It is apparent that there is a general lack of information on field performance of emulsion mixtures as a function of compaction equipment, relative to laboratory compaction methods. This investigation was focused on the effect of the laboratory compaction method on the stiffness modulus. Specimens containing 3.2 % RBC of K-emulsion were compacted to approximately similar bulk densities (2.48 kg/m^3), using gyratory compaction, vibrating compaction, and the Marshall hammer, and then tested using the NAT in the ITSM mode at different curing times.

Compaction method was found to significantly affect the stiffness modulus of the bituminous emulsion mixtures used. The vibratory compactor with its kneading effect was found to be a suitable tool in compacting emulsion mixtures. As shown in Figure 5-4, during early curing, specimens fabricated using the gyratory compactor showed rapid stiffness modulus increase, more so than those from the other compaction methods. On the other hand, stiffness moduli of the specimens prepared using the vibrating hammer were the highest at a later stage of curing.

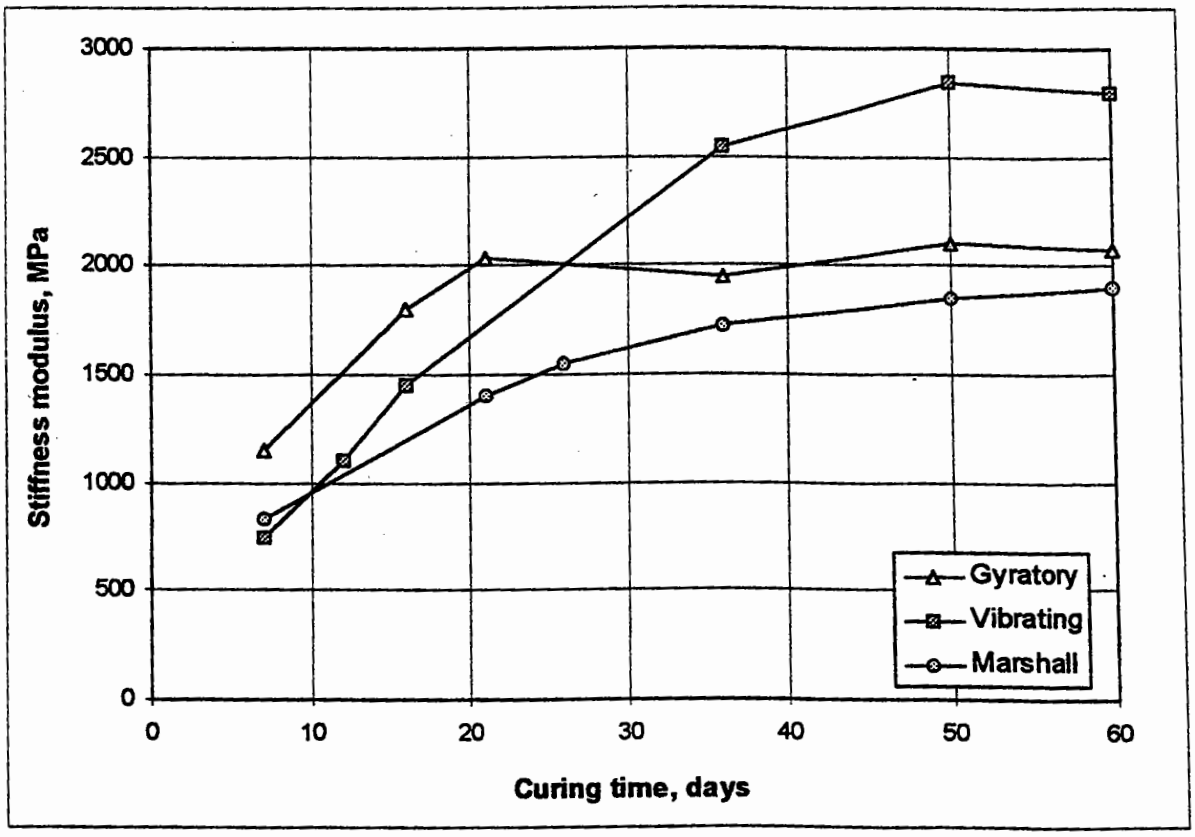


Figure 5-4 Effect of compaction method on indirect tensile stiffness modulus of specimens containing 3.2% RBC of K-emulsion

In vibratory compaction, with a kneading action, the pore pressure within the emulsion and water dissipates much more than in gyratory compaction, because the mixture is less confined during the vibrating compaction operation. Therefore, more interparticle contact and more interlocking are expected. Moreover, it is believed that the vibrating hammer may lead to a decrease in the potential energy of the emulsion bitumen droplets relative to

aggregate particles (the droplets are vibrated against them) and, hence, an improvement in the coalescence process.

Thus, it is believed that the coalescence of emulsion bitumen droplets onto aggregate particles in vibratory compaction is much higher than in the other compaction methods, leading to a higher stiffness modulus after being cured.

Clearly, as well as the compaction effort, the compaction method plays a significant role in the response of emulsion-aggregate mixtures, influencing the interaction between the binder and the aggregate particles and the aggregate structure (see also Chapter 4). Based on this study, both the vibrating hammer and the gyratory compactor were used in fabricating specimens for studying the properties of this type of mixture, disregarding the Marshall hammer.

Effect of Aggregate Gradation

The effect of aggregate gradation was also investigated. This centred on the mid-point of the BS 4987 specification for 20 mm DBM, since it is currently used on a large scale for reinstatement works and pavement layers of low volume roads. In this study, preliminary work showed different performances of emulsion mixtures comprising different types of emulsions, dependent on aggregate gradation. The gradation used was therefore extended to involve the fine and coarse limits of the BS 4987 specification (A and B gradings) as well as the fine and coarse limits of the continuously graded asphaltic mixture designated as C2 and C1 respectively.

Mixtures fabricated using vibrating compactor:

The stiffness modulus of specimens containing dense gradings (A, B, and mid DBM) and A-emulsion, compacted using the vibrating hammer, were determined after curing for 2 days at 48°C. As seen in Figure 5-5, the highest moduli irrespective of the RBC, were for the mid DBM mixtures. In addition, the results indicate that higher values of stiffness modulus are obtained at a lower residual bitumen content. As the RBC increased, the stiffness modulus reduction was less for the fine grading than for the mid DBM, leading to similar performance at higher RBC. However, this finding is certainly also related to the dry

density of specimens and the retained water content at test, which will have been different in the two cases.

To confirm the above result, testing on mid DBM grading specimens containing K-emulsion were carried out. In addition to testing specimens cured for 2 days at 48°C, testing extended to involve specimens cured for 3 and 5 days at 48°C to investigate the effect of curing time on the resulting stiffness modulus as a function of the residual bitumen content. As shown in Figure 5-6, besides the reduction in stiffness modulus as a result of increasing RBC, further curing of the specimens resulted in a greater water loss for the one containing higher RBC and a relatively greater stiffness increase. Therefore, an increase in emulsion content for a mixture containing the mid DBM grading will lead to a higher water content and consequently lower stiffness modulus. It is possible that, more compaction and more curing time would lead to a better response.

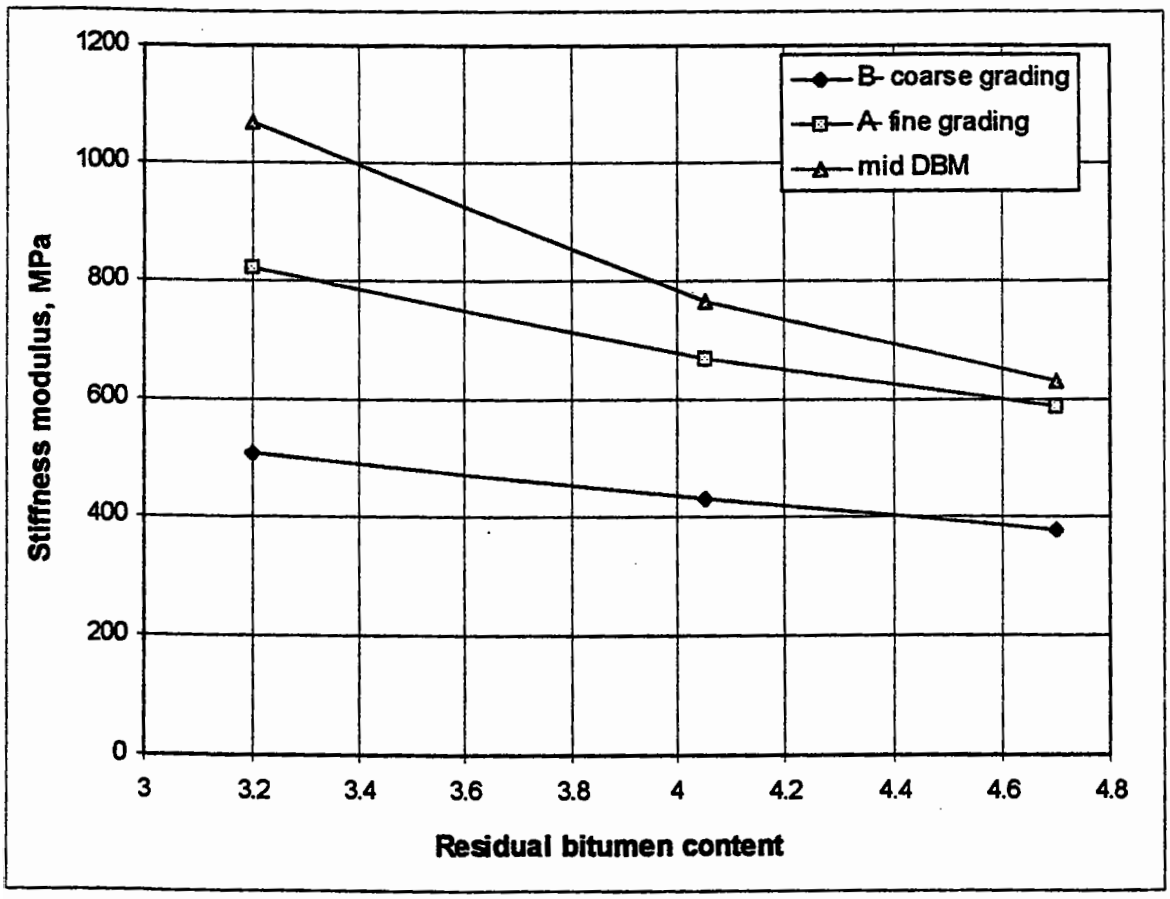


Figure 5-5 Effect of aggregate gradation on stiffness modulus of specimens containing A-emulsion

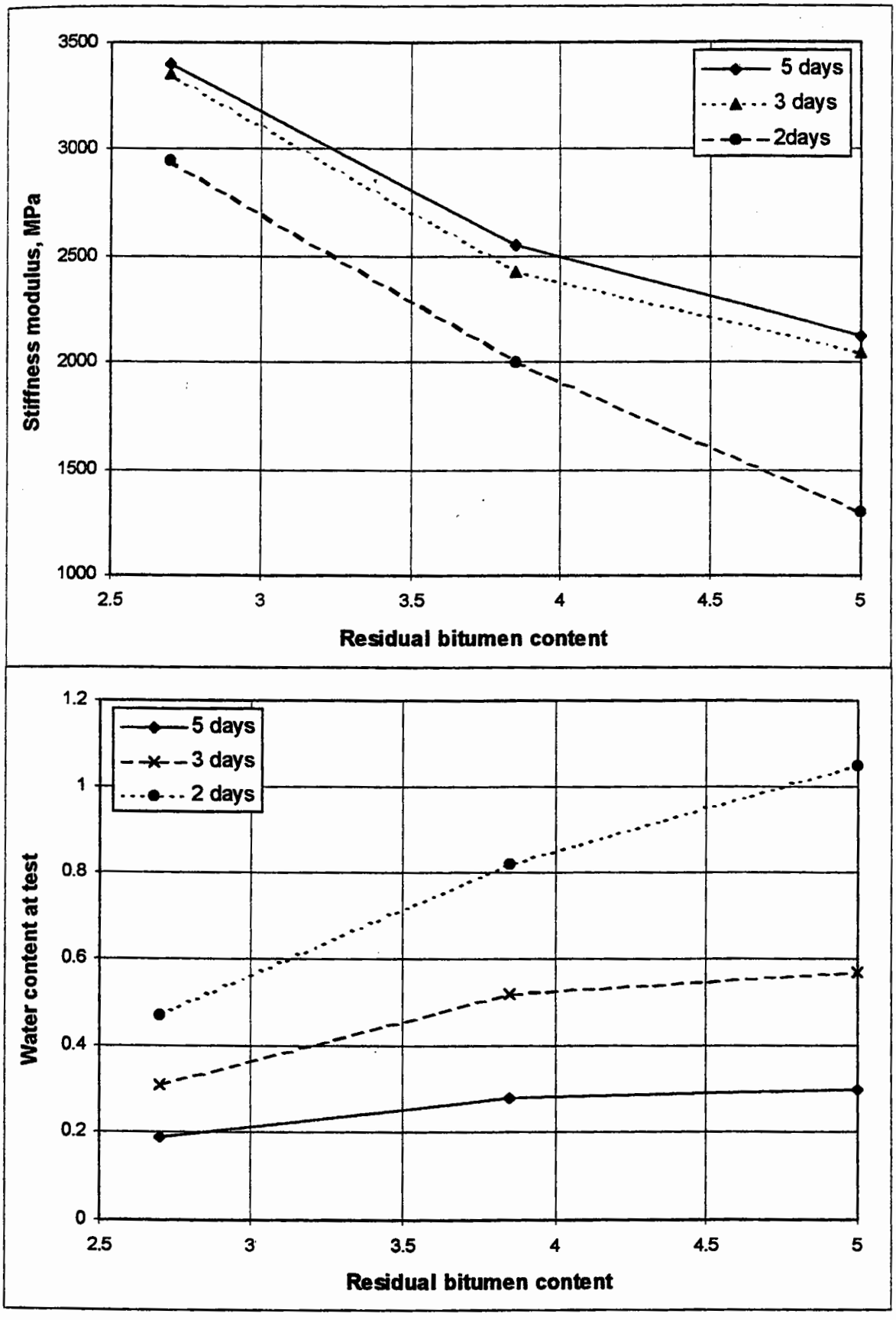


Figure 5-6 Residual bitumen content versus stiffness modulus and water content at test (K-emulsion - curing at 48°C)

Mixtures fabricated using gyratory compactor:

Emulsion mixtures containing C2 aggregate grading and K-emulsion and R-emulsion were also investigated to compare with those of mid-DBM grading.

Presented in Figure 5-7 are measured stiffness moduli for fine grade (C2) and mid-DBM mixtures containing different residual bitumen contents of K-emulsion, at early and later stages of curing. The benefit of using the fine grading can clearly be seen. At both levels of curing, stiffness moduli were much higher for all RBCs used. Unlike the case with the mid-DBM mixtures, increasing RBC increased the stiffness modulus to an optimum, beyond which a rapid stiffness reduction occurred. Also, an increase in the stiffness modulus of the mixtures containing R-emulsion was found when using C2-grading relative to that of mid-DBM grading (Figure 5-8). Using R-emulsion and fine grading, less change in the stiffness moduli as a function of the RBC was observed.

Comparing the results of K-emulsion and R-emulsion mixtures, it can be noticed that the benefit of using R-emulsion is seen at early curing using the mid-DBM grading. Apart from that case, the stiffness response of the mixtures containing K-emulsion is much better.

An important point is that, although the dry densities of the fine-graded mixtures using both emulsions were lower than those of the mid-DBM mixtures, the measured stiffness moduli were higher. The reason for this increase in stiffness may be related to the binder-aggregate interaction, not only to the aggregate structure which contributes to a rapid evaporation of water from the system. What is expected with the mixtures containing fine grading is that, during the compaction process, the aggregate particles act as a filter retaining the bitumen droplets and allowing the water to drain. Due to the higher surface area of the aggregate particles in contact with the emulsion and the induced stresses within the aggregate, the bitumen droplets coalesce, squeezing out most of the contained water, which in turn freely drains from the system. In contrast, the surface area of the coarser grading is lower, leading to re-distribution and free movement of the un-coalesced bitumen droplets, and a consequent non-uniformity of the binder film thickness. In addition, in mixtures with larger particle size, the number of points of contact between the aggregate particles is less,

resulting in fewer high pressure regions and therefore less coalescence of bitumen droplets on themselves and onto the aggregate particles.

The distribution of the K-emulsion within the aggregate particles (the fine particles in particular) is expected to be better than that of the R-emulsion, considering their viscosities which will be discussed in Chapter 10, being lower in the case of K-emulsion. Of course, this better distribution leads to better coating to the aggregate particles and hence better reaction with them. The thin film of residual K-emulsion then leads to a better coalescence and hence higher stiffness modulus. However, the increasing stiffness modulus of the R-emulsion mixtures containing mid-DBM at early curing may be attributed to the fact that the binder is harder and gives better coalescence onto the large particles. This was visually noted during the mixing process.

It can be concluded that aggregate gradation has a most significant effect on the stiffness properties of emulsion-aggregate mixtures. Fine grading appears to give the highest stiffness modulus. The larger the particle size and the coarser the gradation, the less the resultant stiffness modulus of the mixture (see also Figure 5-9 for mixtures containing C1 grading) irrespective of the mixture density, which is higher for the mid-DBM mixtures. Also, the response of the emulsion type used is to a great extent dependent upon the aggregate grading. Emulsion such as the K-emulsion has a relatively better effect on the stiffness moduli of fine graded mixtures. If coarser grading is used, the higher stiffnesses of mixtures containing K-emulsion are biased towards lower RBC. When using R-emulsion with mid-DBM or C1 grading, a higher RBC is required relative to that containing K-emulsion in order to achieve similar performance, as it is related to the emulsion distribution within the aggregate particles and coating of large aggregate particles.

A point to note which might be useful for mixture design is that the curing time did not alter the optimum residual bitumen contents of the above mixtures in the way that it did with the optimum water content at compaction. It can therefore be suggested that curing for a time at 20°C, leading to an early equilibrium water content (not the full curing at which the full strength of the material is attained), is enough for the mixture design purposes.

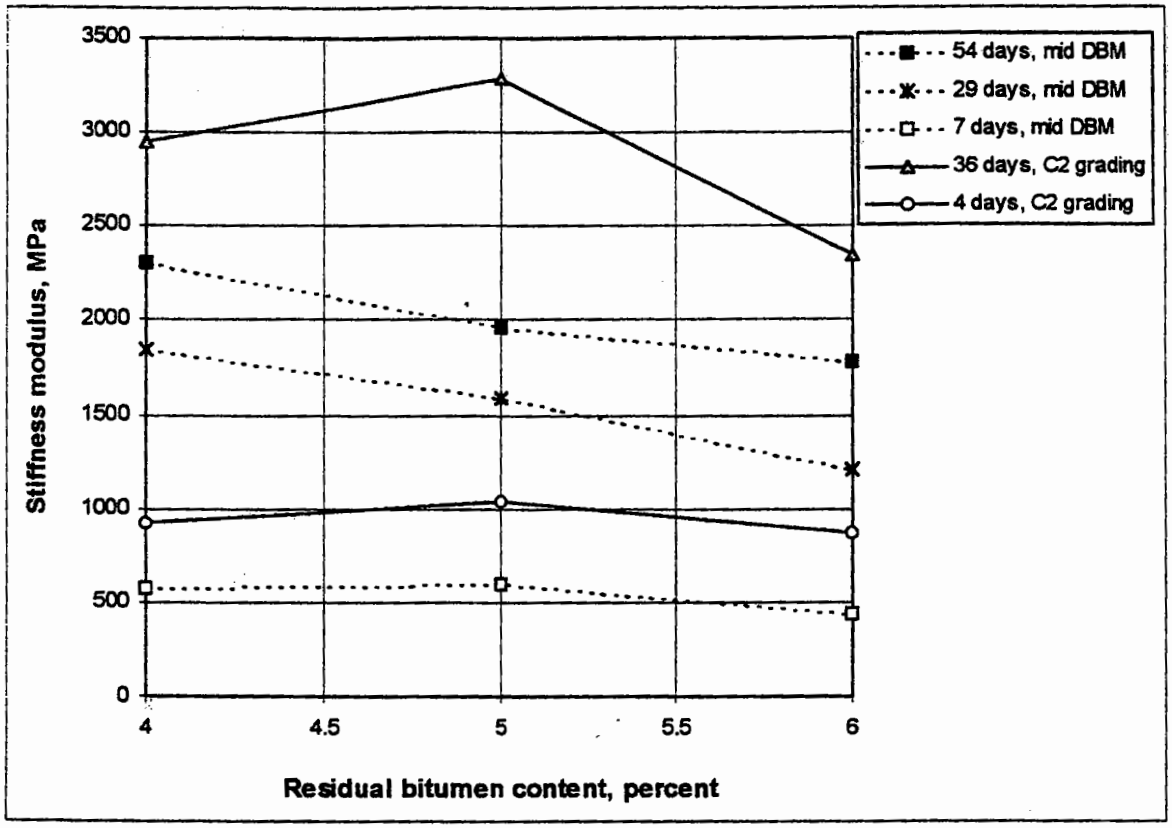


Figure 5-7 Comparison between the effect of fine and mid-DBM gradings on stiffness moduli of mixtures containing K-emulsion as a function of RBC and curing time

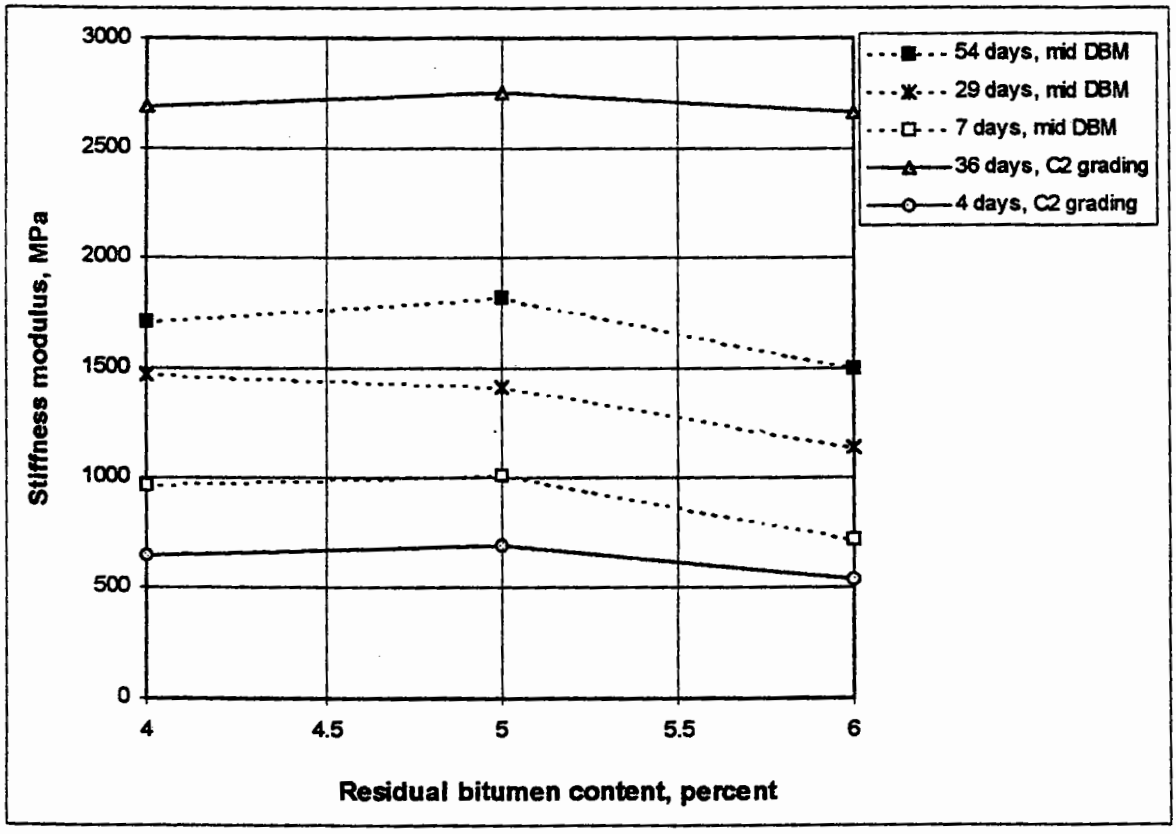


Figure 5-8 Comparison between the effect of fine and mid-DBM gradings on stiffness moduli of mixtures containing R-emulsion at early and later curing as a function of RBC

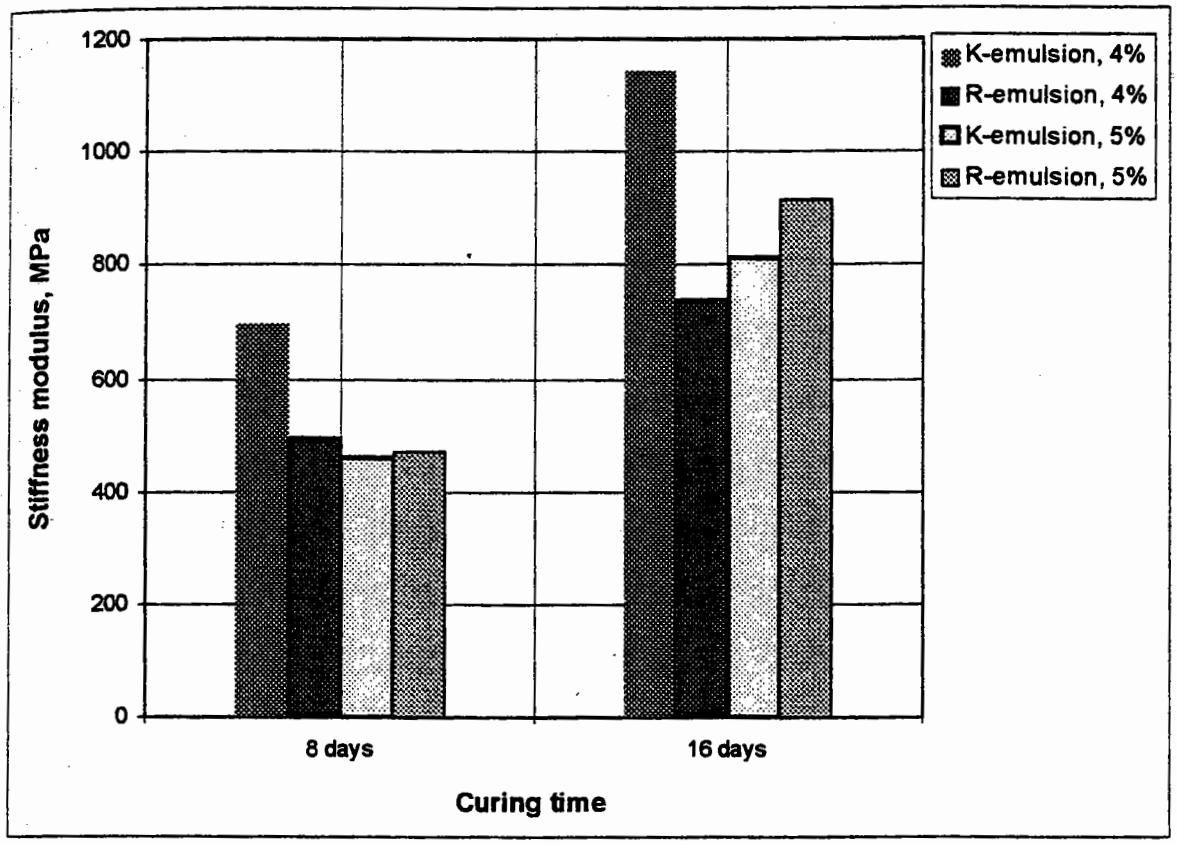


Figure 5-9 Stiffness moduli of mixtures containing C1 'coarse' grading and K or R emulsion at early and later stages of curing

Stiffness Increasing Rate as a Function of Curing Time

It is known that the strength of emulsion mixtures rapidly increases during the early life and then increases at a slower rate until reaching its final value. However, there remains significant concern about selecting an emulsion which is effective in mixtures for use in structural layers of roads. This requires an investigation of the effect of emulsion type and water loss on the stiffness increase rate of mixtures.

Mid-DBM mixture specimens fabricated in the vibrating compactor:

The rate of stiffness increase of emulsion mixture specimens cured at 20°C and the water content at test were monitored, and the effect of emulsion type and content were investigated. As shown in Figure 5-10, K-emulsion was the most effective in terms of coating ability for aggregate particles and stiffness modulus. The stiffness modulus of K-emulsion specimens fabricated using the vibrating hammer was about 2800 MPa after 60

days of curing. In terms of stiffness increase rate, K-emulsion mixtures were the highest of all. Overall, specimens prepared using emulsion based on 100 pen base bitumen (K-emulsion and EN998) gained strength very early. Hence, the specimens could be tested in the NAT after 3 days of curing at 20°C. Conversely, 'A' emulsion mixture specimens (based on softer base bitumen) could not be tested till after curing for two weeks at 20°C.

For all specimens, water contents at test were determined as previously discussed, to find out whether or not the above mentioned increasing rates of stiffness relate to water evaporation. However, it was found that the rates of water loss for specimens which contained a residual bitumen content of 3.2%, irrespective of emulsion type, were approximately the same. The water contents of all specimens were less than 1% after a week of curing, being 0.5% for K-emulsion specimens and 0.77% for EN998 emulsion mixture specimens, Figure 5-11.

It is believed that, in addition to the coalescence of emulsion bitumen droplets onto aggregate particles, which occurs with time and water evaporation, the degree of bitumen droplet flocculation increases and gives rise to a bitumen hardening. This phenomenon is influenced to a great extent by the type and amount of emulsion. A point to note is that no significant correlation between water content at test and stiffness modulus could be found, since the increase in the mixtures' stiffness was associated with a nearly un-changing water content at later stages of curing. However, better correlation of stiffness modulus might be found with curing time. A further discussion on the contribution of binder to emulsion-aggregate mixture response is presented in Chapter 10.

To investigate coalescence further, specimens of different emulsions were sawn into slices in order to investigate the material matrix, and the aggregate bitumen interface, after being cured. Visually, slices of A- emulsion specimens looked like a granular matrix only, that is coalescence of bitumen droplets during the breaking process was mostly onto each other not onto the aggregate particles. On the other hand, specimens of K-emulsion and EN998 emulsion looked something in between a bituminous and granular matrix.

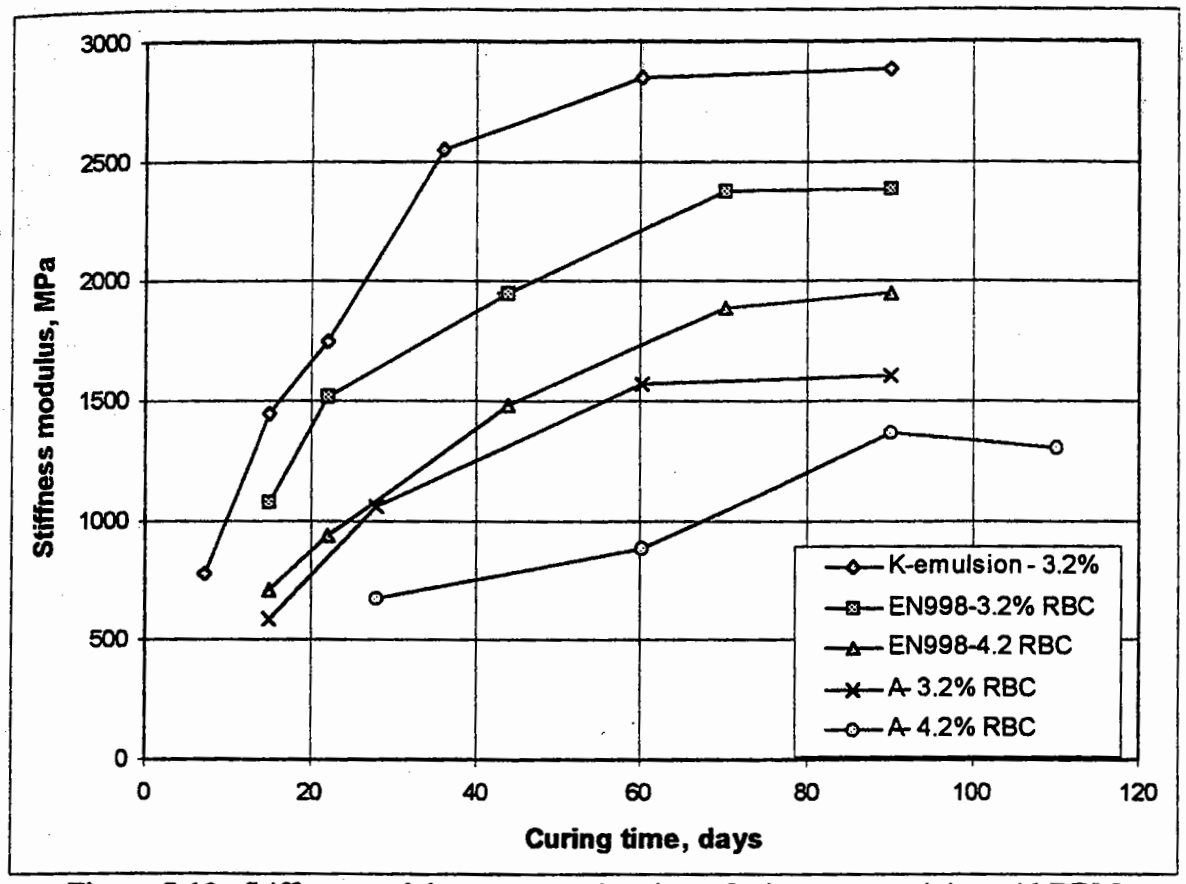


Figure 5-10 Stiffness modulus versus curing time of mixtures containing mid-DBM aggregate grading

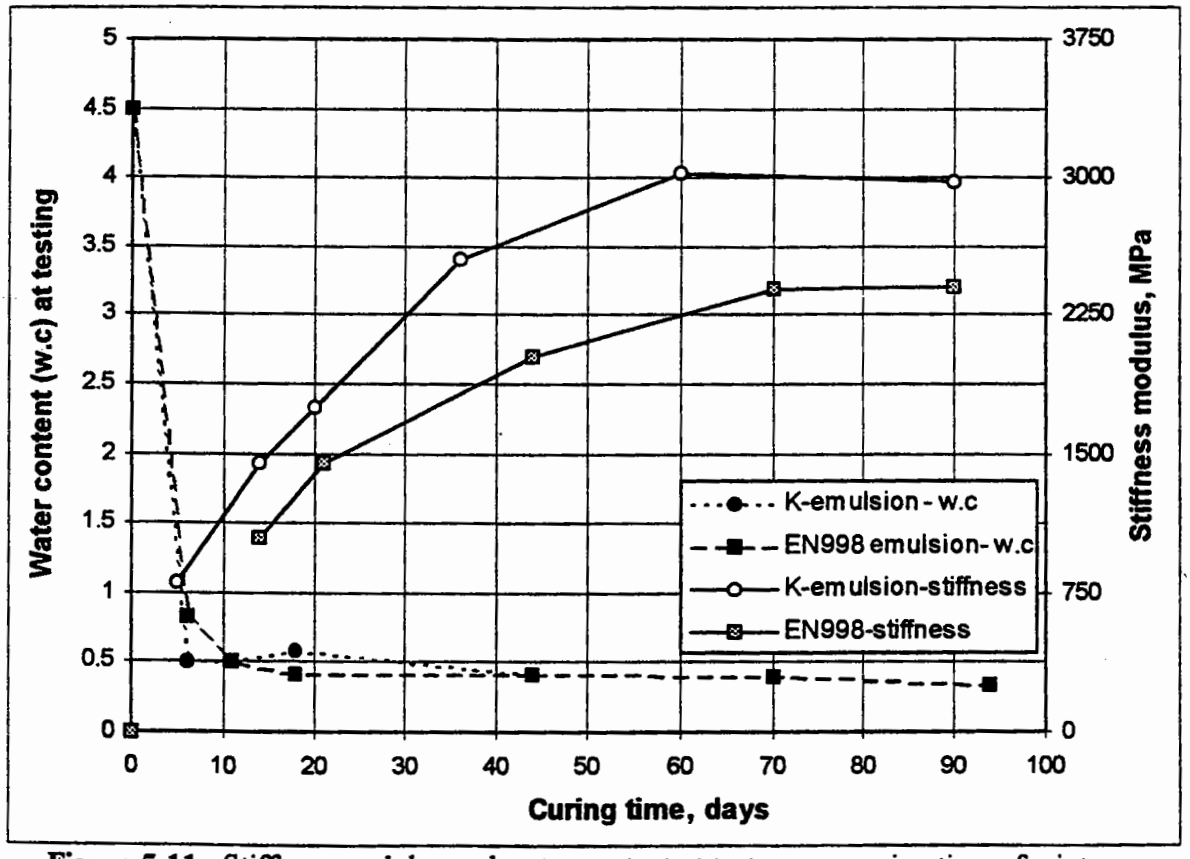


Figure 5-11 Stiffness modulus and water content at test versus curing time of mixtures containing 3.2% RBC

Specimens fabricated in the gyratory compactor:

Figure 5-12 shows the change in the stiffness of mixtures containing mid-DBM grading as a function of the curing time and the emulsion type. The stiffness of K-emulsion mixtures at early curing was less than the stiffness of R-emulsion mixtures. Clearly, the increase in stiffness of the mixtures containing K-emulsion has lead to an opposite response at later curing, as its stiffness is then higher than that of R-emulsion mixtures. In contrast, the results of the fine-graded 'C2' mixtures presented in Figure 5-13 showed that curing time has relatively less effect on the stiffness increase rate of K-emulsion mixtures containing higher RBC and a higher effect on mixtures containing lower RBC.

Obviously, the K-emulsion has the advantage of relatively better distribution in the fine aggregate. The RBC relative to the aggregate surface area is the governing parameter that leads to better adhesion of the K-emulsion residual bitumen with the aggregate particles. However, a higher RBC of this type of emulsion may lead to higher equilibrium water content in the mixtures and hence less stiffness.

The R-emulsion, on the other hand, has the ability to coat the coarse aggregate particles, but gives less coating to the fines. Therefore, using R-emulsion necessitates an increase in the mixing water content. Due to the relatively higher viscosity of this emulsion, it reacts and coalesces onto the aggregate, hence resulting in more water drainage during compaction. This might explain why the increase in stiffness modulus is less than in the K-emulsion mixtures.

Generally, the fine-grading 'C2' in emulsion mixtures gives rise to a better stiffness over the curing period. In addition, the stiffness moduli of these mixtures develop at a higher rate compared to the mid-DBM mixtures.

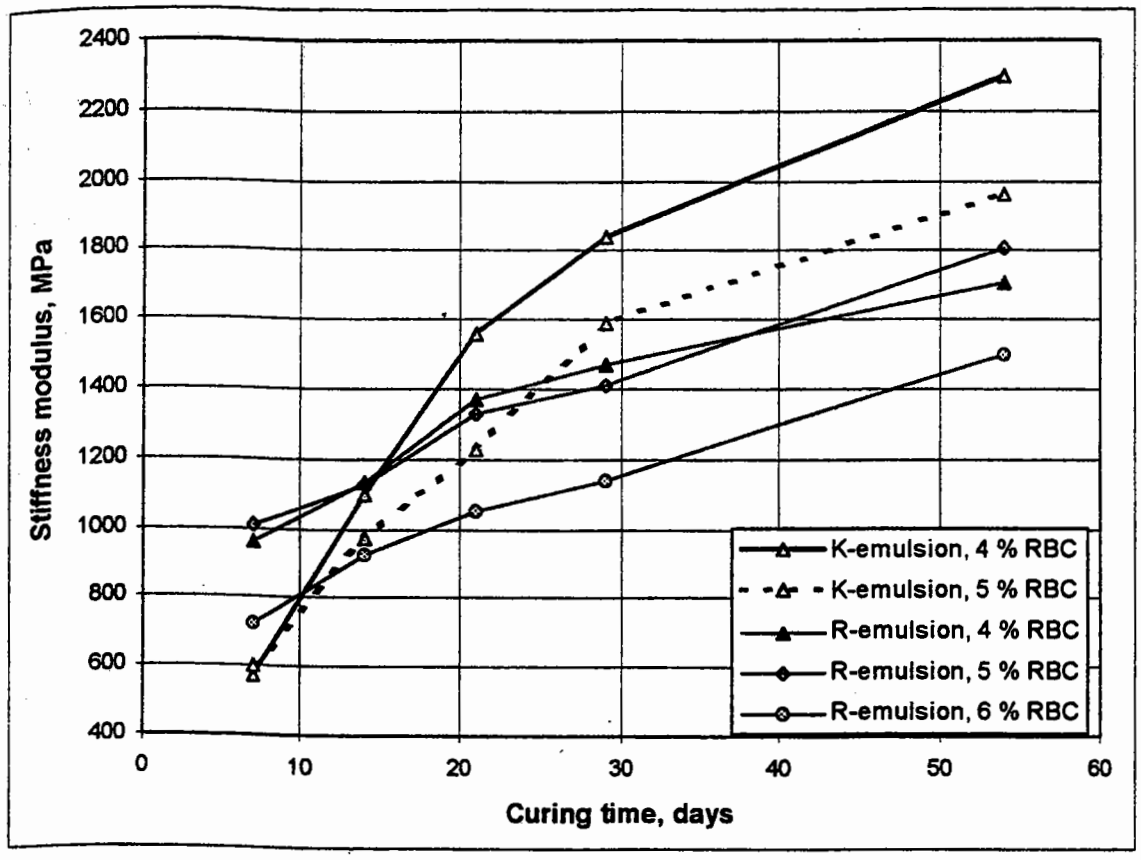


Figure 5-12 Curing time effect on stiffness modulus of R-emulsion mixtures compared to that of K-emulsion mixtures (mid-DBM of BS)

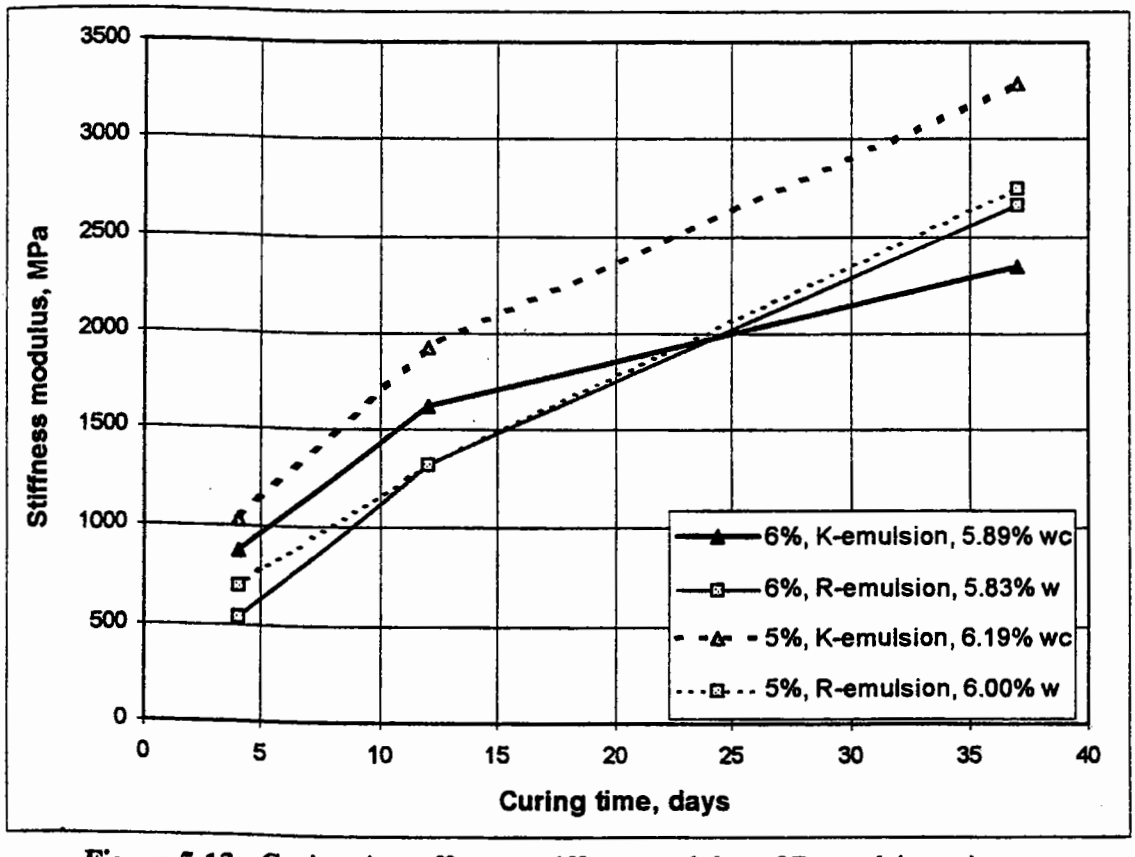


Figure 5-13 Curing time effect on stiffness modulus of R-emulsion mixtures compared to that of K-emulsion mixtures (grading C2- fine)

Curing in Presence of Water

In some trials in the UK, and in a limited number of commercial applications, trafficking has been allowed either directly on the as-laid materials or after covering with an asphalt layer or surface dressing. This course of action during construction surely affects the curing process of the material.

In the laboratory, emulsion mixture specimens (Marshall size) containing K-emulsion (3.7 % RBC) and mid-DBM were subjected to different curing regimes, involving: A) Curing in the mould at 8°C or 20°C for different times, B) Fully wrapped using cling film after curing for 4 days in the mould at 20°C or for 11 days at 8°C, and then tested at different times, C) Fully wrapped using cling film after curing for one day in the mould at 20°C or 8°C, and then tested at different times. The effect of these curing regimes on stiffness modulus of material as a function of curing time was then investigated. Testing of specimens cured at 20°C was at a test temperature of 20°C, whilst that of specimens cured at 8°C was at a temperature of 8°C and then at 20°C. The results are presented in Figures 5-14 and 5-15.

As illustrated in the Figures, the more the curing time, the more the water loss and the gain in stiffness modulus. As in curing regime 'A', exposing the top surface of specimens to aeration led to much better stiffness values. Generally, curing at 20°C has led to a more rapid loss of water content and higher stiffness modulus compared to that from curing at 8°C.

However, both curing temperatures resulted in similar water contents under curing regime 'A' at later stages of curing. Nevertheless, the determined stiffness moduli were different, being higher in the case of curing at 20°. A possible explanation is that equilibrium water content occurred earlier at higher curing temperature than it did at lower curing temperature, leading to differences in stiffness thereafter. After equilibrium is reached, interaction within the emulsion residue and with the aggregate particles continues to take place, as previously discussed. Moreover, the equilibrium water content level itself also clearly affects this behaviour and thus the stiffness

modulus. During the period from laying and compacting the material until an equilibrium in water content is achieved, it is likely that water dominates the material's response. Consequently, stiffness and water content can be correlated. Beyond that, establishing a relationship between them is no longer representative of the real response of material as much of the stiffness gain is then dominated by many other factors in addition to the equilibrium water content value.

Curing regime 'B' at 20°C shows a stiffness increase for the mixture, while the water content kept constant. On the other hand, the mixtures cured at 8°C did not show any measurable stiffness at early curing and showed no stiffness gain in the presence of water, presumably attributable to the higher water contents within them. The stiffness modulus increase, seen in the Figure, is however from water loss during long term curing. Probably, the lower the equilibrium water content, the more chance of internal interaction between the mixture components and stiffness increasing in the presence of water.

Unsurprisingly, stiffness moduli determined at 8°C were higher than those determined at 20°C, at later stages of curing, as in any viscoelastic material.

The implication from the above discussion is that the time of covering emulsion bound material on a site is crucial, as it greatly influences the later stiffness moduli.

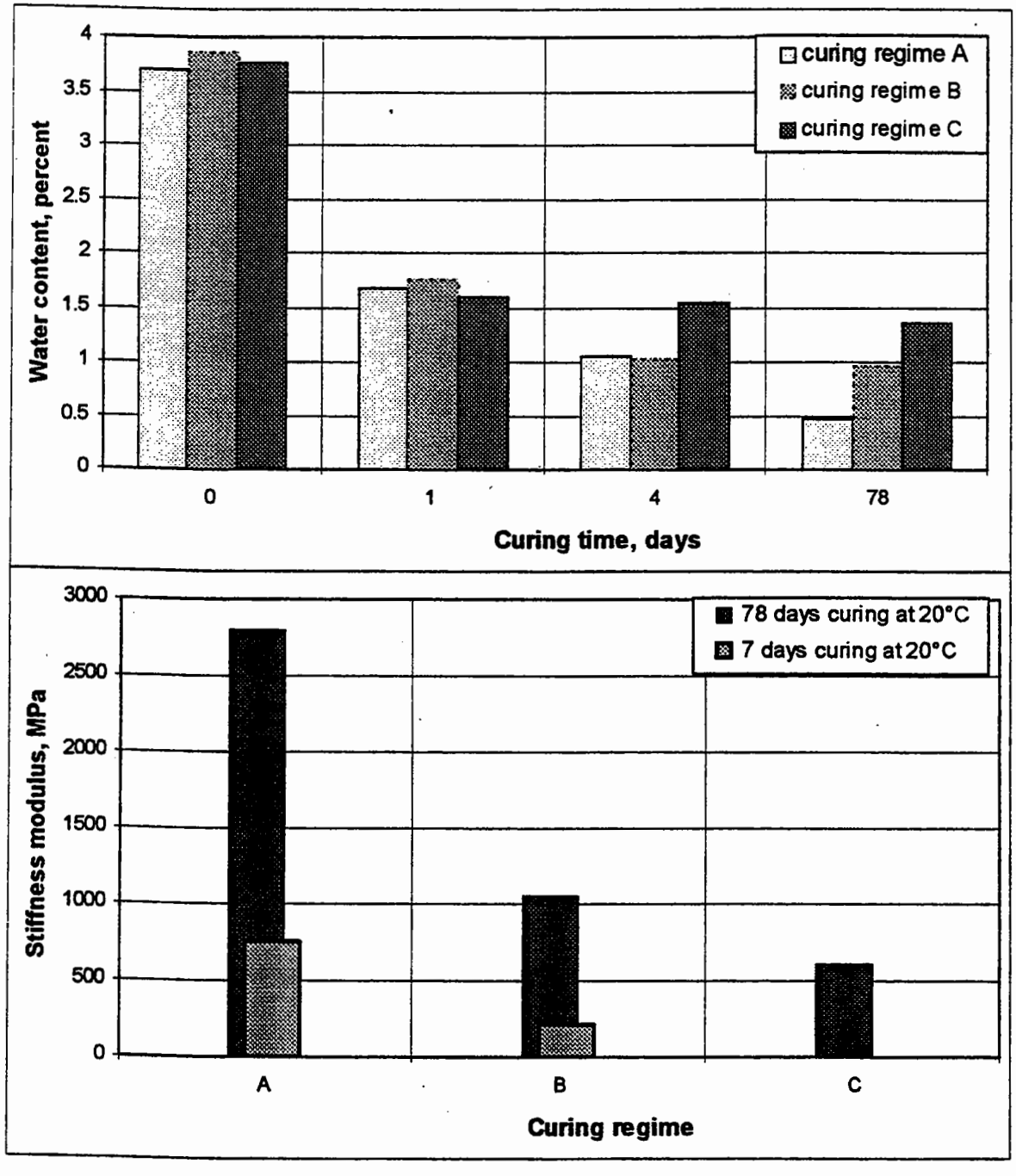


Figure 5-14 The effect of curing regime on stiffness modulus of specimens containing 3.7 % RBC (curing at 20°C)

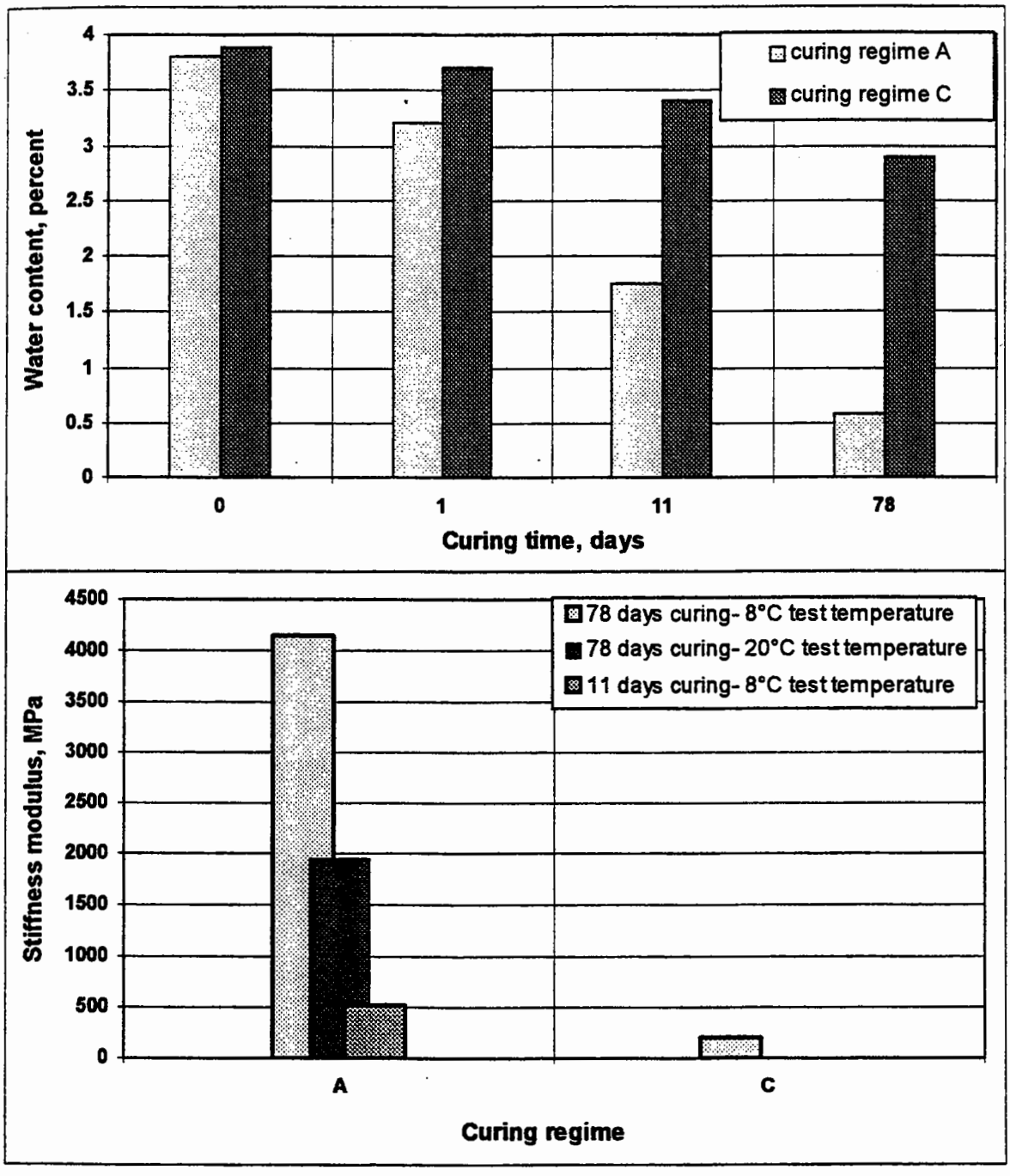


Figure 5-15 The effect of curing regime on stiffness modulus of specimens containing 3.7 % RBC (curing at 8°C)

5.1.4 Stress Dependency of Material

As in hot bituminous mixtures, stiffness modulus is often determined using the NAT in its indirect tensile mode, both to evaluate the relative quality of a material and to use as an input parameter for pavement design. In fact, different applied vertical load levels have been suggested in the literature.

The ASTM D4123-82 (re-approved 87) recommends applying stresses (compressive with a haversine or other suitable waveform) on the specimens in the range of 10 to 50 % of the indirect tensile strength, or load ranges from 4 to 35 N/mm of core or specimen thickness, provided that the total cumulative vertical deformation occurring during the test is not greater than 0.025 mm. However, both the instantaneous and total resilient moduli are determined from the average recoverable and total horizontal deformations.

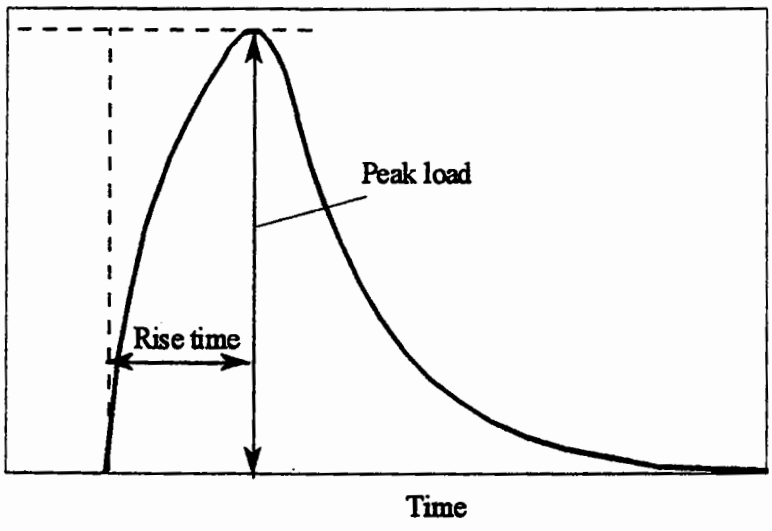


Figure 5-16 Definition of the peak load and rise time of the applied pulsating load in the NAT

The British Standard DD 213:1993 recommends testing in the indirect tensile mode using a peak load value with a rise time of 124 ms ± 4 ms (Figure 5-16), which achieves a peak transient horizontal deformation of at least 5 μm. On the other hand, the Highways and Utilities Committee (HAUC) set up in the UK in 1986, recommends testing using the Nottingham Asphalt Tester (NAT) apparatus, with a pulsed vertical force equivalent to a load of 150 N per 750 mm^2 of specimen cross-sectional area, for permanent cold-lay surfacing materials - PCSMs (Appendix A10- New Roads and Street Works- Act 1991).

The literature reveals that emulsion mixtures behave similarly to unbound aggregate at very early stages of curing; that is, their response is highly stress dependent in the triaxial mode of loading. On the other hand, at early and later curing, the material is treated as hot mixture in the indirect tensile mode of test and stiffness modulus is determined from interpreting the results in terms of linear elastic theory. However, an emulsion mixture generally has a variable response over the curing period and the selection of appropriate applied stress level is therefore important in conducting the indirect tensile test, as far as the elastic response is concerned. Therefore, the effect of loading magnitude was explored in a study to examine the non-linearity of emulsion mixture specimens, both partially and fully cured, relative to corresponding hot bituminous mixtures, and to decide on the stress and strain levels at which tests should be performed. The tests were carried out at the stress levels that resulted in horizontal deformation in the range of 5 to 20 μm. Re-loading at a lower stress, of specimens already tested at a higher stress level, was also carried out.

Specimens fabricated using the vibrating hammer, were tested after 40, 55, and 70 days of curing at 20°C and 5 days of oven curing at 48°C. The results are presented in Figure 5-17. The determined stiffness moduli of the mixtures for the particular residual bitumen contents used, were highly dependent on the level of stress applied. Clearly, the material exhibits stress dependency during the curing period, varying according to the type of emulsion and curing regime. As can be seen, although the stiffness moduli of EN998 emulsion mixtures were less than those of K-emulsion mixtures, their stress dependencies were also lower. The oven curing process appeared to reduce stress

dependency. Hence, on the evidence of these results, accelerated curing by oven drying for design purposes could lead to misleading results. It is considered that this may be due to changes in the material's micro-structure in terms of the binder itself and its adhesion to the aggregate particles.

Re-loading of specimens at lower stress level, resulting in horizontal deformation of 5 μm, after being loaded at higher stress level, with horizontal deformation of 10, 15, or 20 μm, showed that some damage occurs in the specimens when using a higher stress level. Typical results are shown in Figure 5-18. Generally, at all curing times, testing at a higher stress level resulted in a lower stiffness than that from the lower stress level. But, re-testing the specimen at the lower stress level, with horizontal deformation of 5 μm, resulted in a stiffness modulus similar to that from the higher stress level.

Accordingly, the stiffness-stress relationships from the indirect tensile mode are not due entirely to an inherent stress dependency of material, but also from the damage occurs in the microstructure of the mixture due to the applied load level. It is probable that the stress levels used in this mode of testing are beyond the yield stresses of the emulsion-mixtures, leading to a debonding and an internal distortion in the aggregate structure due to insufficient adhesion between the binder and the aggregate particles. That is, the region of elasticity associated with emulsion-mixtures is much smaller than that for hot mixtures. However, this load-dependency response is not seen with comparable hot mixtures, indicating a lack of similarity in the behaviour of hot bituminous mixtures and emulsion-aggregate mixtures.

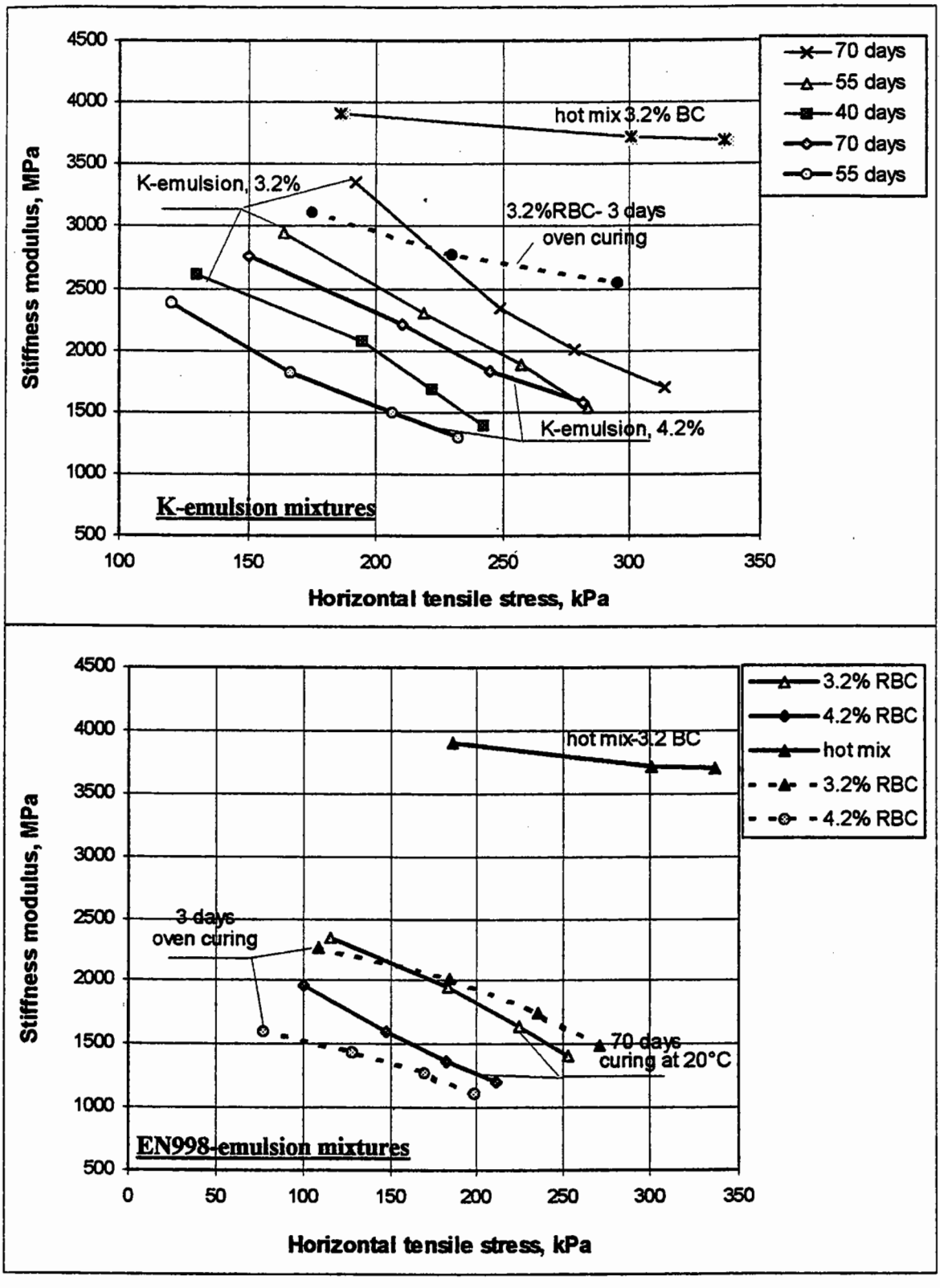


Figure 5-17 Effect of loading magnitude on stiffness modulus of specimens containing K and EN998 emulsions

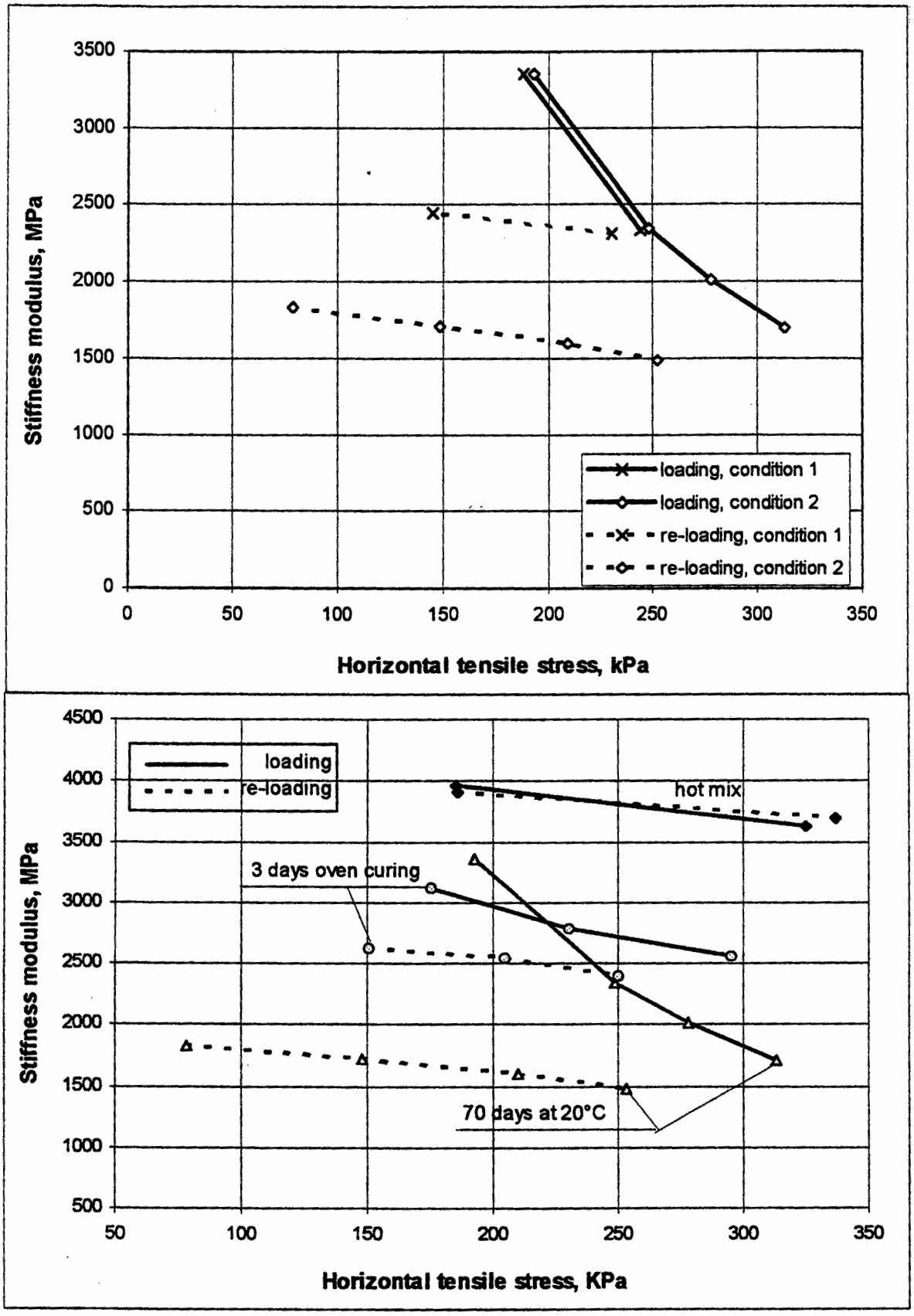


Figure 5-18 Effect of re-loading emulsion mixture specimens in the indirect tensile mode on the elastic response of material

Similar results were found with mixtures prepared using the gyratory compactor. Variables were mid-DBM and C2 'fine' gradings as well as both K and R emulsions. In this group, in addition, the effect of loading specimens using a higher stress level at early curing stage, on the stiffness-stress relationships at a later curing stage was investigated. The results were as shown in Figures 5-19 through 5-22. .

Some important points can be drawn. The rate of stiffness reduction as a function of the horizontal stress induced in the K-emulsion and R-emulsion mixture specimens are similar at early curing. Also, as the K-emulsion mixture specimens (containing mid DBM or C2 gradings) undergo curing, the stiffness increases and the reduction of stiffness with stress is similar to that at early curing. Obviously, this response to the applied load of K-emulsion mixtures at early and later curing and of R-emulsion mixtures at early curing is dominated by the aggregate structure and the adhesion with the binder but to a lesser extent by the emulsion type. However, R-emulsion mixtures (containing mid DBM or C2 gradings) show less stiffness reduction with stress at later curing times. As shown, early loading at higher stress levels did not prevent stiffness gain as a function of curing time, that is healing occurred. At later curing, the determined stiffness modulus again showed dependency on the applied load level.

The evidence that less load dependency is associated with the R-emulsion mixtures at later curing leads one to say that this emulsion reacts better with the aggregate particles, but its problem lies in the way the emulsion distributes between the fine particles.

Based on the above discussion, testing at the loads specified by the standards for hot mixtures or cold mixtures will lead to different determined stiffness moduli. On the other hand, testing at lower load level will lead to a higher stiffness modulus which will not be representative of actual performance. However, in dealing with this type of mixture in the indirect tensile mode, tests should be carried out at different load levels to establish a stiffness-stress relationship for design purposes.

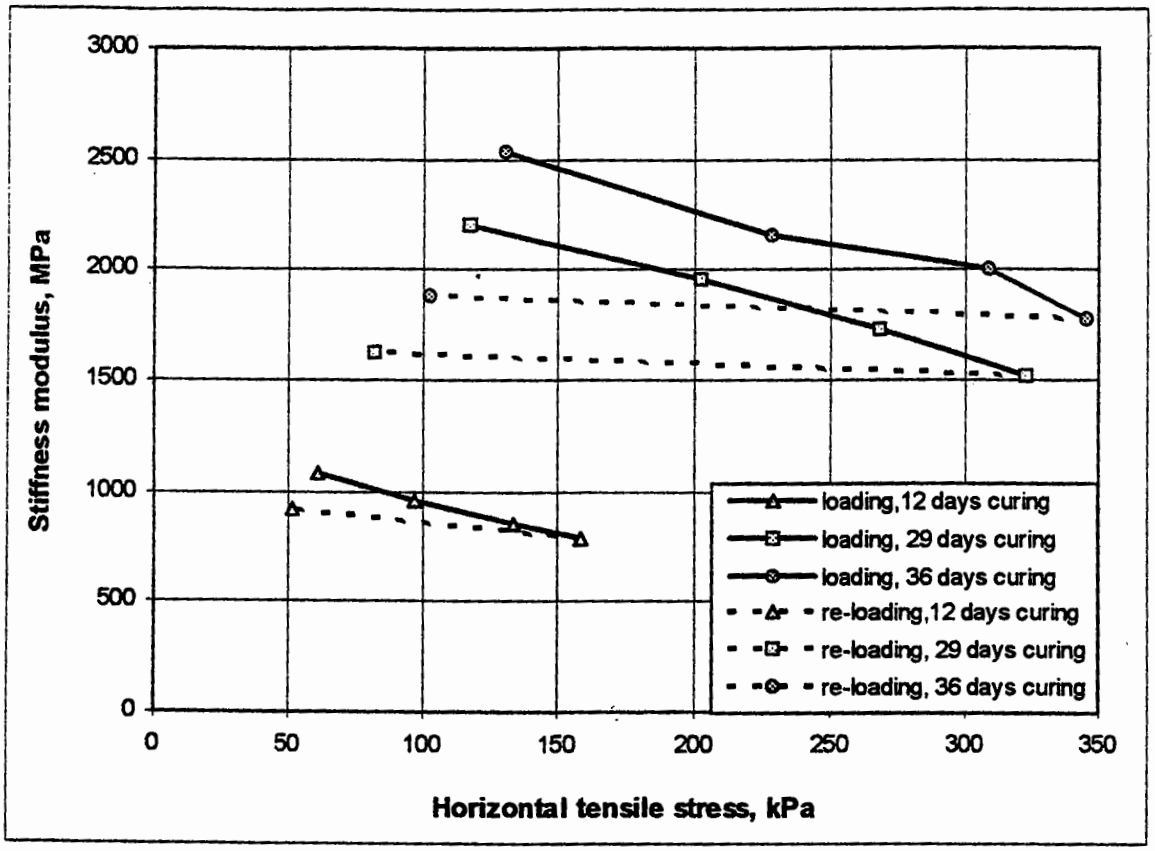


Figure 5-19 Loading magnitude effect on the elastic response of mixtures containing K-emulsion and mid DBM grading as a function of curing time

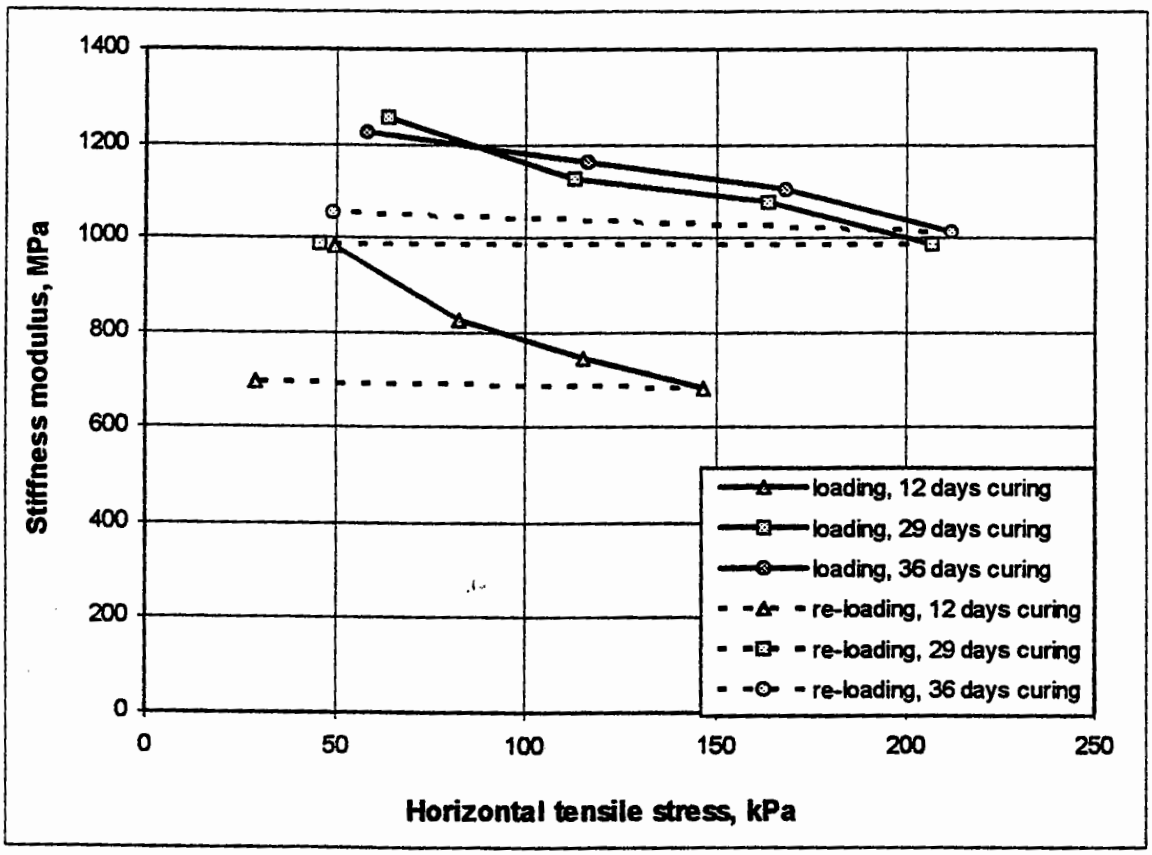


Figure 5-20 Loading magnitude effect on the elastic response of mixtures containing R-emulsion and mid DBM grading as a function of

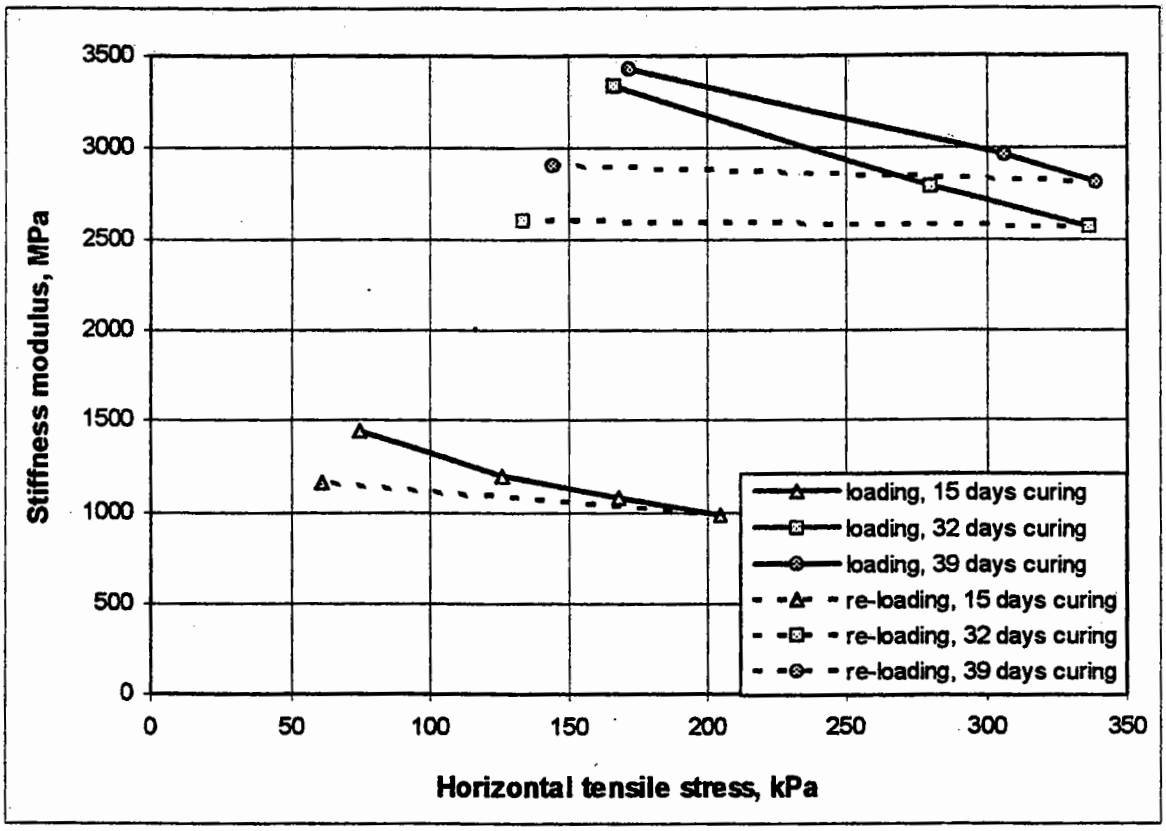


Figure 5-21 Loading magnitude effect on the elastic response of mixtures containing K-emulsion and C2 'fine' grading as a function of curing time

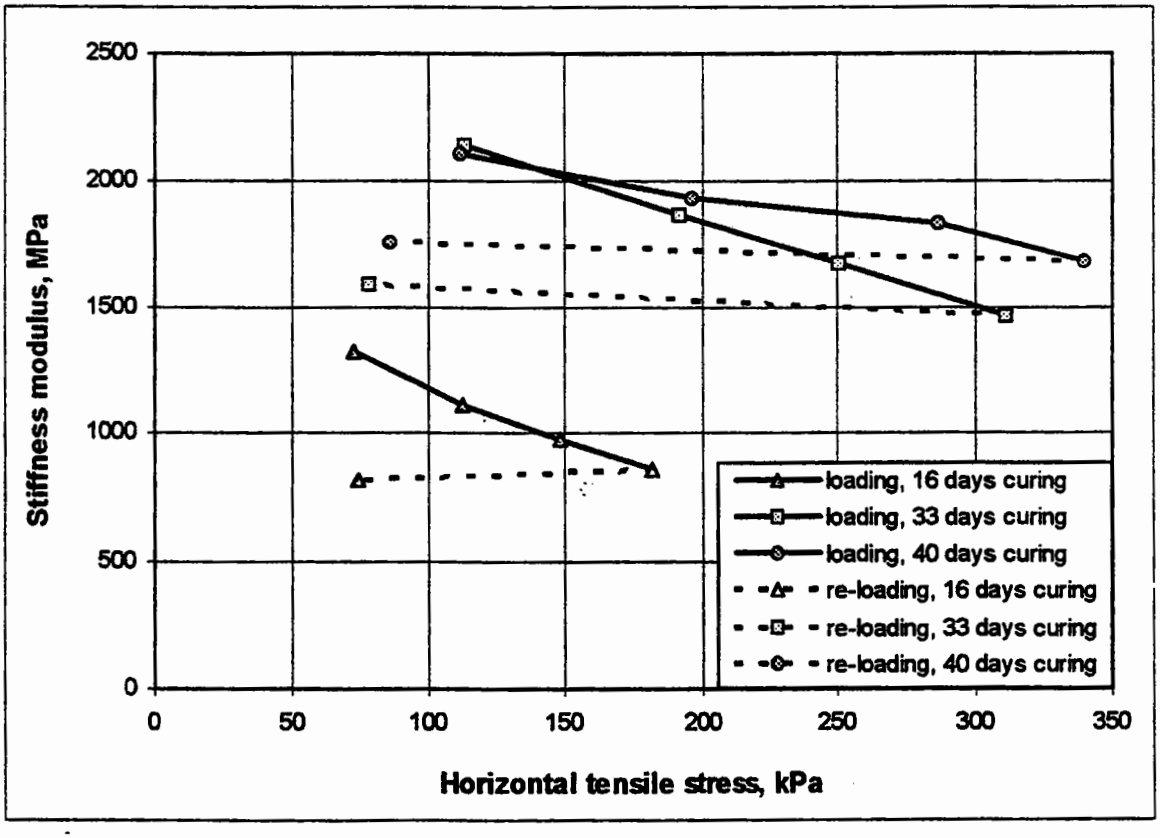


Figure 5-22 Loading magnitude effect on the elastic response of mixtures containing R-emulsion and C2 'fine' grading as a function of curing time

5.2 ELASTIC PROPERTIES IN TRIAXIAL MODE

Stiffness modulus determined from the indirect tensile mode of testing is sensitive to the value assumed for Poisson's ratio. Unfortunately, the distributions of stresses and strains across the diameter of the specimen are non-uniform. Also, a non-uniform distribution of water within the specimen, at time of testing, is expected, being higher in the inner part. Accordingly, the value of Poisson's ratio is likely to be variable. However, the determined stiffness modulus will be biased towards the properties of the material in the inner part of the specimen. In testing emulsion mixtures, particularly at early curing, in the indirect tensile mode, an accurate result for modulus will not therefore be reached. In addition, emulsion-aggregate mixture behaviour is unlike that of hot mixtures (Ibrahim and Thom, 1997). The Poisson's ratio will be varied over the curing period and should be determined rather than assumed to be similar to asphaltic mixtures.

Accordingly, and because of the need for determination of stiffness modulus at early curing, to mimic the field situation in which early trafficking is expected, the triaxial mode of testing was employed in this study. For this purpose, a new assembly in the NAT, allowing measurement of stiffness modulus in compression using confinement, was developed. The following were studied:

- Effect of applied stress level at early and later stages of curing, compared to that of unbound aggregate and of hot bituminous mixtures.
- Effect of material composition and test condition on Poisson's ratio.
- Effect of compaction method.

5.2.1 Specimen Preparation

Cylindrical specimens (101 mm diameter × 160 mm height) were fabricated, some using a vibrating hammer under controlled constant weight, and some in a gyratory compactor, as previously described in Chapter 4. To allow the mounting of LVDTs on the specimens for vertical and horizontal deformation measurements, studs were inserted in the specimens during the compaction process through holes in the split moulds, and specially made screws were used, as seen in Figure 5-23. The studs were

made with a size and shape that allowed mounting of the hoops shown in Figure 5-24. The fabricated cylindrical specimens were side wrapped with cling film after one day in the mould and left to cure until the time of testing.

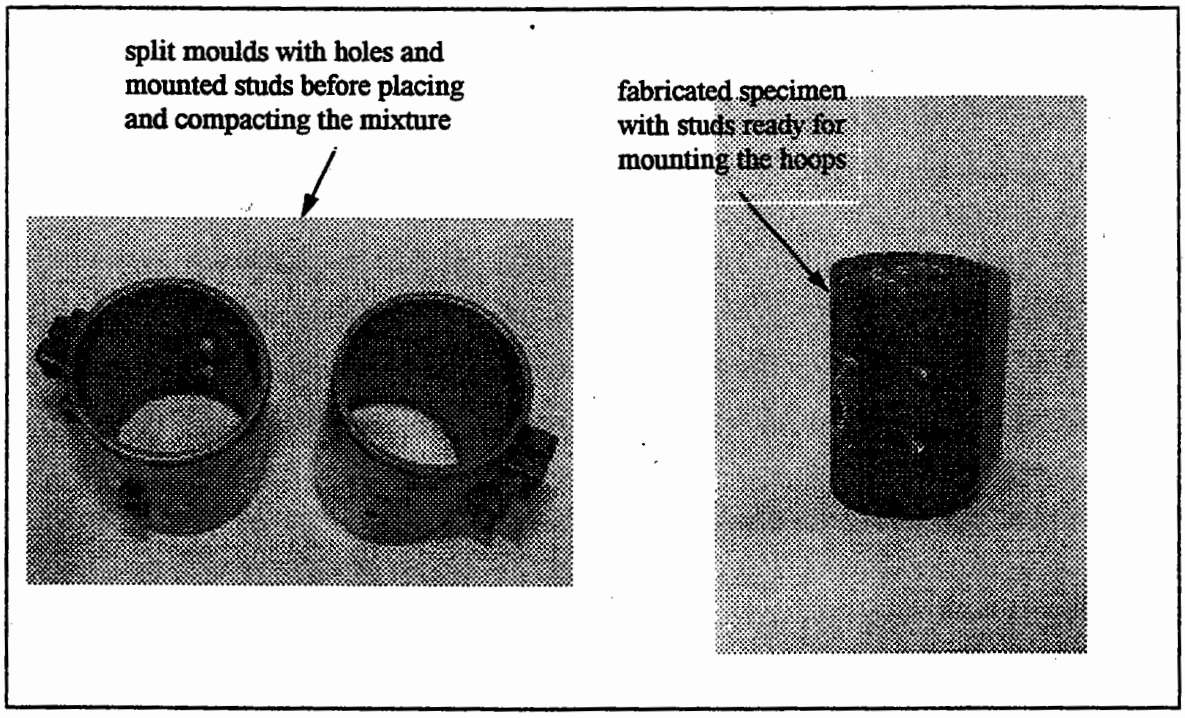


Figure 5-23 Photographs of the split moulds used in fabricating triaxial specimens

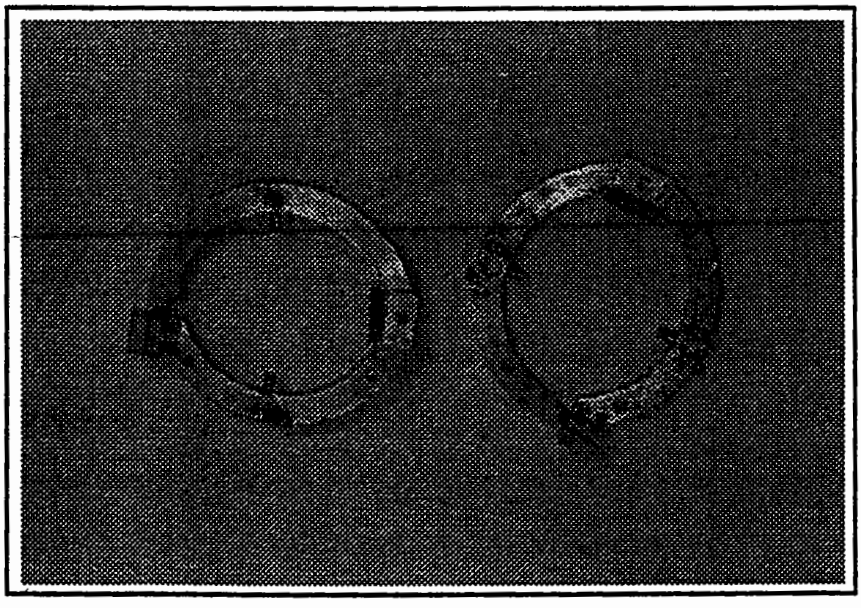


Figure 5-24 Hoops used for mounting vertical and horizontal LVDTs on triaxial specimens

5.2.2 Development of Triaxial Mode in the NAT

The stiffness moduli of the prepared specimens were determined using the NAT in the triaxial mode. As described in Figures 5-25 and 5-26, the prepared cylindrical specimen is placed in a rubber membrane, which is attached to top and bottom steel platens by means of O-rings. The confining pressure is achieved by applying a vacuum inside the membrane through the top platen. This test assembly allows the application of a maximum constant confining pressure of 90 kPa. Axial and radial strains are measured by means of LVDTs mounted on the specimen. Figure 5-27 shows an example of the test measurements. During the test, the half height time (that is the time from half the peak load being applied to the time when the load reduces again to half the peak level) of the repeated stress pulse was kept at 120 ms. Generally, in this configuration of testing, the lower the applied pulsating load, the more the disruption to the captured deformations from the LVDTs and the difficulty of determining the resilient deformation, due to noise effects. Therefore, it is recommended to use higher load levels in conducting the test under stress control.

This assembly in the NAT was considered useful and suitable for routine testing of emulsion mixtures as it allowed:

- Testing for stiffness modulus determination at different temperatures.
- Accelerated curing and testing of the same specimens for establishing time-stiffness relationships.
- Determination of stiffness modulus of specimens containing water after immersion for different times.
- Testing for permanent deformation under constant confining pressure.

It should be reported here, that a water loss of up to 0.2% was recorded during tests on specimens at early stages of curing, which lasted up to 5 hours. Most of this water loss occurred within the first 30 minutes after applying vacuum. Therefore, prior to testing, the specimens were brought to a stable water content by applying vacuum through the top platen, and water contents of specimens were determined again after each test was finished.

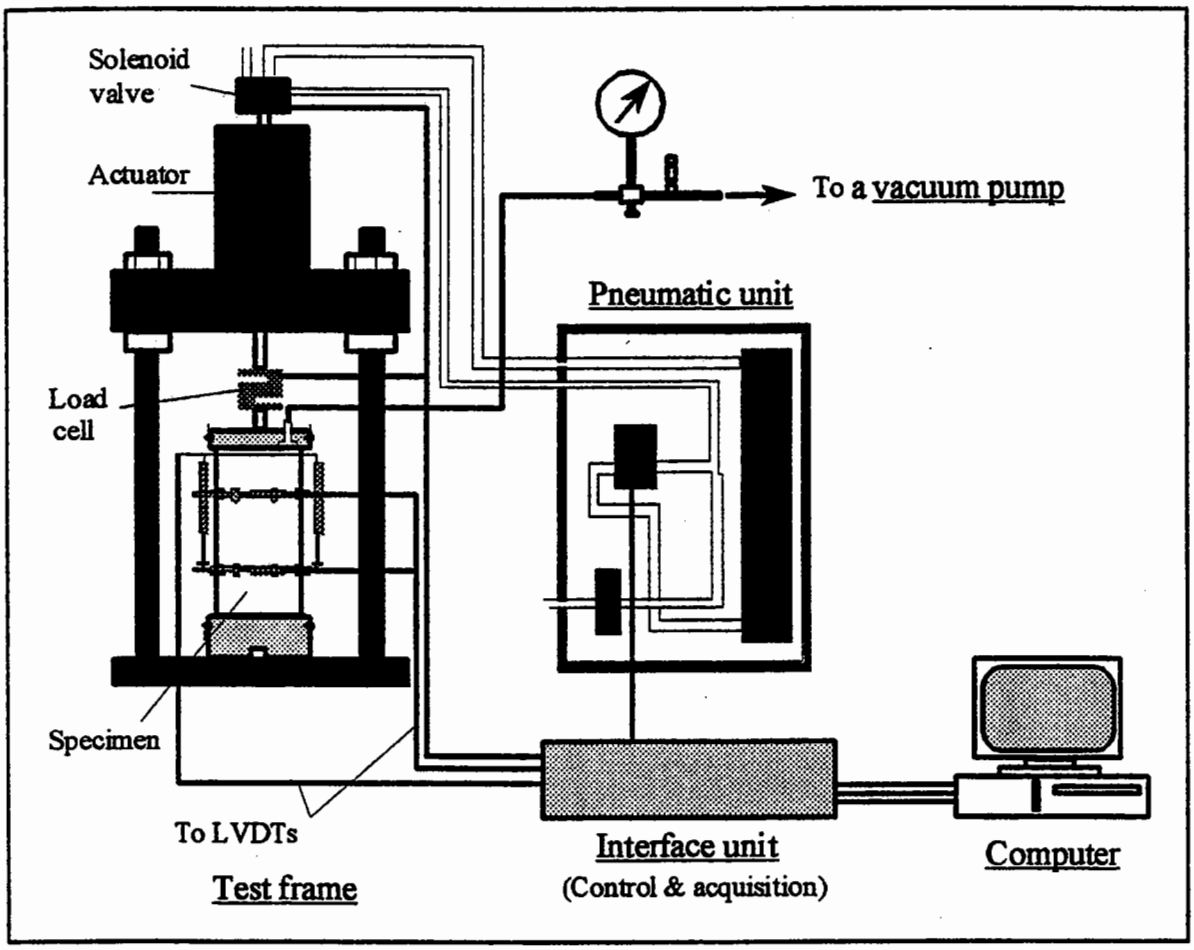
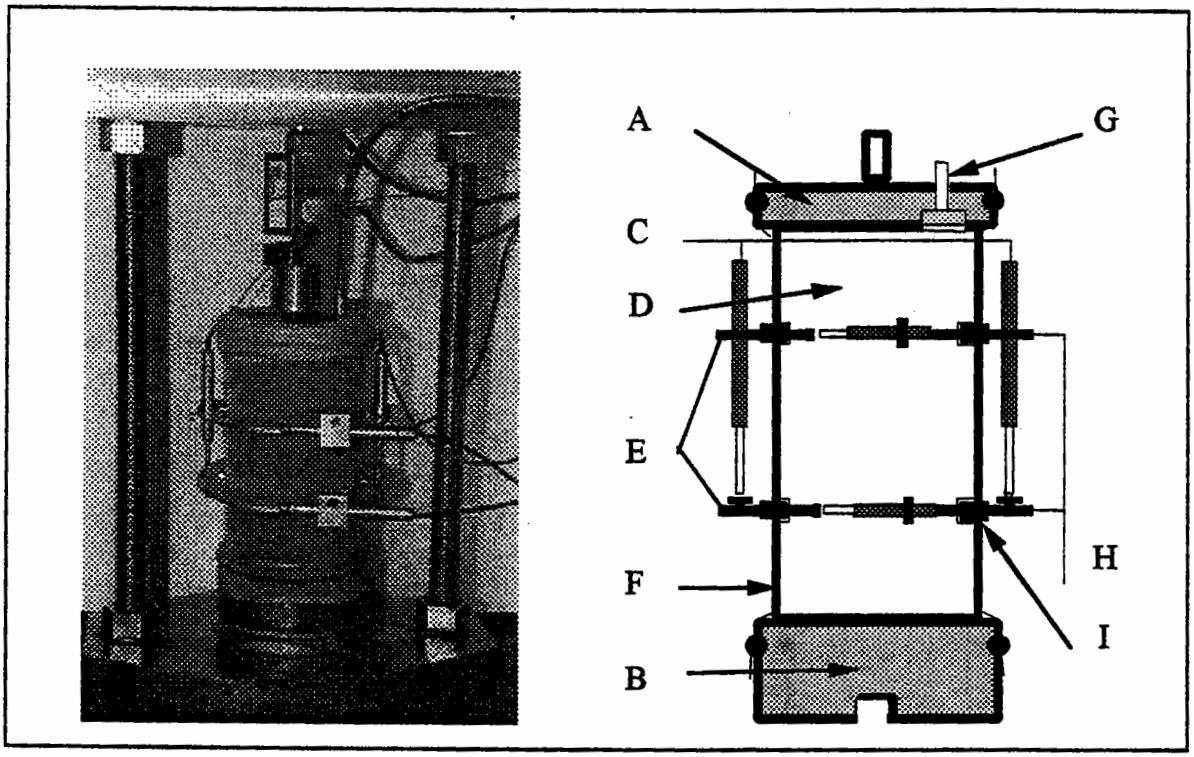


Figure 5-25 Configuration of the NAT for new triaxial testing



A top platen

B bottom platen with hole underneath for fixing in the test frame.

C two vertical LVDTs

D cylindrical specimen

E two horizontal hoops

F rubber membrane

G orifice through the top platen for applying vacuum

H two horizontal LVDTs

I four studs in the specimen for fixing the hoops and mounting the LVDTs.

Figure 5-26 View and schematic diagram of the NAT test assembly in triaxial mode

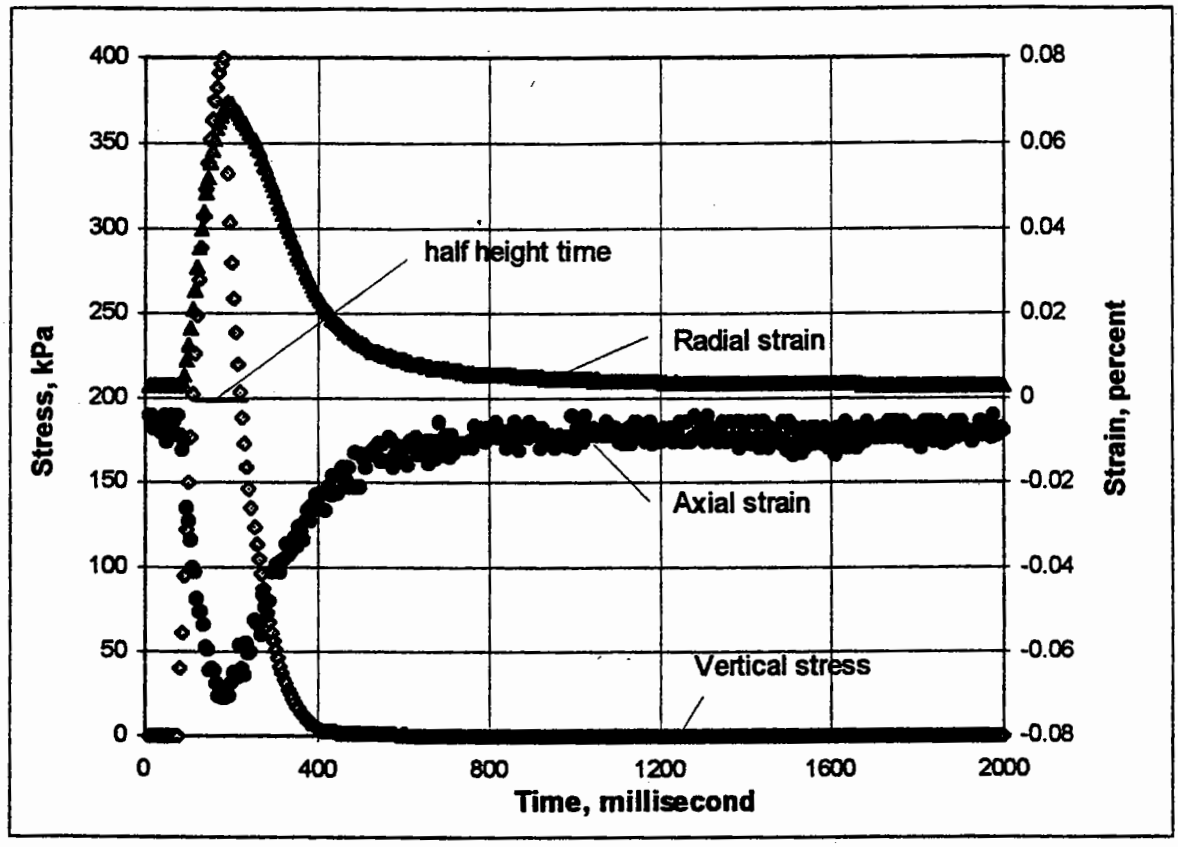


Figure 5-27 A test measurement from the NAT in triaxial mode

5.2.3 Material Response in the Triaxial Mode

To supplement the findings from the indirect tensile testing discussed above, the response of emulsion aggregate mixtures was investigated in the triaxial mode of loading. Specimens at early and later stages of curing were first conditioned by applying repeated stress pulses, keeping the confining pressure constant at 70 kPa, followed by series of repeated stress pulses (100 pulses) at different stress levels for stiffness modulus determination. During both conditioning and testing, radial and vertical strains were recorded to enable determination of Poisson's ratio.

Test Conditioning

Prior to triaxial testing for stiffness modulus, specimens were conditioned to approach a steady response state. For unbound aggregates, conditioning for up to 20000 pulses (Paute et al, 1993) has been reported at principle stress ratios of 2 to 7 (Sweere, 1990).

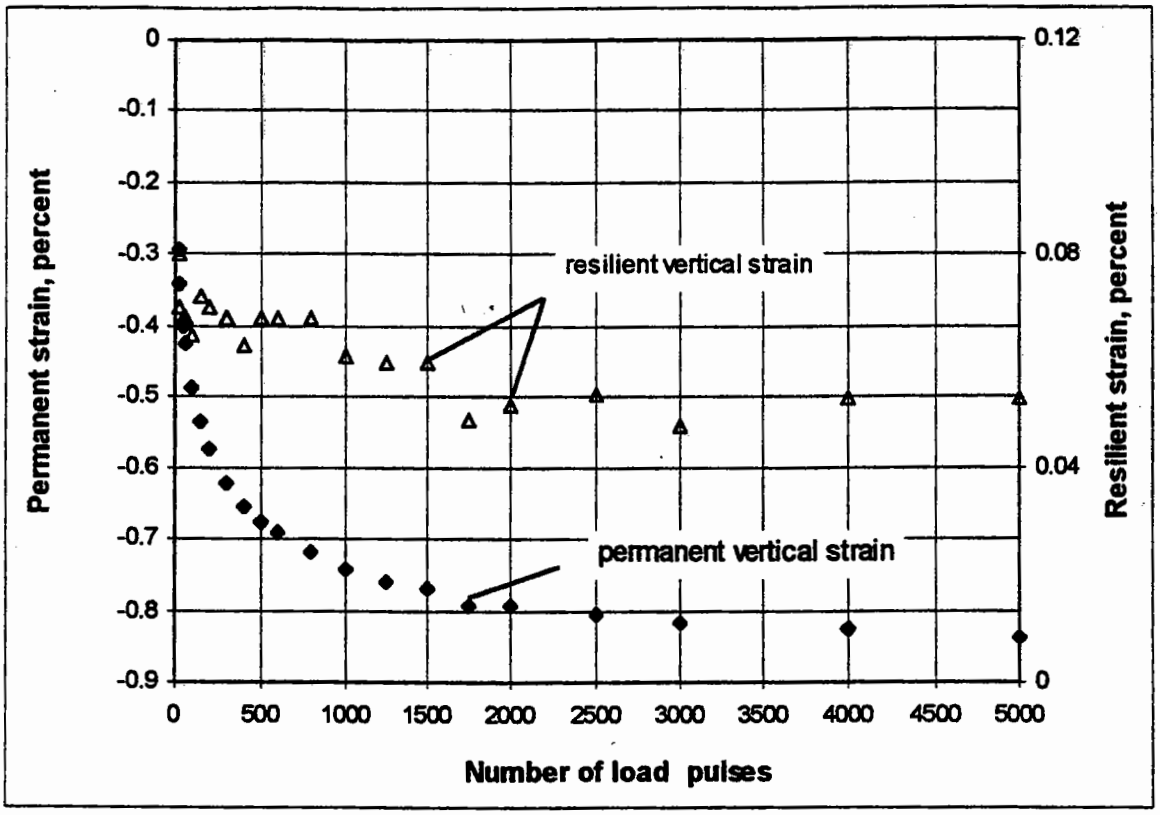


Figure 5-28 Effect of conditioning load pulses on permanent and resilient strains of early stage specimens (3.7% RBC, 9.6% void content, 2.14% water content)

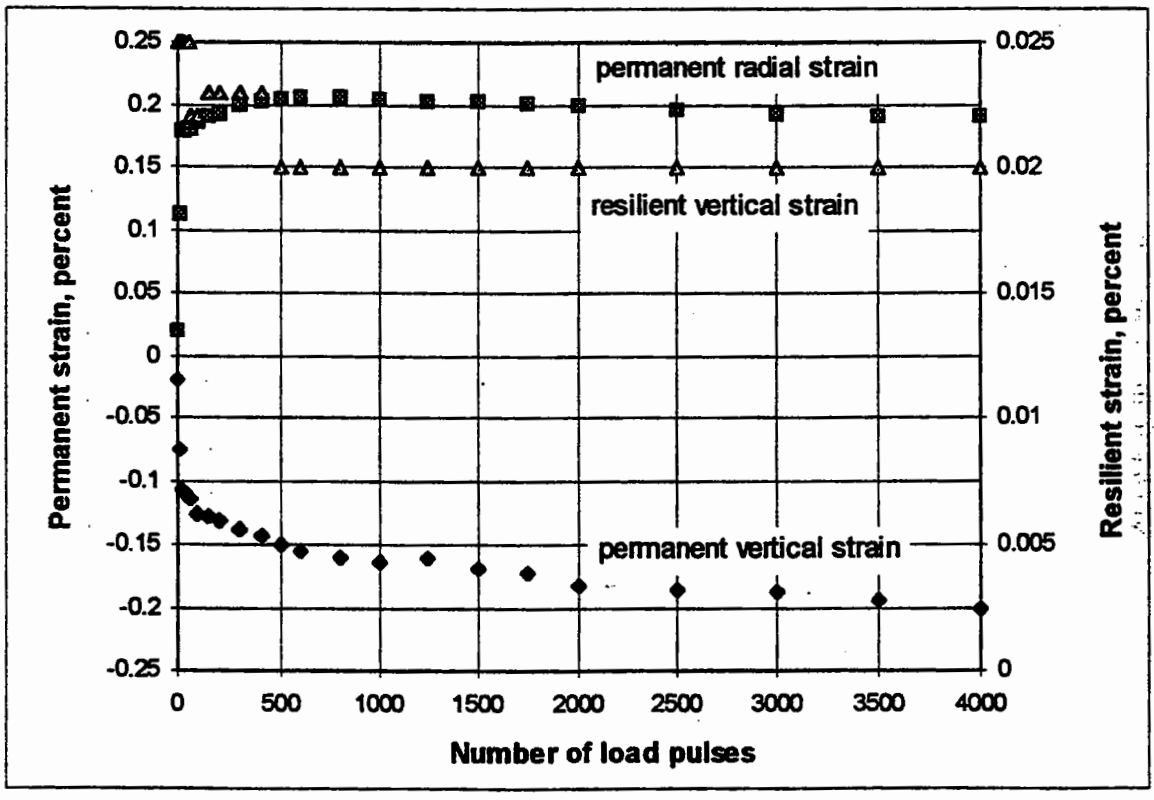


Figure 5-29 Effect of conditioning load pulses on permanent and resilient strains of later stage specimens (3.7% RBC, 10.2% void content, 0.74% water content)

In this study, conditioning at both early (5 days at 20°C) and later (20 days for the vibrating hammer specimens and 40 days for the gyratory specimens, both at 20°C) stages of curing has been carried out using stress pulses of 180 kPa and a constant confining pressure of 70 kPa (i.e. to a stress ratio of 3.56). During conditioning, permanent and resilient strains (both vertical and radial) were recorded. For instance, the results presented in Figures 5-28 and 5-29, for specimens containing 3.7% residual bitumen content (RBC), illustrate two different responses. The resilient strains for the 'early stage' specimens reached a steady condition after about 2000 pulses, while those for the 'late stage' specimens took about 500 pulses. However, the permanent vertical strain component of all specimens continued to increase. Based on these findings, early stage and later stage specimens have been conditioned at 2000 and 500 pulses respectively.

Stiffness Modulus

Triaxial tests in the NAT have been carried out on specimens containing 3.7 % and 5 % residual bitumen contents (RBC), fabricated in the gyratory compactor, at two different test temperatures, 20°C and 40°C. Figures 5-30 and 5-31 present the results of mixtures containing mid-DBM grading, while Figure 5-32 presents the results for mixtures containing C2 'fine' grading, both for early and later stages of curing, as indicated in the Figures.

The results generally indicate that the material stiffness varies according to the applied stress level. As level of applied stress increases, material stiffness modulus increases. In fact, the results fitted the K- θ model (Hickes and Monismith, 1971), usually applied to unbound aggregate, quite well. Curing of specimens certainly resulted in higher stiffness modulus values and reduced the degree of stress dependency. While test temperature greatly influenced stiffness modulus and stress dependency of specimens at the later curing stage, it was not found to be so significant for specimens at an early stage of curing, as seen for example in the results presented in Figure 5-31. This might be due to increased bitumen coalescence and adhesion onto the aggregate particles caused by the temperature increase which, for specimens at an early stage of curing,

corrects the expected temperature induced softening. Bear in mind that similar water contents were present at both temperatures. Another possible reason is that the response of the material in the triaxial test, at early stages of curing, is dominated by aggregate structure.

The fine grading mixtures appeared to have a higher stiffness than those of mid-DBM grading, in line to the trend of results from the indirect tensile mode of testing.

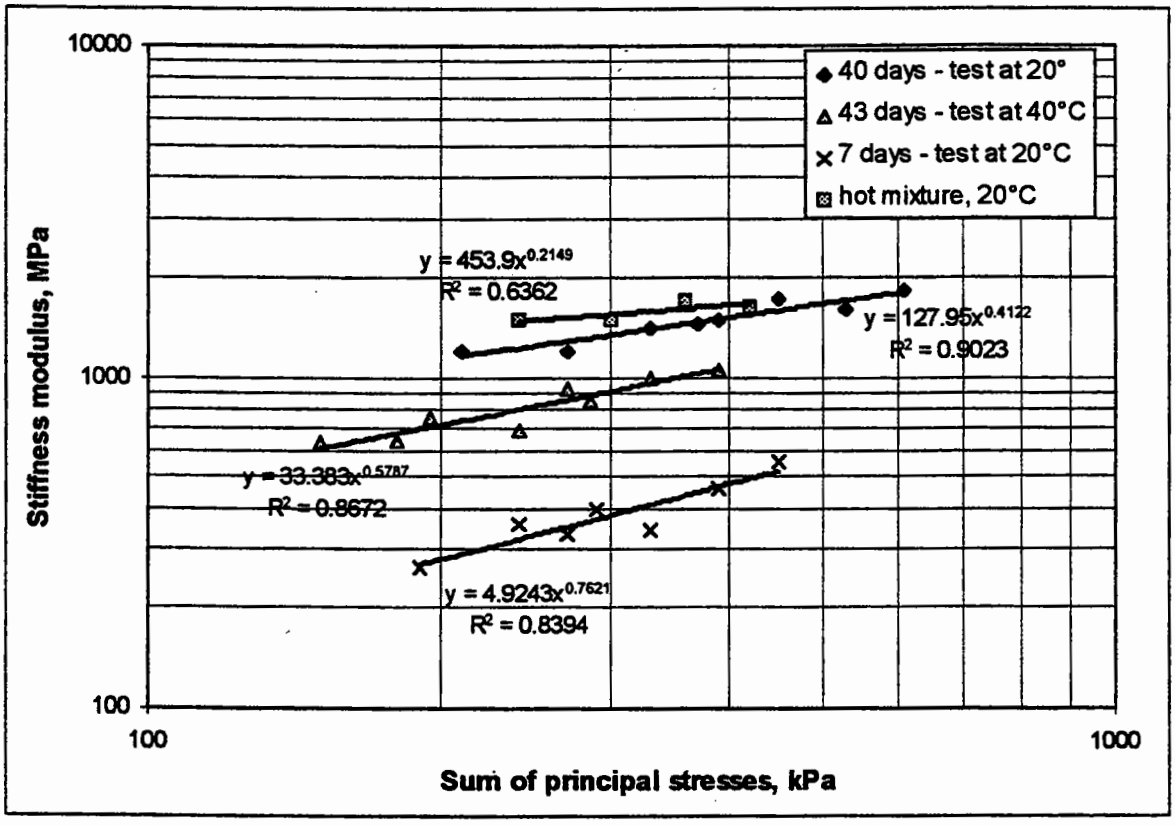


Figure 5-30 Stiffness modulus versus Bulk stress of specimens containing 3.7% RBC of K-emulsion and mid-DBM grading at early and later curing

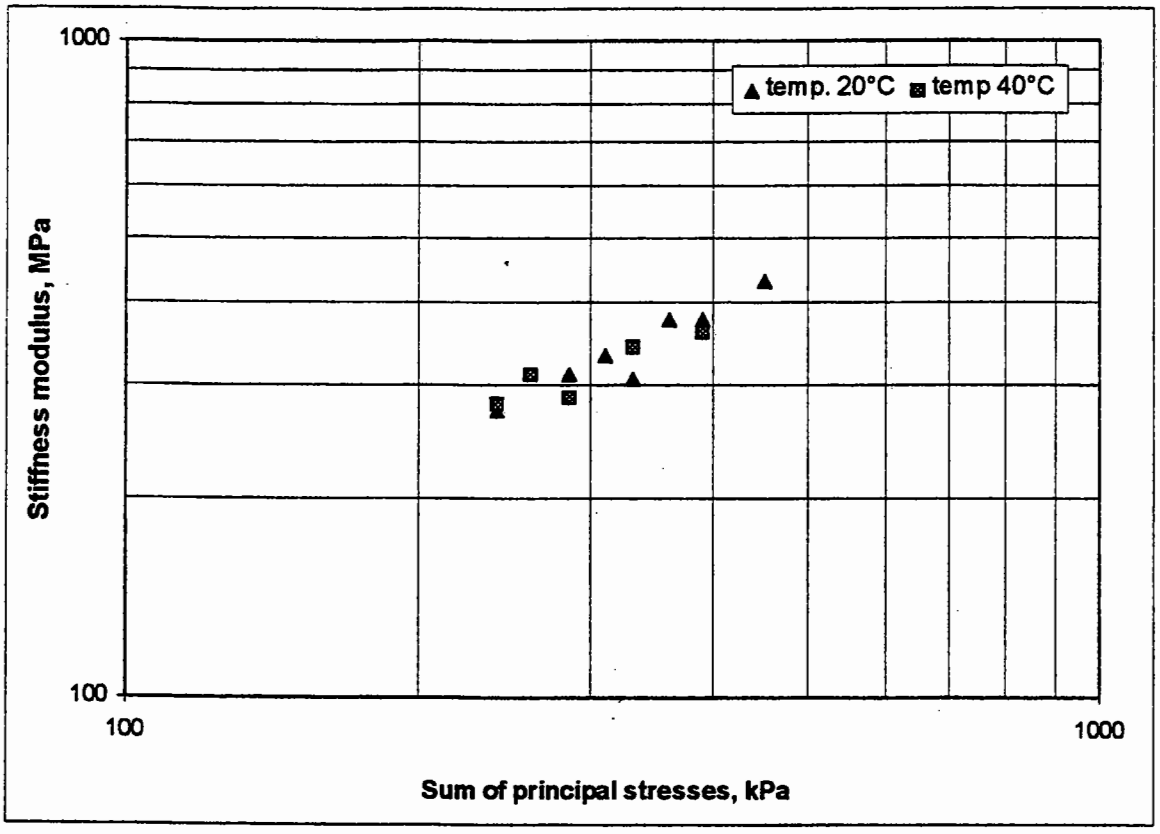


Figure 5-31 Stiffness modulus versus Bulk stress of specimens containing 5 % RBC of K- emulsion and mid-DBM (curing for 7 days at 20°C)

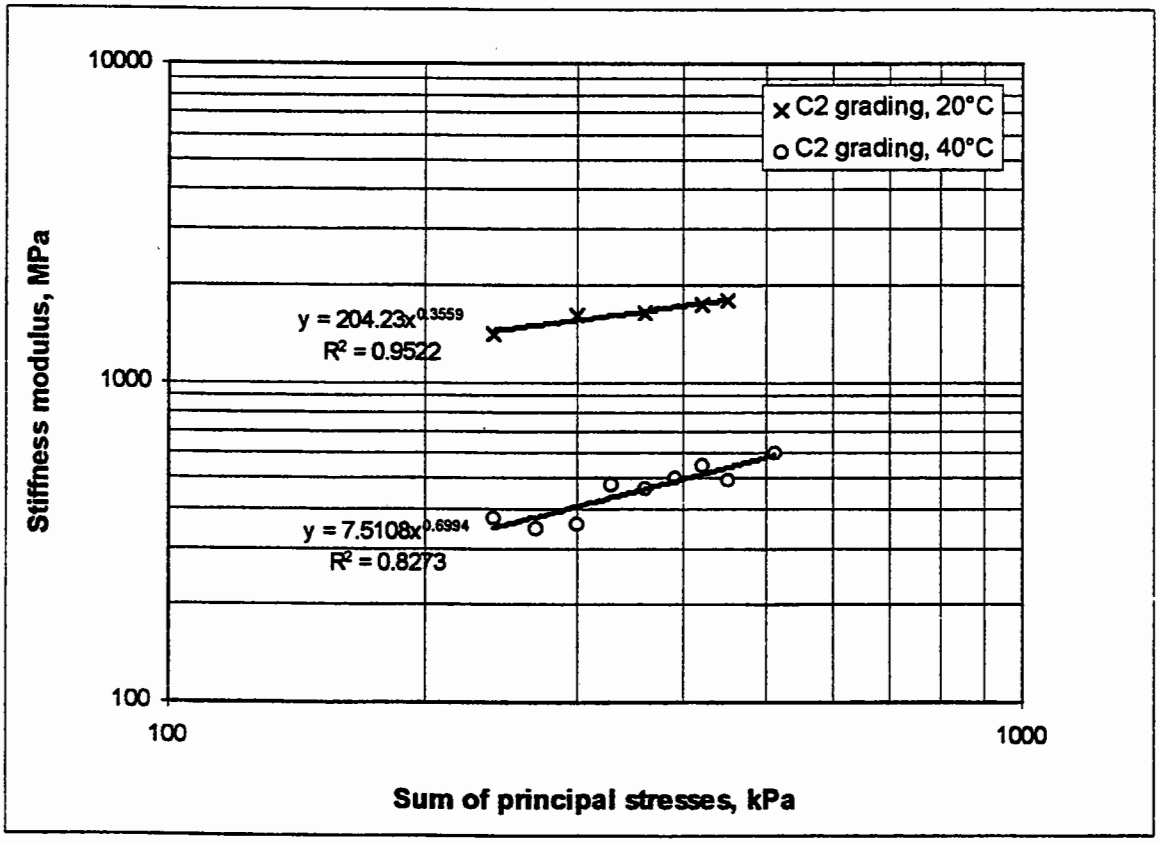


Figure 5-32 Stiffness modulus versus Bulk stress of specimens containing 5 % RBC of K-emulsions and C2 'fine' grading, (curing for 14 days at 20°C)

Effect of Early Conditioning on Later Stiffness of Material

Once emulsion aggregate mixtures are laid in the pavement structure, the curing process occurs in which water evaporation continues, bitumen droplets coalesce on each other and onto aggregate particles, and both bitumen hardening and adhesion with the aggregate particles increase. Thus, curing leads to great improvements in the mechanical properties of the material. In general, stiffness modulus in the laboratory has been determined at different curing levels, for both mixture and pavement design. This section considers the effect of early loading of the material on its rate of stiffness modulus increase.

As illustrated in Figure 5-33, two deviator stress levels, 180 kPa and 300 kPa, were used for conditioning specimens, containing 3.7% RBC and mid DBM grading, compacted using the gyratory compactor, at a very early stage of curing (3 days at 20°C, sided wrapped) giving 2000 and 400 pulses respectively (condition A). The conditioned specimens were left 20 days for curing at 20°C, after which stiffness moduli were determined. The results were then compared with the corresponding stiffness moduli of a specimen being similarly cured but without the early conditioning (condition B). Two different responses were found. The specimen conditioned at 180 kPa (principal stress ratio of 3.6) gained in stiffness modulus more than the unconditioned one, in the order of 35% extra. This may be attributed to better aggregate particle interlock and bitumen coalescence resulting from early loading of the specimens. Conversely, conditioning at 300 kPa (principal stress ratio of 5.3) resulted in stiffness moduli which were less than in the unconditioned case. It seems likely that some micro-cracking occurred, due to this higher stress level, resulting in less bitumen aggregate interaction.

Thus, it may be concluded that very early loading of this type of material will generally influence the curing process and should be considered in determination of any time-stiffness relationship for design purposes. According to the stress levels expected, a correction factor for stiffness modulus should be determined.

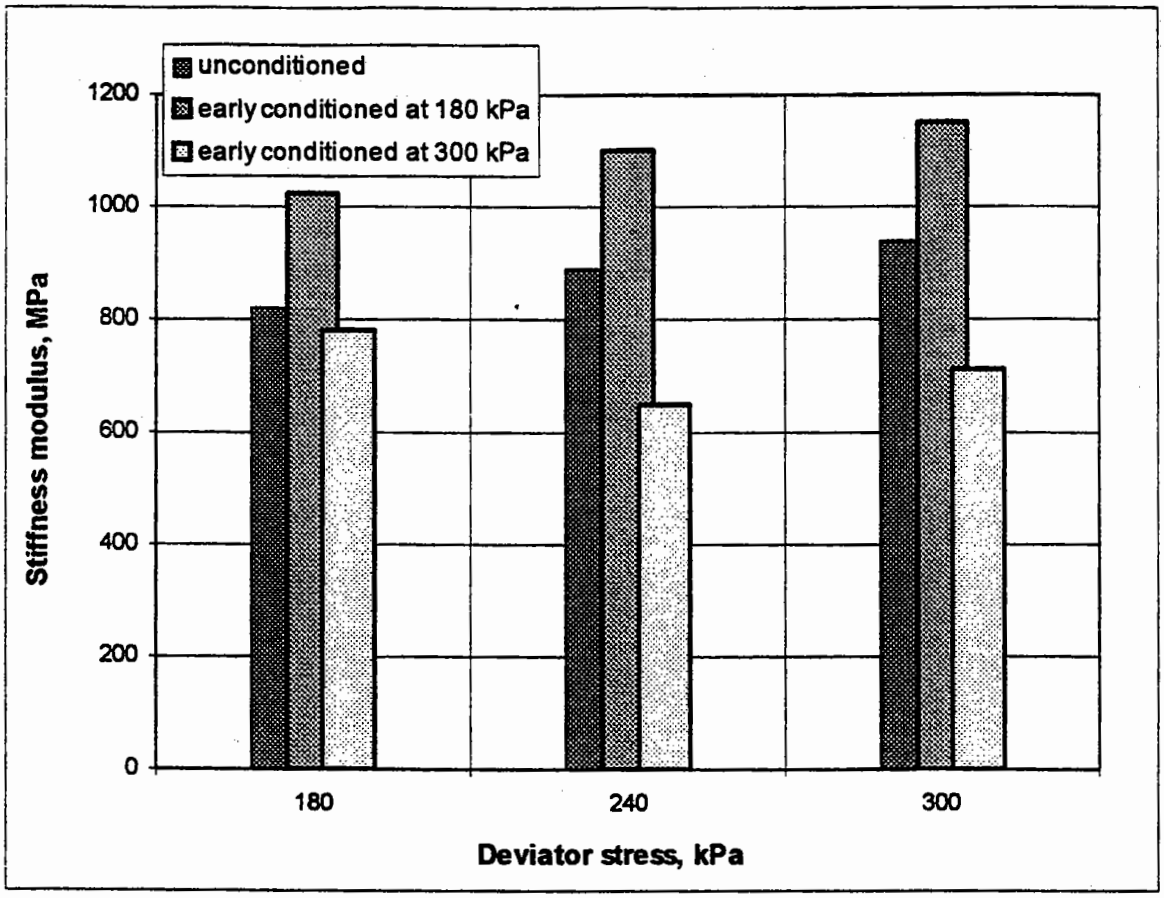


Figure 5-33 Effect of early load-conditioning of emulsion mixture specimens on later cured stiffness moduli (70 kPa confining pressure - curing time 20 days at 20°C)

Poisson's Ratio

It is important to know the value of Poisson's ratio for evaluating Indirect Tensile Stiffness Test data and also in pavement structural design. Because of the difficulty of measuring this value in the indirect tensile mode, at early curing in particular, triaxial testing has been carried out in both the NAT and the Nottingham Triaxial Test equipment (usually used for granular materials). As shown in Figure 5-34, the values presented are for NAT test specimens containing 3.7% RBC, compacted using two different pieces of equipment, at very early and later stages of curing. Two levels of load conditioning were used, 180 kPa (condition 1) and 300 kPa (condition 2). At the early stage of curing, values of Poisson's ratio were much higher than at later stages of curing. Overall, the values varied between 0.26 and 1.00 depending on the test stress level and the curing time. The value of Poisson's ratio is clearly not a function of compaction method or conditioning stress level.

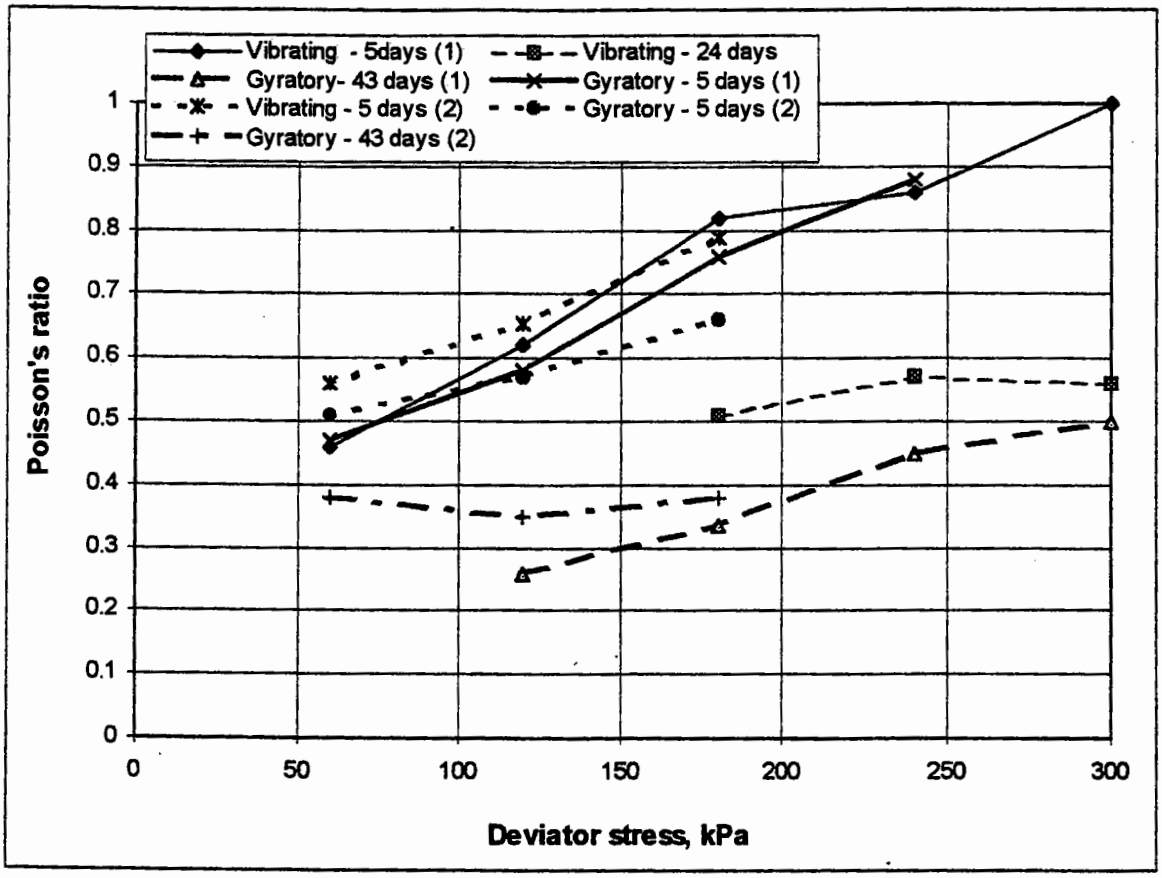


Figure 5-34 Effect of curing, compaction method, and condition stress level on value of Poisson's ratio.

Similar values of Poisson's ratio have been measured in the larger triaxial equipment (specimens 150 × 300 mm) under the same test conditions. A point to note, in testing this larger specimen, is that different radial deformations were measured at two different levels of the specimen. It is thought that variation in water content distribution within the specimen, resulting from uneven curing, gave rise to this difference. Based on this finding, the majority of the work of this study was carried out on 101 ×160 mm specimens, to ensure more uniformity of water content.

The material can generally be considered anisotropic during very early life when it contains a relatively high water content, resulting in a very low viscosity of binder.

5.3 COMPARISON OF STIFFNESS MODULI IN ITSM AND TRIAXIAL MODES

Emulsion aggregate mixtures generally exhibit different behaviour under indirect tensile and triaxial testing. In indirect tensile mode, in which the specimen is subjected to a combination of tensile and compressive stresses, the binder has a significant role in providing the tensile resistance of the material. However, in triaxial testing (mainly compressive and shear stresses) both the aggregate particles' interlock and the binder stiffness give rise to shear resistance, resulting in compressive strength development.

As previously explained, testing in indirect tensile mode may result in a misleading value of stiffness modulus, because of the dependency to applied load level (not due entirely to an inherent stress dependency of the material, but also from the damage which occurs in the microstructure of the mixture) and variations in Poisson's ratio. In triaxial mode, on the other hand, the material behaves non-linearly similar to unbound aggregate. Therefore, stiffness modulus from the two loading modes has been compared at a later stage (40 days). Cylindrical specimens were sawn to Marshall size, after being tested in the triaxial mode, to enable testing in the indirect tensile mode. A comparison then between the resulting stiffness moduli has been made. The results presented in Figures 5-35a and 5-35b indicate that the indirect tensile stiffness moduli at the normally used horizontal deformations (5 - 10 microns) were higher than those from the triaxial mode.

Referring to the results carried out in this research in the indirect tensile fatigue test (ITFT), which presented in Chapter 7, it was found that this material tends to have a relatively poor fatigue resistance over the whole curing period and in the long term. This drawback might be related to bitumen hardening, poor adhesion with aggregate particles, and high void contents. Decreasing the mixture void content, of course, improves this characteristic. Also, Snaith et al (1993) presented work by J. F. Lafon of LCPC (Toulouse) on mixtures with air voids in the range of 12-15%. He concluded, "such void levels would result in the oxidation of the binder resulting in poor fatigue

performance". As he reported, over a period of fifteen years on a road, bitumen penetration dropped to 40% of its original value. Based on these reported facts, the material will behave similar to an unbound material. It is therefore considered that the material may best be characterised in the triaxial mode of testing for a more conservative design,.

However, the results from the indirect tensile mode were generally found to be sensitive to the mixture variables, and can therefore be used for material ranking tasks and hence for mixture design purposes. On the other hand, stiffness modulus from the triaxial mode is greatly preferred for pavement structure design purpose, since the material behaves non-linearly.

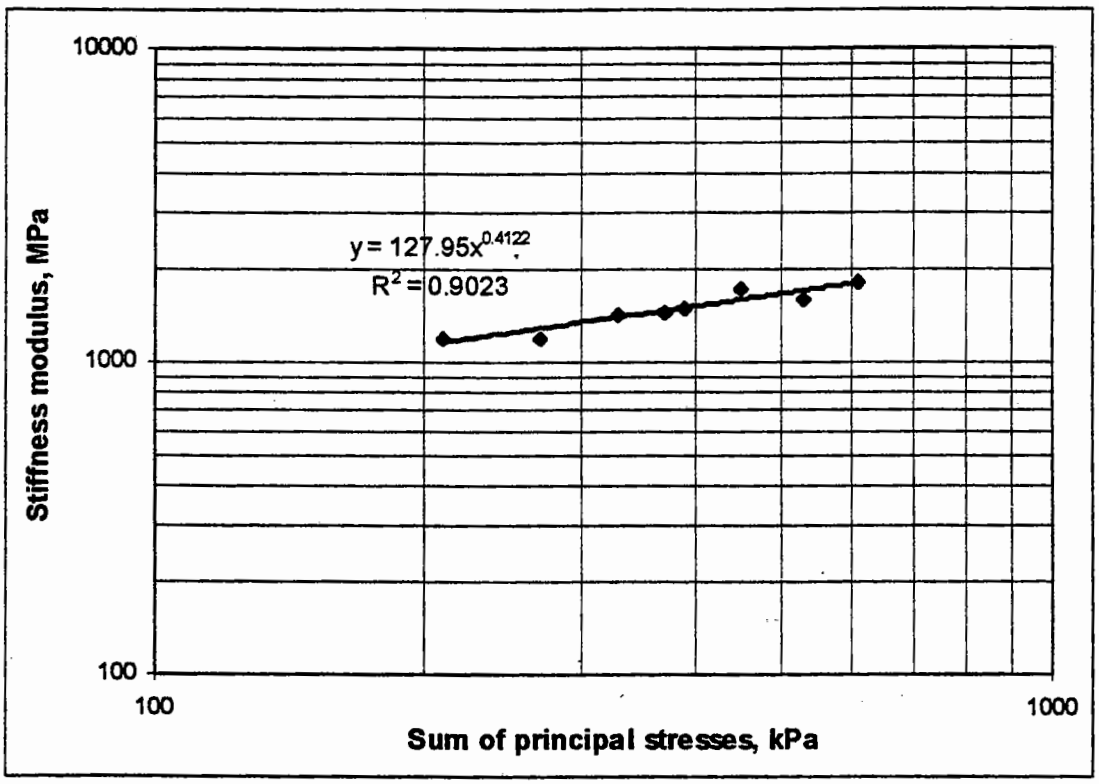


Figure 5-35a Stiffness of emulsion mixtures measured in the triaxial mode of loading in NAT (4.0% RBC, curing 40 days at 20°C)

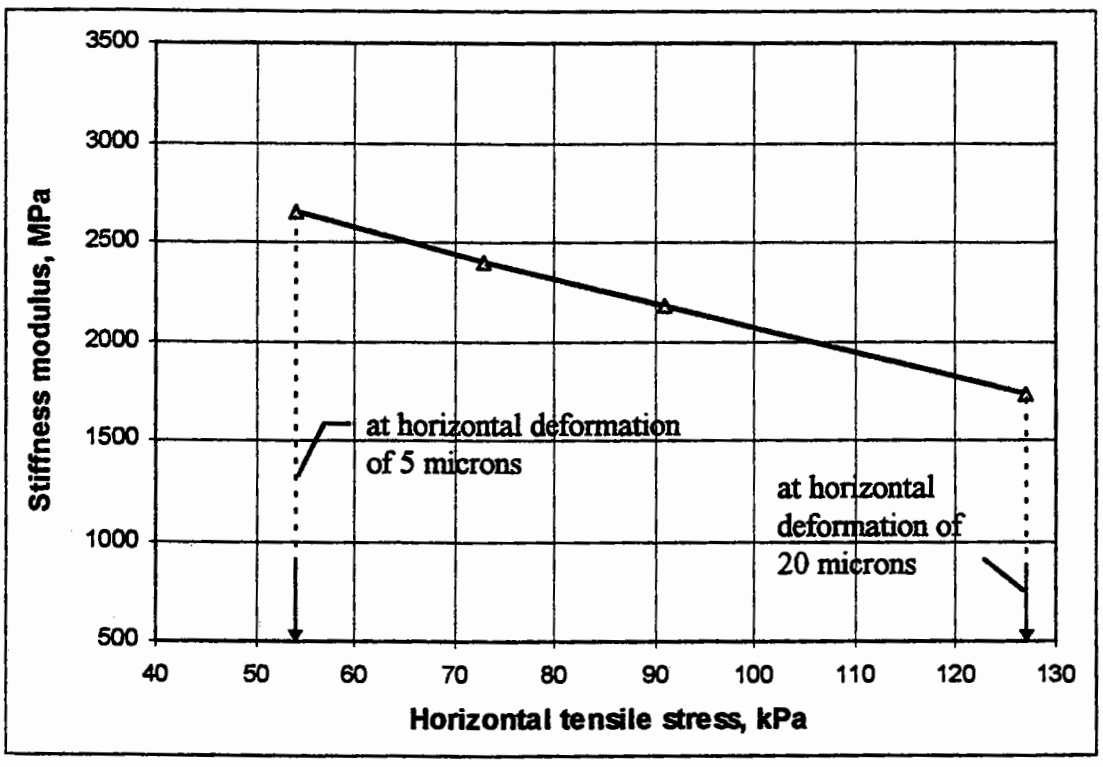


Figure 5-35b Stiffness modulus of emulsion mixtures measured in the ITSM on specimens after being tested in the triaxial mode

5.4 SUMMARY

Compaction method, aggregate gradation, curing regime and emulsion type were found to be the most significant factors affecting the stiffness modulus of emulsion-aggregate mixtures and consequently the determined optimum residual bitumen content (Chapter 4). The interaction between the binder and the aggregate particles, as well as the aggregate structure, was found to be influenced by the compaction method. As a result, the stiffness moduli as a function of curing time were different for specimens compacted using the Marshall hammer, vibrating compactor and gyratory compactor. Fine dense graded mixtures generally showed better stiffness moduli, determined either from the indirect tensile test or from the triaxial test, than DBM mixtures, depending on the emulsion type used, despite their relatively lower dry densities. It was also found that oven curing at high temperature is not a suitable accelerated curing regime, as it may affect the binder-aggregate interaction leading to better response of the material.

The stiffness modulus of the material was also found to be more dependent on the applied load level than was found for hot mixtures. In indirect tensile testing, the stresses induced when applying a load of 150 N over the 750 mm^2 cross-sectional area (specified by HAUC, 1992) were found to be beyond the yield stresses (outside the region of elasticity) for early cured specimens. Stress dependency of the material was observed in the triaxial testing in the NAT, and followed the K-θ model, usually applied to unbound aggregate. Generally speaking, the material exhibits a high stress dependency and variation in Poisson's ratio over the curing period, and this should be considered in stiffness determination or in mix and pavement structural design. Emulsion aggregate mixtures may however be characterised better by the triaxial mode of testing than the indirect tensile mode. In addition, triaxial testing is a suitable tool for assessing the material's resistance to permanent deformation and the resistance to water effects, as discussed in the next chapter and Chapter 8 respectively.

CHAPTER

6 EVALUATION OF RESISTANCE TO PERMANENT DEFORMATION

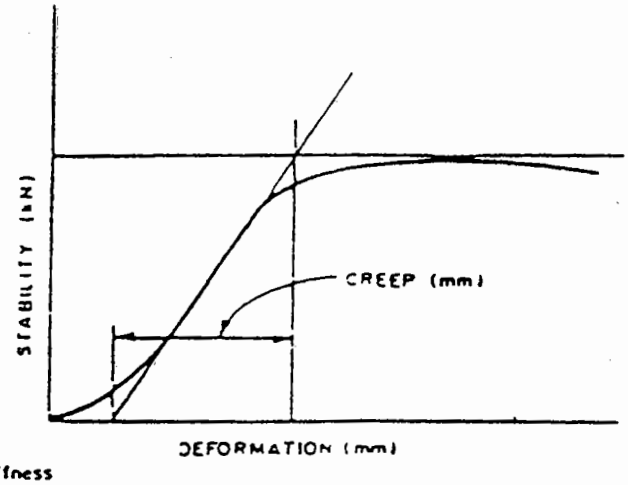
6.1 INTRODUCTION

When a flexible pavement is subjected to a wheel load, it undergoes both recoverable and irrecoverable deformations. The recoverable deformation is related to fatigue cracking, while the accumulated irrecoverable deformation leads to pavement rutting. A pavement is considered to have failed when the deformation of its components is sufficiently large to cause either an intolerably uneven riding surface or cracking of the material resulting from repeated stress over a prolonged period of time.

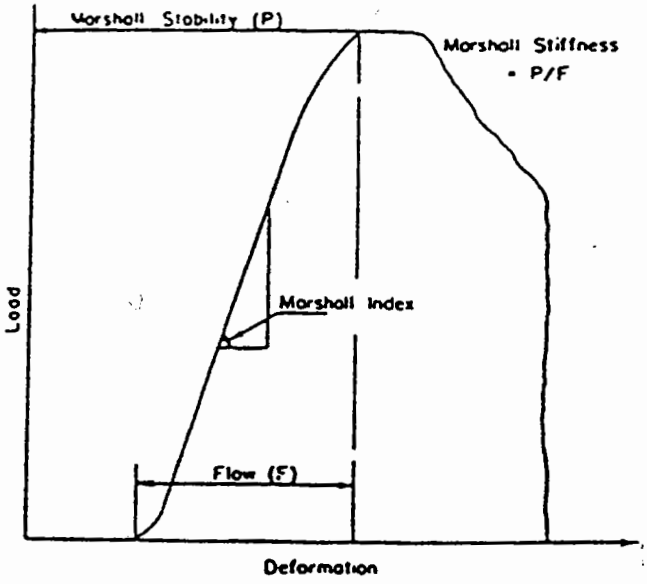
However, progressive accumulated permanent deformation due to cyclic dynamic loading is thought to occur due to the following mechanisms:

- Material densification due to the repeated loading. This mechanism is especially important in the case of poorly-compacted layers.
- Accumulation of shear deformation due to the repeated action of shear and tensile stresses. The importance of placing materials at high densities in order to minimise shear deformation was emphasized.

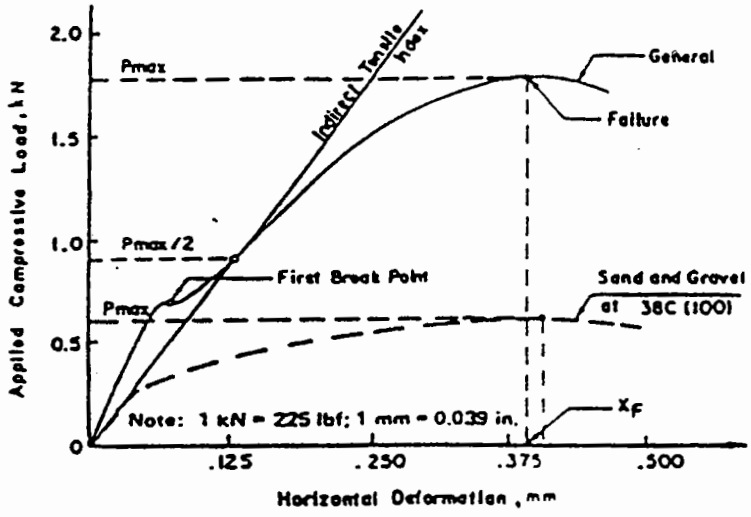
Therefore, some initial shear strength of emulsion-aggregate mixtures for use in a pavement structure is required to prevent deformation in the layer itself under traffic, which is affected by environmental conditions. In the literature, the deformation potential of the material has been determined by direct or indirect means. Of the direct techniques for measuring the resistance of the material to permanent deformation, normally used in hot mixtures, the uniaxial creep test, the uniaxial repeated load test, and the wheel tracking test, have been used. Indirect assessment of the material's resistance to permanent deformation involved one of the following parameters (Figure 6-1, see also Chapter 2):



(after Marais and Tait, 1989)



(after Gadallah et al, 1977 and Mamlouk et al, 1980)



(after Mamlouk and Wood, 1979)

Figure 6-1 Parameters used in assessing the deformation potential of emulsion-aggregate mixtures

- The Marshall stiffness defined as the quotient of the stability and creep (that is 'flow') values (Marais and Tait, 1989).

- The Marshall stiffness (stability/flow) and/or Marshall index (the slope of the linear portion of the load versus deformation plot (Gadallah et al, 1977 and Mamlouk et al, 1980).

- The indirect tensile index (Mamlouk and Wood, 1979) represented by the slope of the line between the origin and the point corresponding to 50 % of the maximum load on the load versus deformation curve.

In this study, the repeated load axial (RLA) test and repeated load triaxial test (RLT), both in the NAT, as well as the wheel tracking test, were used to investigate the significant factors affecting the deformation potential of such types of mixtures and to develop a parameter to be used in assessing this property (in terms of relative assessment between specimens). This parameter should reflect the accumulation of the material's permanent deformation during the curing process and after gaining its full strength. In other words, the change of the material properties with time should be accounted for in using such a parameter. The variables included in the NAT tests were test temperature, emulsion content, emulsion type, aggregate gradation, applied stress magnitude, confining stress level, and curing time, while the emulsion content and curing time were varied for testing in the wheel tracking test. Results have been compared with those for corresponding hot mixtures.

6.2 REPEATED LOAD AXIAL TESTING IN THE NAT

6.2.1 Test Description

The NAT was used configured for the repeated load axial test (RLA). For monitoring the overall strain of specimens, two LVDTs were mounted on the upper loading platen as shown in Figure 6-2.

In the test, the specimens were subjected to a static stress of 10 kPa for a duration of 10 minutes, to ensure that the loading platens were properly seated on the specimen prior to running the test for deformation measurements. The pulsating load, nominally square, of one second duration followed by a rest (no-load) period of one second duration was applied repeatedly for 3600 cycles. The tests were mainly carried out at 40°C; however, some were carried out at 20°C at early curing times.

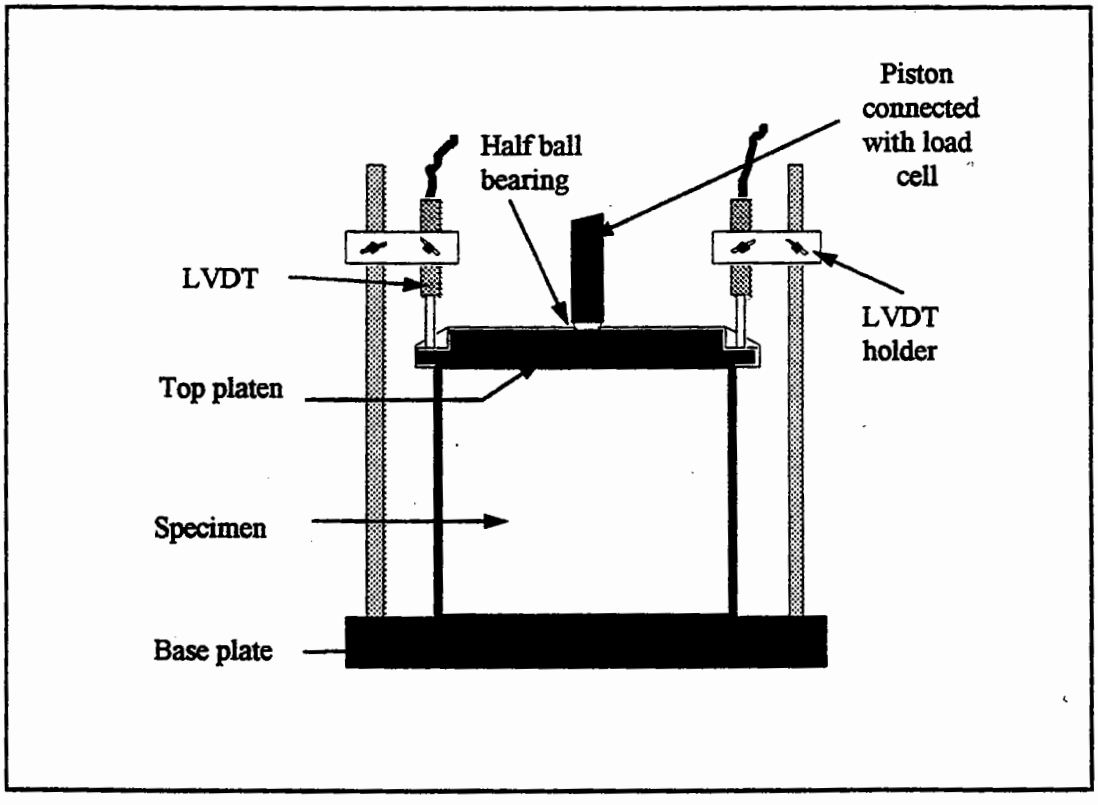


Figure 6-2 Schematic of the repeated load axial assembly for testing in the NAT

6.2.2 Factors Influencing Permanent Deformation

A typical plot of deformation against load cycles, obtained from permanent deformation tests, shows three phases of material response (Preston, 1991):

- Primary phase, in which a combination of seating of the loading platens and material densification occurs; generally, the strain rate gradually decreases in this phase.
- Secondary phase, in which a linear response takes place, attributed to a restructuring of the mineral aggregate matrix.
- Tertiary phase, representing a viscous flow of the binder within the aggregate.

Plots of axial strain versus number of load pulses for the emulsions used, and for conventional hot mixture (100 pen base bitumen), are shown in Figures 6-3 to 6-9. Primary and secondary phases can be distinguished.

Since there is no established parameter for use in assessing the response of emulsion-aggregate mixtures in the RLA test, a comparison of the results was provisionally made, using the minimum strain rate (strain rate of the linear portion, $(\varepsilon_{3600} - \varepsilon_{1000})/2600$) and the mean strain rate reported by Brown et al, (1995) and Gibb (1996) for hot-bituminous paving mixtures, defined as $(\sum\Delta\varepsilon/\Delta N)/N$, where:

$$\Delta\varepsilon = \varepsilon_{i+1} - \varepsilon_i , \quad \Delta N = N_{i+1} - N_i$$

- ε_i is the strain recorded at increment i.
- N_i is the number of cycles elapsed at increment i.
- N is the number of increments at which strain is recorded.
- ε_{3600} is the strain recorded at 3600 pulses.
- ε_{1000} is the strain recorded at 1000 pulses.

They reported that the mean strain rate parameter is weighted to emphasise performance of the specimen in the initial phase of the test whereas the minimum strain rate reflects more the behaviour of the specimen in the later stages. They also reported, "the minimum strain rate may not be sufficiently sensitive to discriminate effectively between better performing materials which would exhibit low rates of strain".

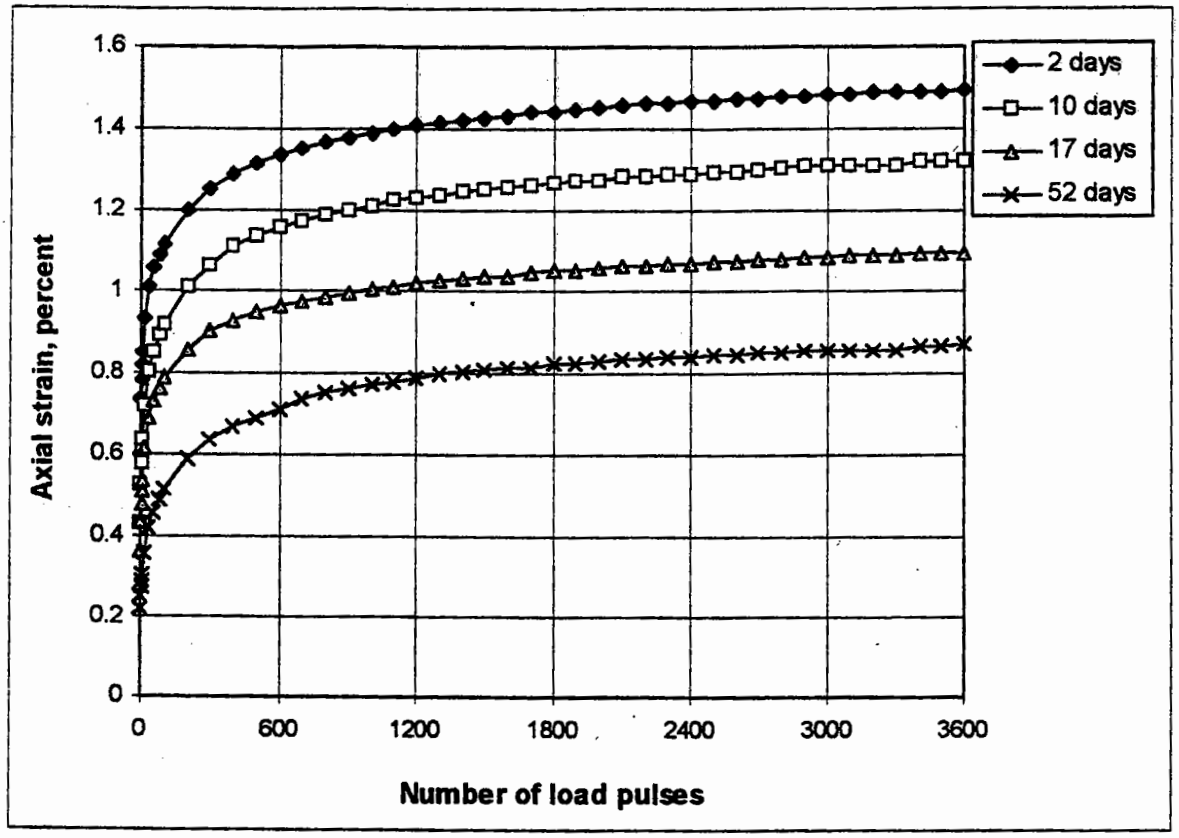


Figure 6-3 Repeated load axial test results of K-emulsion mixture specimens containing 3.2% RBC, test temperature 40°C

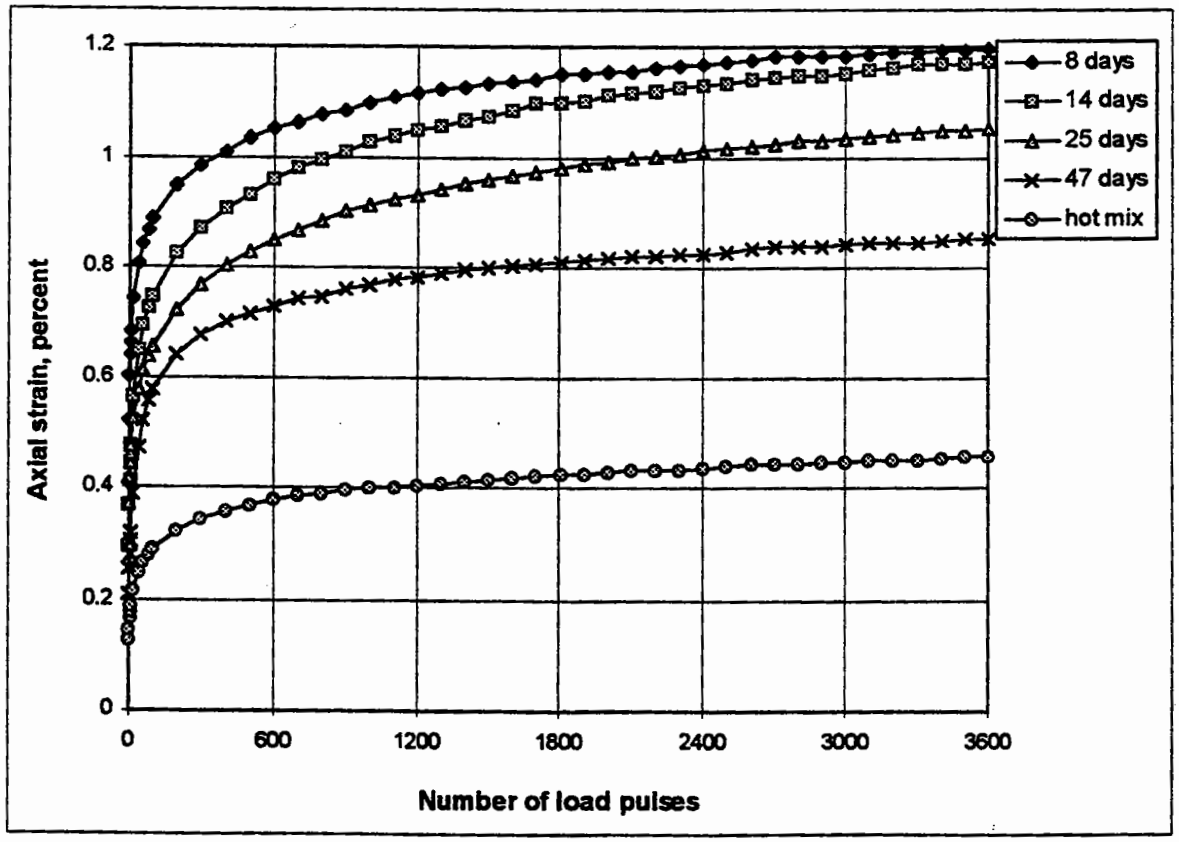


Figure 6-4 Repeated load axial test results of K-emulsion mixture specimens containing 3.2% RBC, test temperature 30°C

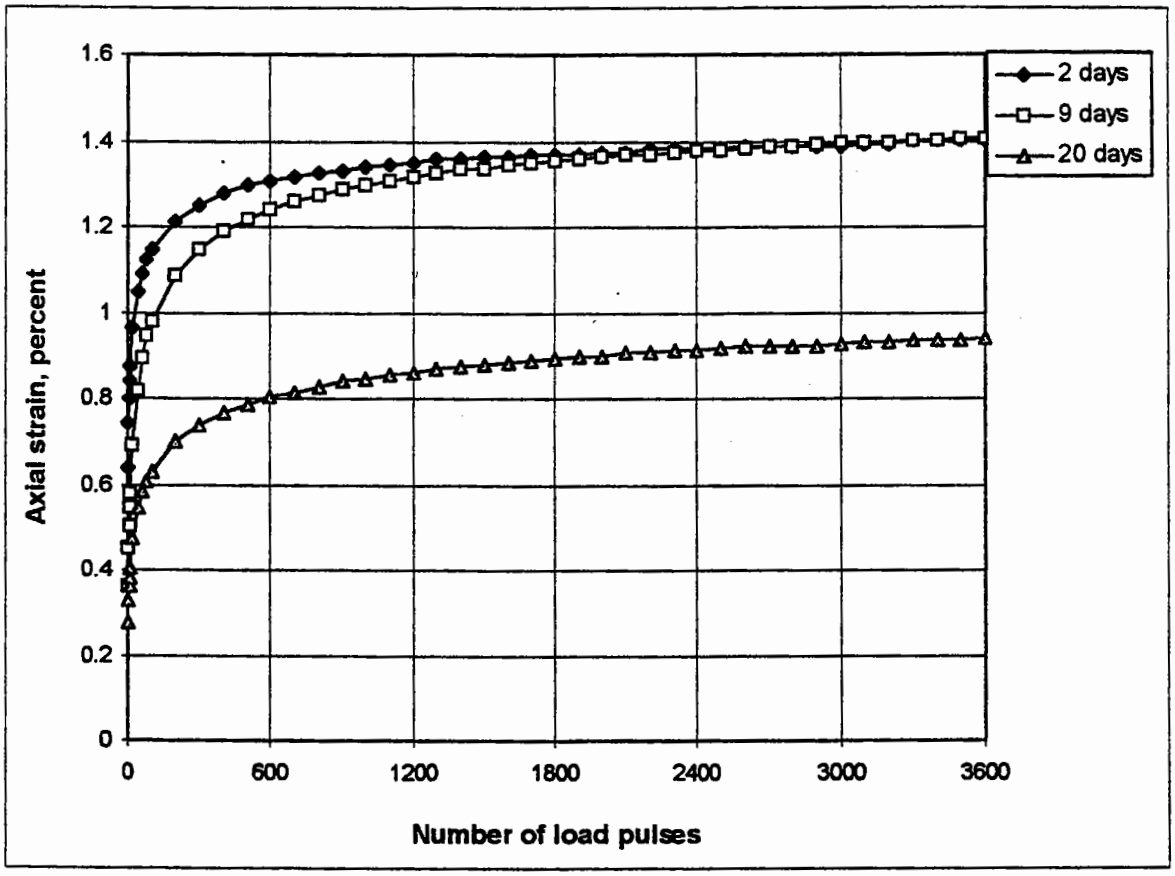


Figure 6-5 Repeated load axial test results of K-emulsion mixture specimens containing 3.2% RBC, test temperature 20°C

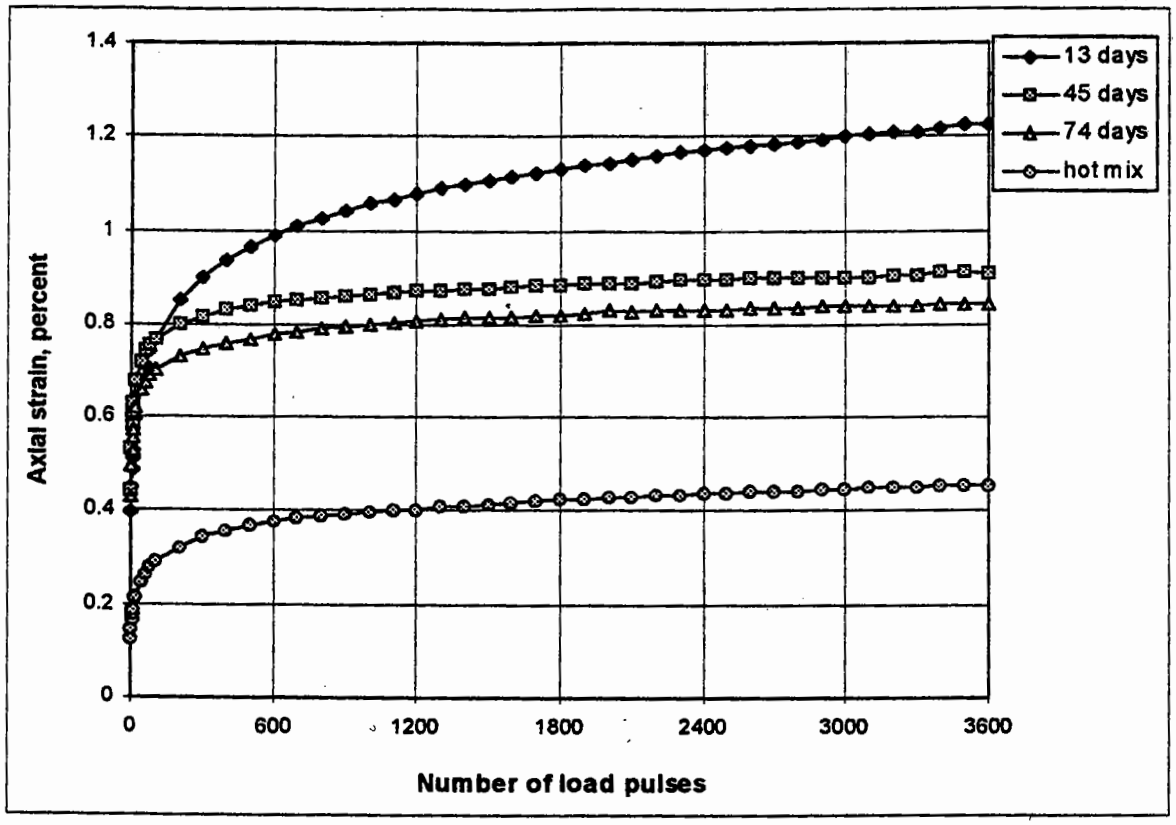


Figure 6-6 Repeated load axial test results of EN998-emulsion mixture specimens containing 3.2% RBC, test temperature 30°C

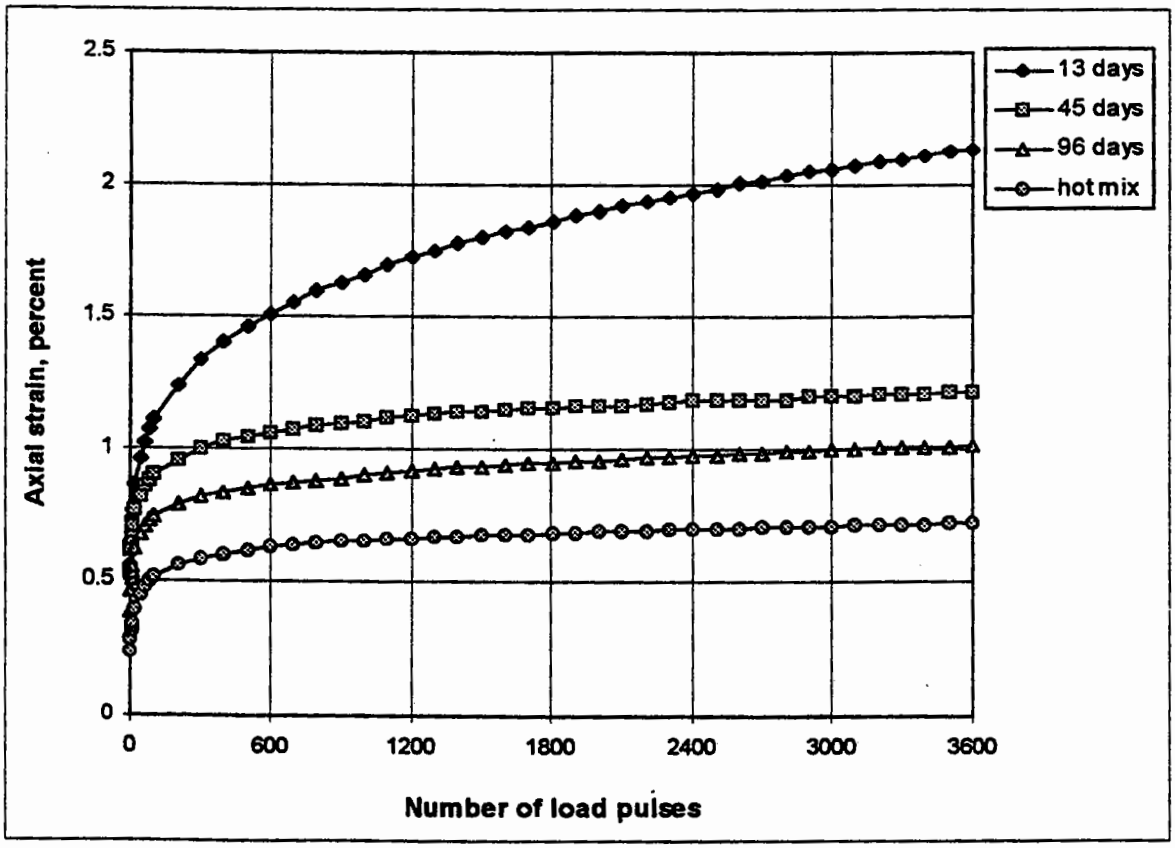


Figure 6-7 Repeated load axial test results of EN998-emulsion mixture specimens containing 4.2% RBC, test temperature 30°C

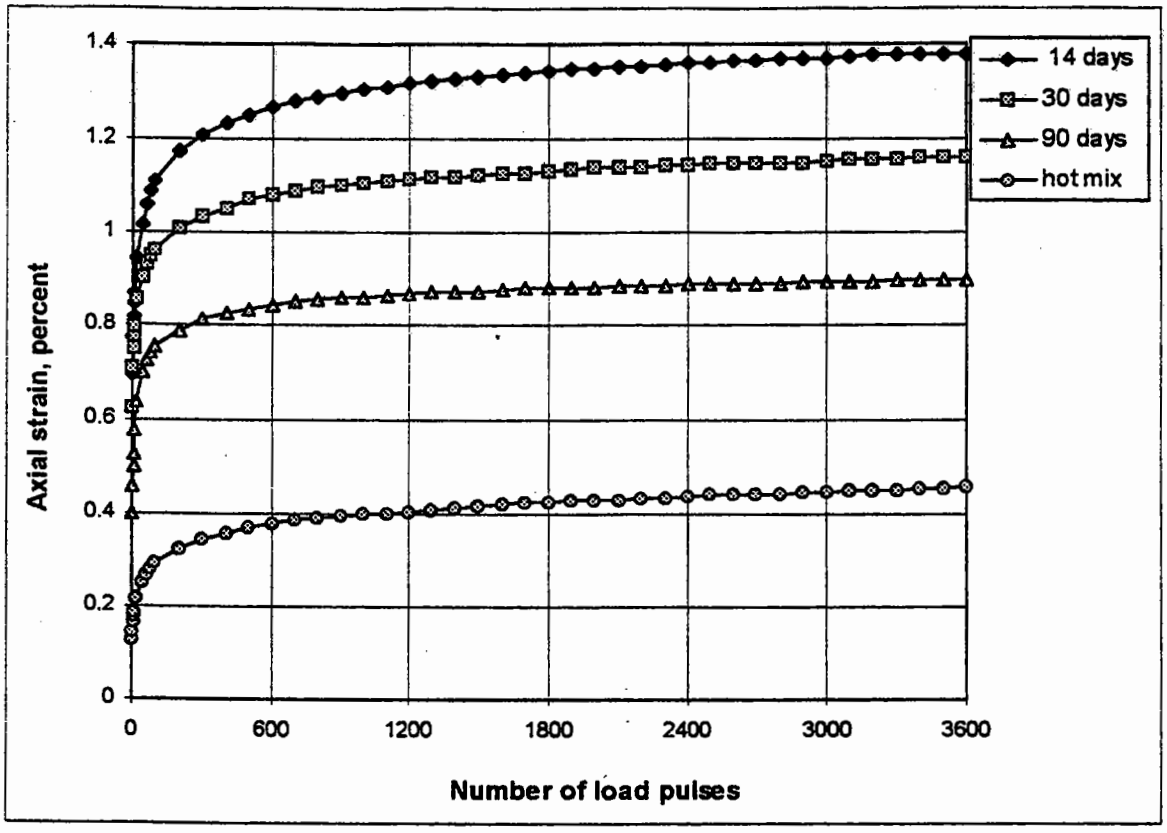


Figure 6-8 Repeated load axial test results of A-emulsion mixture specimens containing 3.2% RBC, test temperature 30°C

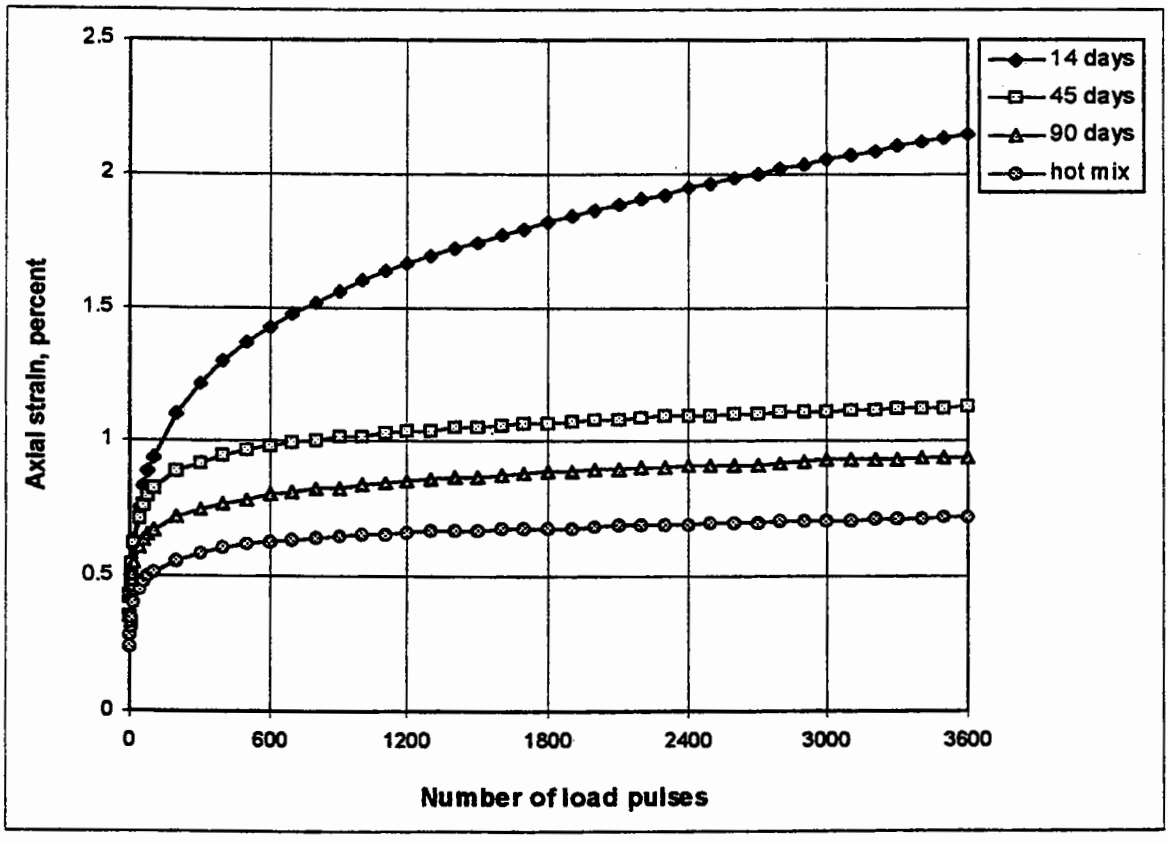


Figure 6-9 Repeated load axial test results of A-emulsion mixture specimens containing 4.2% RBC, test temperature 30°C

Table 6-1 Calculated Parameters for the RLA test results

Test condition	Curing time (days)	Mean strain rate (με/cycle)	Strain rate (linear portion) (με/cycle)	Regression parameters: ($\log \varepsilon = \log \varepsilon_1 + b \log N$)			Test condition	Curing time (days)	Mean strain rate (με/cycle)	Strain rate (linear portion) (με/cycle)	Regression parameters: ($\log \varepsilon = \log \varepsilon_1 + b \log N$)		
				ε_1	b	R square					ε_1	b	R square
K-emulsion	2	32.34	0.393	6590	0.105	0.971	EN998	13	30.29	1.81	3064	0.238	0.999
3.2% RBC	17	23.48	0.345	3970	0.131	0.966	4.2% RBC	45	23.14	0.428	2886	0.144	0.991
40°C	52	12.79	0.376	2074	0.183	0.985	30°C	74	22.52	0.438	3810	0.113	0.982
K-emulsion	8	22.06	0.393	5401	0.100	0.987	EN998	13	19.6	0.635	3814	0.145	0.995
3.2% RBC	25	15.42	0.532	3229	0.164	0.976	3.2% RBC	45	23.45	0.171	5155	0.073	0.925
30°C	47	16.88	0.326	2274	0.171	0.957	30°C	74	18.12	0.17	4738	0.074	0.956
K-emulsion	2	30.80	0.228	7111	0.088	0.941	A emulsion	14	30.27	2.107	5028	0.175	0.999
3.2% RBC	20	17.92	0.350	2918	0.150	0.973	4.2% RBC	45	26.62	0.425	4263	0.108	o.975
20°C	52	15.49	0.436	2118	0.181	0.983	30°C	90	20.32	0.382	5549	0.098	0.987
Hot mixture (test temperature 30°C):							A emulsion	14	23.84	0.292	7251	0.083	0.972
3.2% BC		8.866	0.222	1302	0.158	0.981	3.2% RBC	30	22.95	0.216	6715	0.070	0.963
4.2% BC		14.72	0.245	2606	0.149	0.965	30°C	90	23.28	0.139	4599	0.088	0.91

Effect of Curing

Emulsion-aggregate mixtures behave in a different way from hot-bituminous mixtures, in that their behaviour is greatly influenced by the contained water. Nevertheless, characterisation of the deformation performance in either routine testing for Marshall stability and indirect tensile strength, or in RLA testing, has tended to be on specimens at later curing stages, neglecting the response at early life. To examine the performance of this type of material in the RLA and investigate the validity of ranking materials using test results from fully cured specimens, testing was carried out on different compositions at different curing times. The results are shown graphically in Figures 6-3 to 6-9 and the determined mean and minimum strain rates are presented in Table 6-1.

As noted, the mean strain rate is dependent on curing time. For all specimens tested at early stages of curing, the mean strain rates were relatively higher than those of older specimens, mainly seen in the material response during the initial stage of the test, where densification of the material occurs. The investigated mixtures also appeared to have different responses during the second phase of testing (linear response phase). The minimum strain rate $(\varepsilon_{3600} - \varepsilon_{1000})/2600$ of the K-emulsion mixture specimens were approximately the same, 0.32 - 0.39, at different curing times. On the other hand, the strain rates of the EN998 and 'A' emulsion specimens were greatly influenced by curing, being higher at early curing. With curing time, a gradual decrease in the minimum strain rate until it reached to a constant value similar to that corresponding to conventional hot mixtures was observed.

Undoubtedly, water in an emulsion-aggregate mixture dominates its deformation behaviour. At early curing, it is likely that the binder is less viscous and the adhesive bond with the aggregate particles is insufficient, giving less mixture cohesion. Hence, both the viscous resistance contributed by the binder, or rather the mortar in the mixture (binder + filler), and the frictional resistance contributed by the mineral aggregate matrix are low at this stage of curing, leading to movement between the aggregate particles. As the material undergoes a curing regime, by which water evaporates, both the viscous and frictional resistance increase due to hardening of the emulsion residue and adhesion build-up. Consequently, a lower strain rate increase occurs during the primary phase of deformation.

This response of material in the RLA is dependent upon specimen density, bitumen content and test temperature.

However, during the linear phase, at all curing levels, the strain rate may be similar. Increasing RBC in a mixture may increase the strain rate depending on the emulsion type and how far it distributes amongst the aggregate particles.

Thus, in reality, the mixture will deform with an increasing rate at early life, during which densification takes place, followed by the second stage during which steady increase in strain occurs. Since the overall deformation of the mixture in the field is the result of the accumulation of deformation that occurs during its life, this is likely to be dominated by its response at early curing times. This will then influence the ranking of the different mixture combinations for design purposes. Partially cured specimens should then be representative of the condition of the paving mixture at time of commencement of trafficking.

Generally, the results from the RLA indicate that emulsion-aggregate mixtures exhibit less permanent deformation resistance compared to corresponding hot mixtures.

Effect of Aggregate Gradation

For this purpose, RLA tests were carried out on K-emulsion mixtures containing different gradings (C1 'coarse', C2 'fine', and mid-DBM) at 40°C after 24 days curing at 20°C. The results are shown in Figures 6-10 and 6-11.

It can be observed from Figure 6-10 that increasing RBC of C1-mixtures led to failure of specimens before the end of the test. Decreasing the RBC of such mixtures resulted in better performance, as it had less effect on the frictional resistance of the aggregate matrix. On the other hand, best performance was found for mid-DBM specimens.

Although the fine graded mixtures showed better elastic response, as discussed in Chapter 5, and the C1-mixtures showed less load susceptibility, both had relatively lower permanent deformation resistance than the mid-DBM mixtures (Figure 6-11).

The determined levels of ultimate strain of fully cured specimens, from the RLA tests, are considered acceptable. The problem therefore comes from the material performance during early life, which will affect the overall performance. Decreasing the RBC and using denser mixtures will certainly mitigate this problem. Additionally, controlling time of trafficking is important.

It should be reported that some of the tests in the RLA on early cured specimens which could not be trimmed, showed inconsistent results and were therefore omitted from the comparison. During the compaction process, the surfaces of these specimens in contact with the tamping foot in the vibrating compactor or the ram in the gyratory compactor were inevitably rough, resulting from partial coalescence of bitumen droplets, depending on the compaction level. Testing of such specimens in the RLA will lead to end constraint and barrelling and, consequently, less permanent deformation. Thus, consideration should be given to producing specimens with good surfaces for use in RLA testing at early curing.

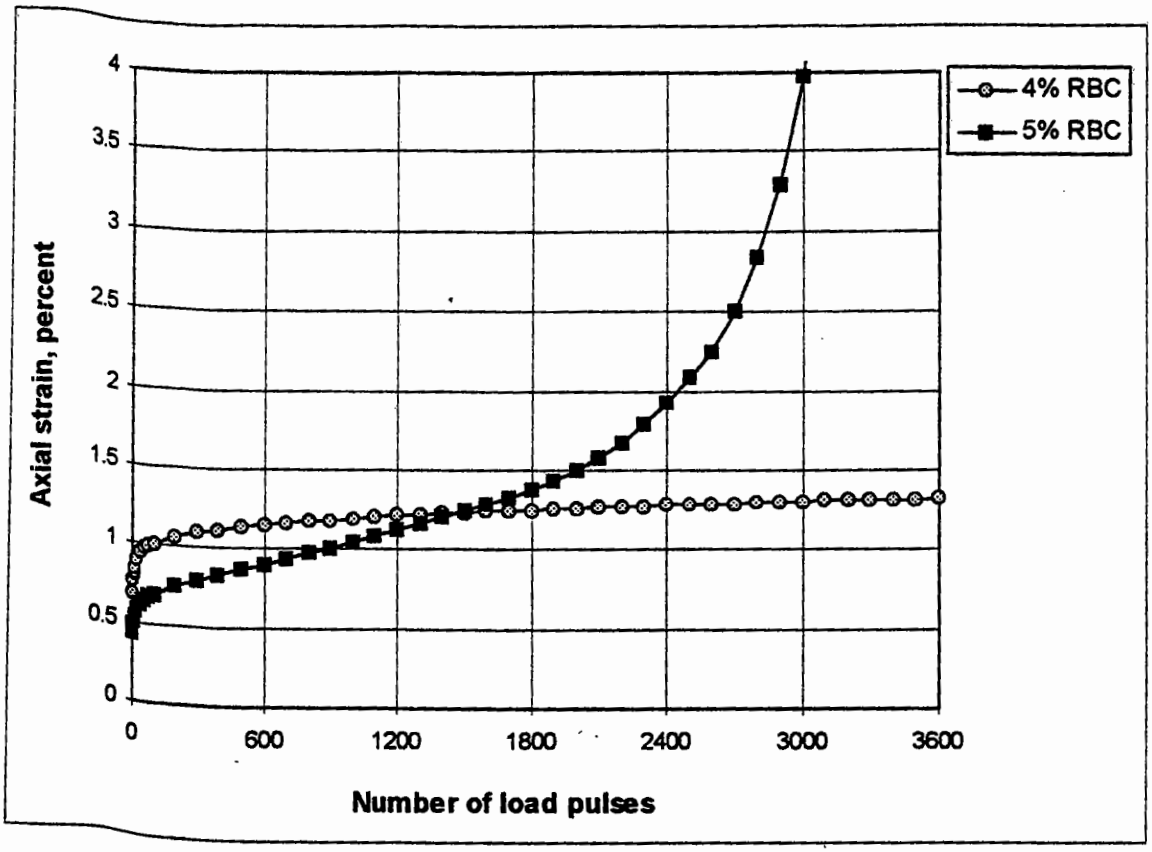


Figure 6-10 Effect of RBC on the permanent deformation performance of K-emulsion mixtures containing C1-grading

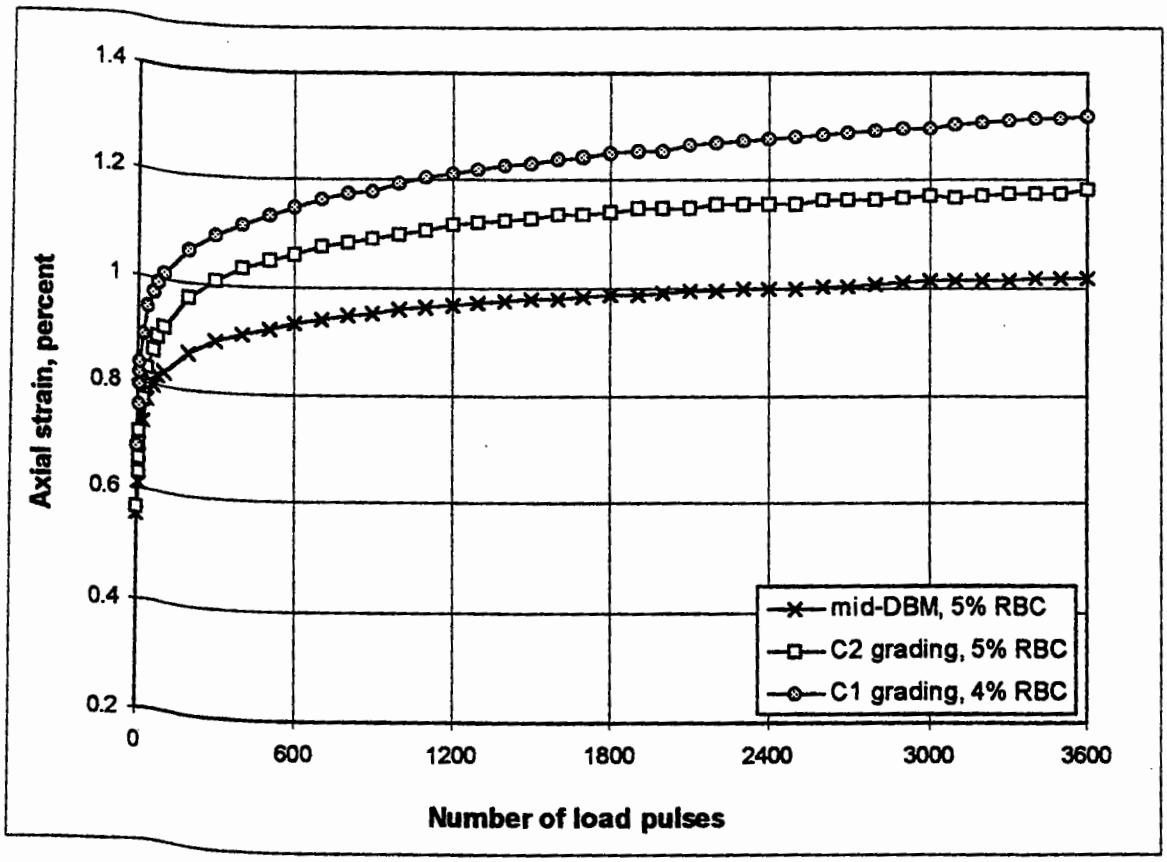


Figure 6-11 Effect of aggregate gradation on permanent deformation, measured in the RLA test at 40°C

6.3 TRIAXIAL TESTING IN NAT

The use of the triaxial test is beneficial for assessing the permanent deformation resistance of emulsion aggregate mixtures, particularly at early curing. The effect of confinement makes it a more realistic test and, because taller specimens are used (aspect ratio, height to diameter over 1.5), a more uniform vertical stress is achieved over the gauge length (Smith, 1996).

Therefore, tests were carried out in the triaxial mode of the NAT, previously described in Chapter 5, some with a pulsed load of 0.120 sec rise time and others with 1 sec loading time.

6.3.1 Effect of Confinement

Testing was performed on cylindrical specimens (101 × 160 mm) containing 5 % RBC of K-emulsion. The results are shown in Figures 6-12 and 6-13. Figure 6-12 shows the results of testing using a pulsating stress of 250 kPa and half height time of 120 ms (condition A), while Figure 6-13 presents the results of testing using 100 kPa deviator stress and a pulse duration of 1 second (condition B). A gauge length of 50 mm was used in all tests.

Clearly, increasing the confinement level significantly reduced mean strain rates. Regarding the strain rate of the secondary phase of the deformation characteristic, different responses were observed. Loading condition 'A' resulted in a slight change in the strain rate, while, loading condition 'B' caused higher strain rates when confinement decreased from 40 kPa to 20 kPa. This may be a result of the pulse time used.

Generally, it can be said that decreasing confinement level will lead to higher deformations, as the frictional resistance of the mixtures is affected, allowing more relative movement between the aggregate particles. This result is similar to that of hot mixtures reported by Huschek (1985), who explained that increasing confinement decreases the plastic deformations contributed by the aggregate particles.

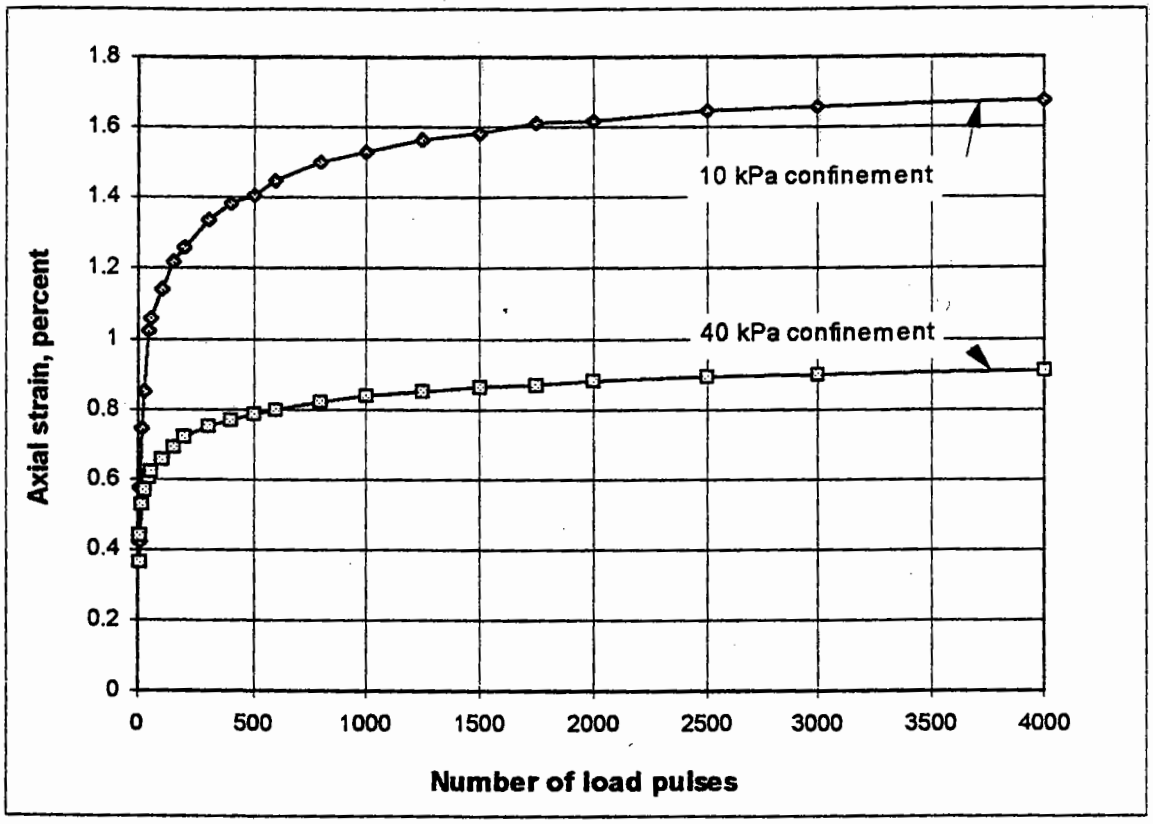


Figure 6-12 Effect of confining pressure on the permanent deformation of K-emulsion mixtures containing 5 % RBC (curing at room temperature '22°C' for 7 days, test temperature 20°C, loading condition A)

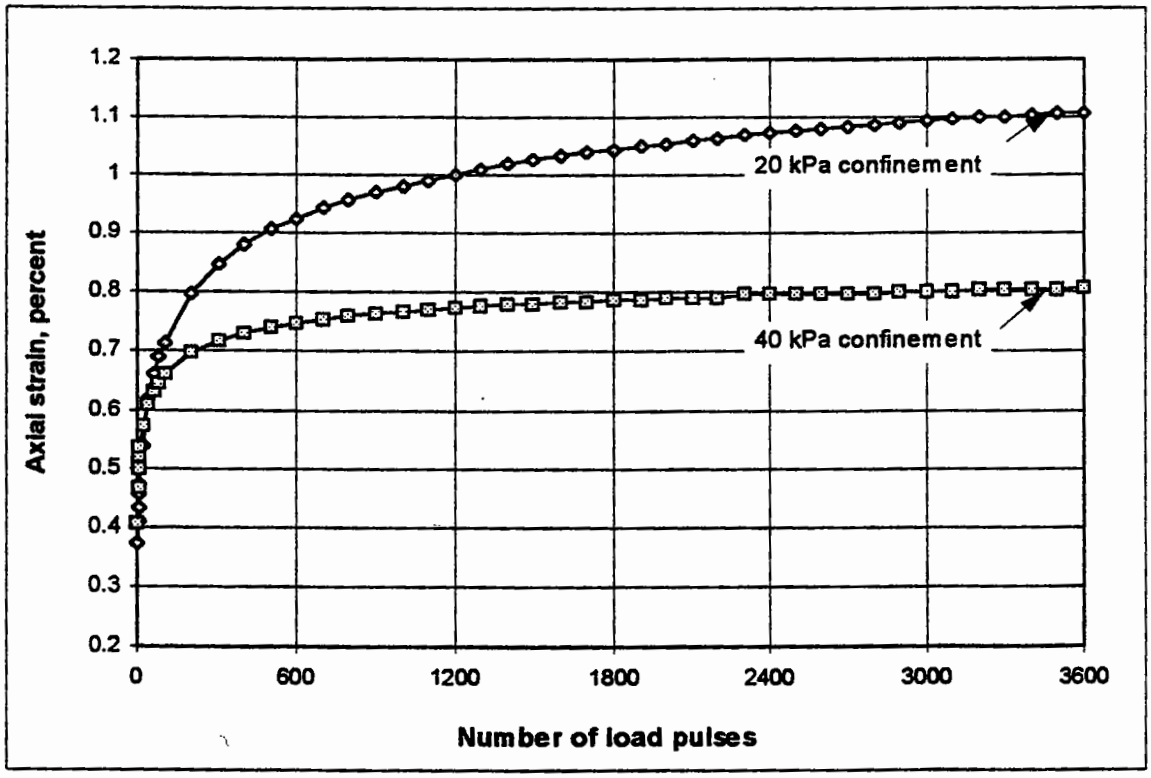


Figure 6-13 Effect of confining pressure on the permanent deformation of K-emulsion mixtures containing 5 % RBC (curing for 2 days side wrapped and 7 days fully wrapped, test temperature 40°C, loading condition B)

6.3.2 Effect of Test Temperature

Triaxial testing was carried out in the NAT on K-emulsion specimens containing 4 % and 5 % RBC, cured for 5 days at 20°C. The test temperatures used were 20°C and 40°C. The results are shown in Figures 6-14.

The test temperatures used significantly affected the deformation characteristic of the material, depending on the RBC used. Only a slight difference in the parameters was found for the mixtures containing 4 % RBC, while a significantly increased mean strain rate was noted at a test temperature of 40°C when 5 % RBC used. However, no significant difference could be distinguished in terms of the minimum strain rates.

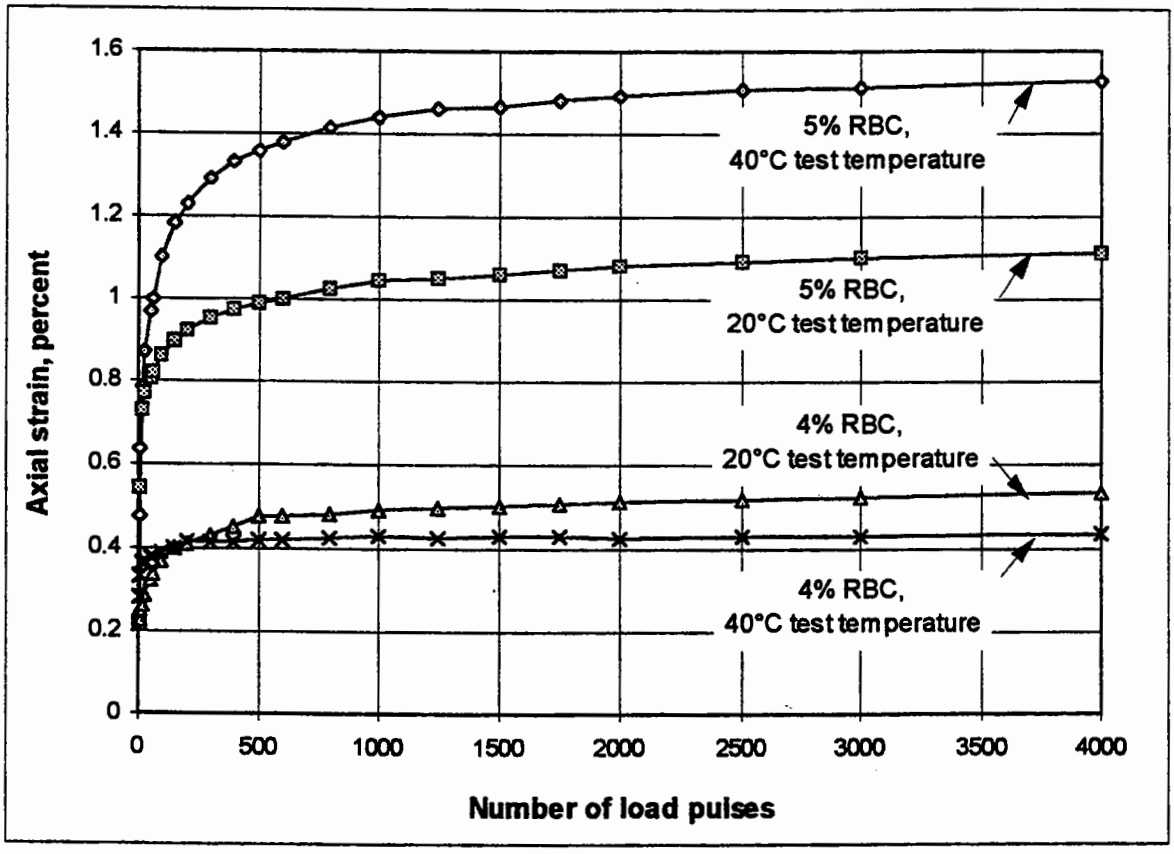


Figure 6-14 Effect of test temperature on the permanent deformation response (curing at 20°C for 5 days, deviator stress 250 kPa, confining pressure 40 kPa)

6.3.3 Effect of Residual Bitumen Content

As shown in Figure 6-15, increasing RBC from 4 % to 5 % had an influence on the mean strain rate, not the minimum strain rate, in which the role of the aggregate in the mixture is dominant under the confinement level used. This trend was found to be similar when load conditions A and B (previously explained) were compared.

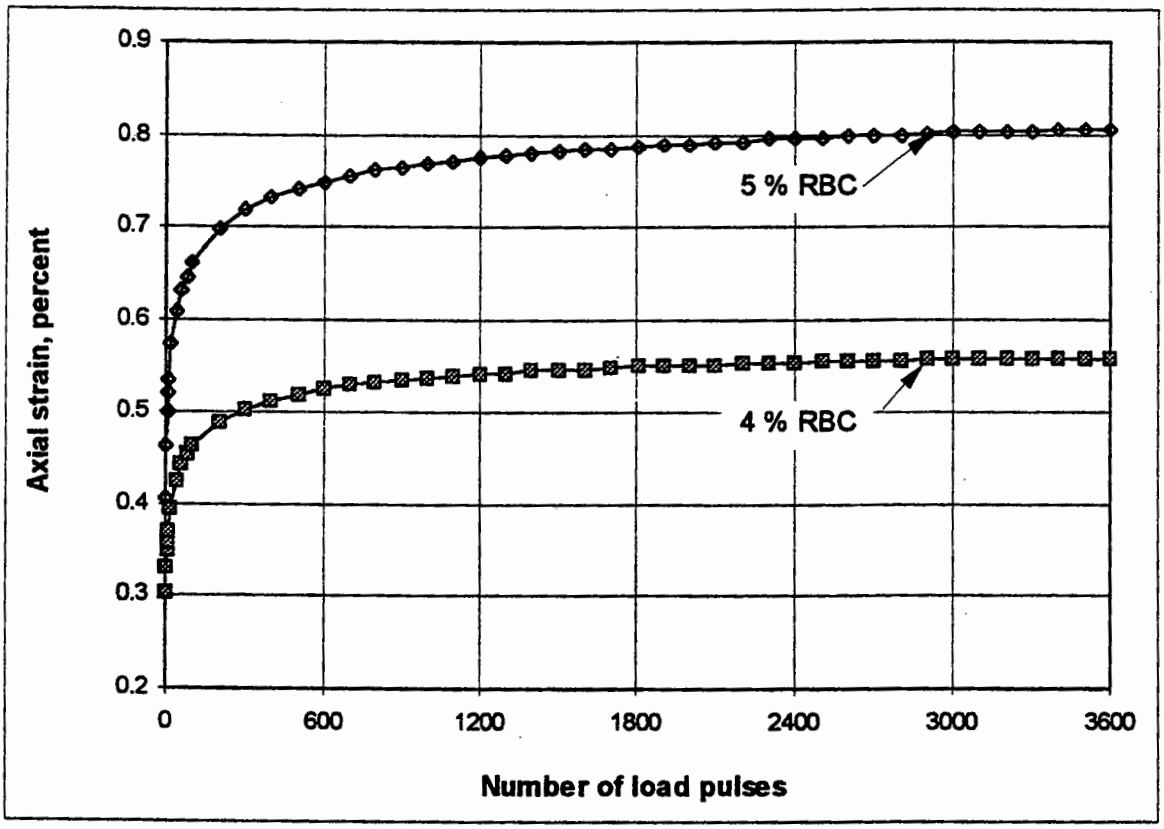


Figure 6-15 Permanent deformation response as a function of RBC (100 kPa deviator stress, confinement 40 kPa, curing for 2 days side wrapped and 7 days fully wrapped, 40°C test temperature)

6.3.4 Effect of Applied Stress Level

Testing of K-emulsion mixture specimens containing 5 % RBC was carried out using pulsed stresses of 100 kPa and 250 kPa. The aim was to investigate the deformation performance of this mixture when applying a higher stress level relative to a lower one.

It is apparent from Figure 6-16, for lightly cured specimens (3 days, sided wrapped), that a higher stress level resulted in higher strains, as both mean and minimum strain rates increased.

However, using a higher stress level in triaxial testing has some benefits:

- Less electrical noise is usually associated with higher stress levels allowing better determination of irrecoverable strain under a load pulse.
- It allows better and reliable comparison between the different mixture combinations. Sensitivity of the test to mixture components is expected to be high when a higher load level used.
- When using the material as a layer in pavements, a high stress level is expected, based on calculated values using multilayer elastic theory. It is therefore considered more realistic.
- In triaxial testing for stiffness determination (Chapter 5), load conditioning of specimens at a higher stress level is essential to reach a steady condition of Poisson's ratio and to eliminate the effect of permanent deformation. Permanent deformation characteristics of the mixture can then be determined by capturing strain values during the conditioning of specimens.

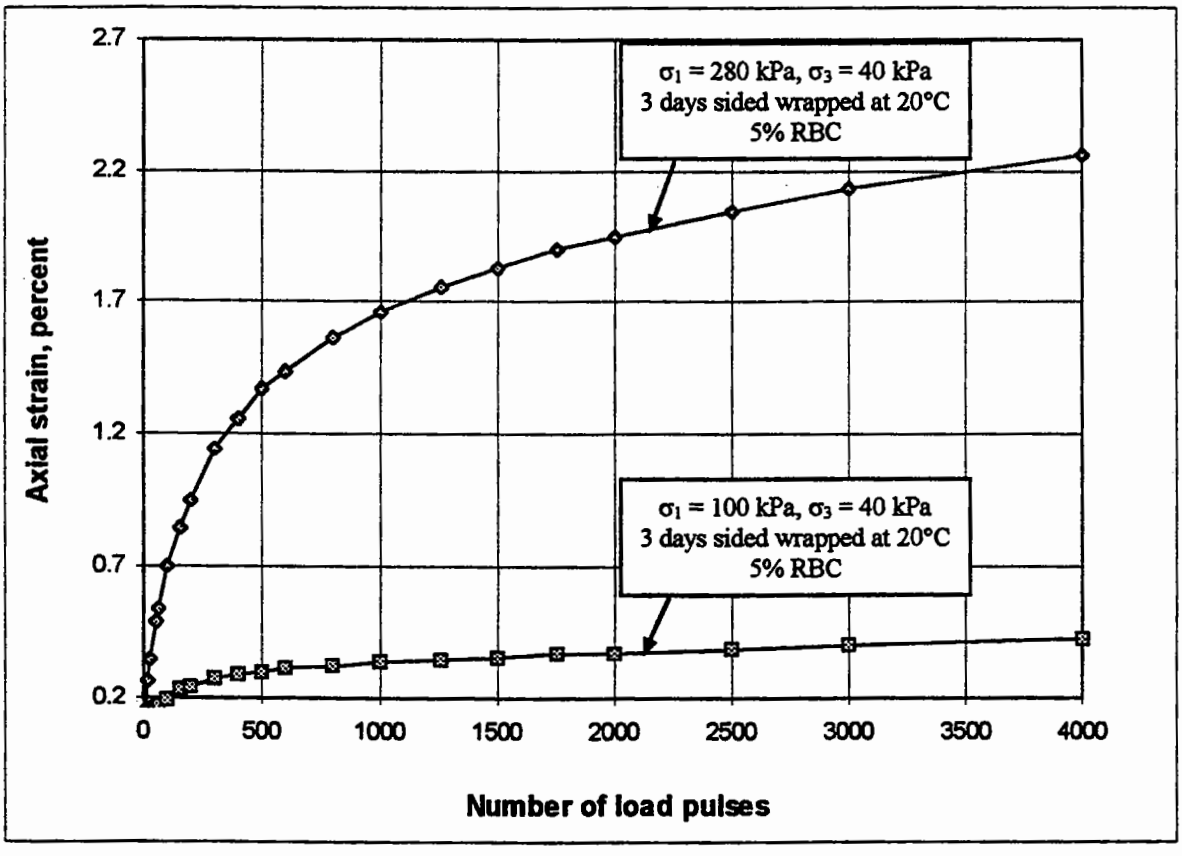


Figure 6-16 Effect of applied stress level on permanent deformation performance of K-emulsion mixtures

6.4 PERFORMANCE UNDER WHEEL TRACKING

The wheel tracking test is generally less sensitive to void contents less than 16% of bituminous mixtures (Sosnovske et al, 1994 and Gibb, 1996) but it is able to rank effectively the rutting resistance of mixtures, with bitumen type having the most significant effect on performance. The purpose was then to compare the relative rutting resistance of emulsion aggregate mixtures to that of hot mixtures.

6.4.1 Description of Test Equipment

As shown diagrammatically in Figure 6-17, the wheel tracking test equipment comprises the following:

- Test specimen, either a core of 200 mm diameter or a slab with horizontal dimensions of 404 × 280 mm, confined in a steel mould, which can be placed in its position in the equipment on a trolley and driven to and fro beneath a loaded wheel.
- Loaded wheel has an overall diameter of 200 mm, and a width of 50 mm. The wheel is fitted with a solid rubber tyre and is mounted on a pivot lever arm through which a constant load is applied.
- A linear variable differential transducer LVDT mounted on the test frame in a position that allows levelling with the lever arm for zero reading. The LVDT monitors the vertical position of the wheel as the test progresses, reflecting the development of rutting in the specimen.
- A slotted slide attached to the specimen passes through an optical trigger, causing the LVDT signal to be captured at eleven positions along the central 100 mm length.
- Drive shaft connected to the trolley carrying the specimen and an electric motor. Rotation of the drive shaft causes linear movement of the slab beneath the wheel. A travelling distance of 225 mm is normally achieved. The rate of oscillation is normally set at 42 passes per minute.

Measurements of the LVDT can be captured and recorded via an analogue-digital converter (A/D), normally every 20 passes.

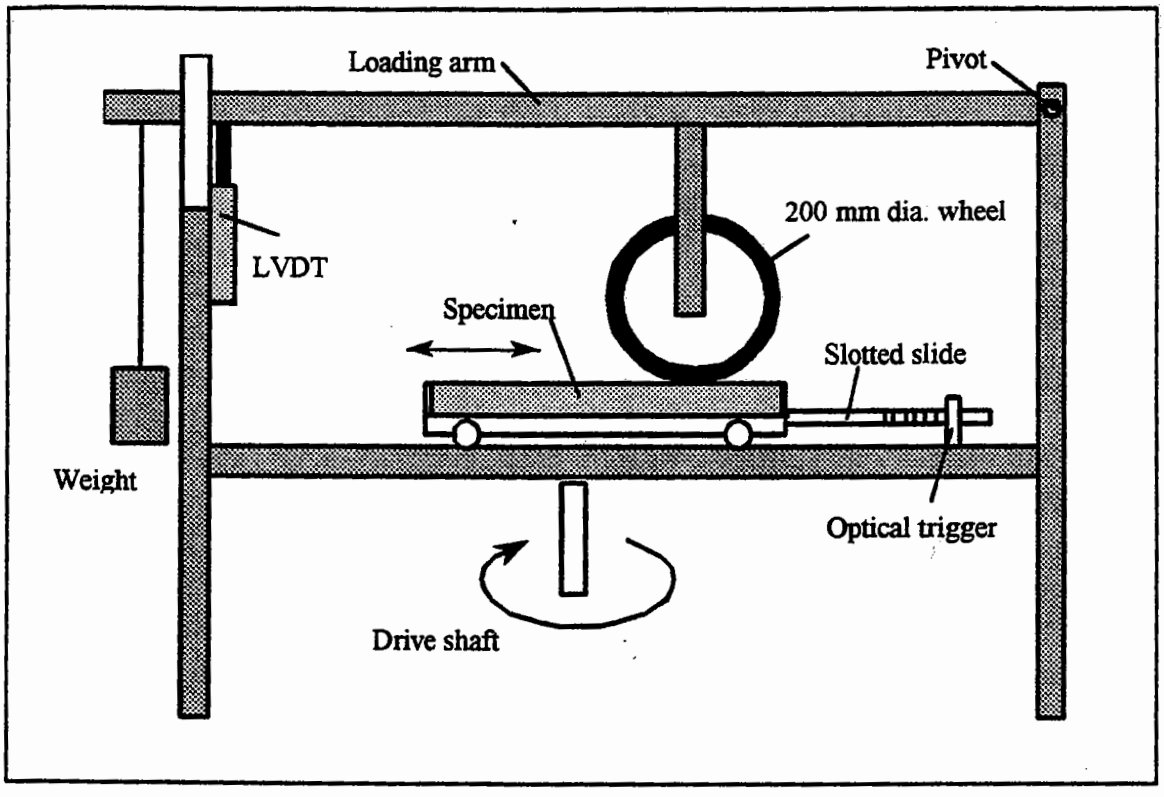


Figure 6-17 Diagram of the wheel tracking apparatus

6.4.2 Specimen Preparation

Specimens were manufactured by first mixing the components mechanically, following the preparation procedure proposed in this study, presented in Chapter 4 for cold mixtures or the British Standard (BS 598 : part 3, 1985) for hot mixtures. The mixture was then placed in a steel mould dimensioned 404 × 280 mm horizontally and 100 mm deep, fixed in its position on a trolley in the roller compactor. For better uniformity, the loose material was placed in 5 trays using a riffle box.

The dry density of all specimens was kept constant by predetermination of the required amount of individual materials and compaction to a similar specimen height. An average void content of 10.8 % was achieved.

6.4.3 Test Programme

Normally, specimens for testing in the wheel tracker are conditioned at the required test temperature for at least 3 hours, prior to testing. This, in turn, would lead to water evaporation from emulsion-aggregate mixture specimens and curing would then be induced. Testing of lightly cured specimens at higher temperatures was therefore avoided. The test temperature for such specimens was 20°C.

For comparing the performance of later cured emulsion-aggregate mixtures with that of hot mixtures in the wheel tracker, testing was carried out at 40°C.

Two levels of bitumen content were used, 4 % and 5 %. All tests were carried out using applied wheel load of 554 N so that a contact stress of 650 kPa was achieved. The tests lasted for 8000 passes.

6.4.4 Test Results and Discussion

The measured permanent strains of the different mixture combinations are graphically presented in Figures 6-18 to 6-20. The following were observed:

1. Ultimate permanent strains of lightly cured emulsion mixture specimens were governed by the material performance during the initial phase of the test. Increasing the residual bitumen content from 4 % to 5 % caused an increased strain rate and the ultimate strain was apparently influenced by the performance of the material throughout the test.

2. At later stages curing, 36 days at room temperature (average 22°C), both the ultimate strains and mean strain rates decreased dramatically. A noticeable point is that the curing regime used did not influence the strain rate of the second phase of the test on the mixtures containing 4 % RBC, whereas it did on the mixtures containing 5 % RBC. The similarity in the resulting strain rates of both mixture combinations (4 % and 5 % RBC) at the later stage of curing indicates that the performance of such mixtures during the later phases of wheel tracking is less sensitive to the binder and is dominated by the aggregate structure. This explanation may be supported by comparing strain rates from

the mixtures containing 4 % RBC. Although different test temperatures used, similarity in the results was observed.

3. A lower RBC in a mixture, at each stage of curing, gives rise to a performance dominated by the frictional resistance of the aggregate matrix. In this case, the viscous component of the mixture is not sufficient to affect the strain rate, leading to better internal friction between the aggregate particles than that of the mixtures containing higher RBC. It should be remembered that voids in the mineral aggregate were similar for both mixtures.

4. As mentioned, fabricating specimens to similar VMA allowed comparison of the results of the different mixture combinations. By comparing the results of the cured emulsion mixtures with those of the hot mixtures, a significant difference in the material performance in the wheel tracker can be distinguished. In hot mixtures, bitumen content has a great influence on the mixture response, much more so than in cured emulsion mixtures. Therefore, ranking of materials and investigating the effect of bitumen content in hot mixtures can be done using the strain rate parameter of the linear phase. The results generally showed higher rates of strain in hot mixtures during the duration of the test.

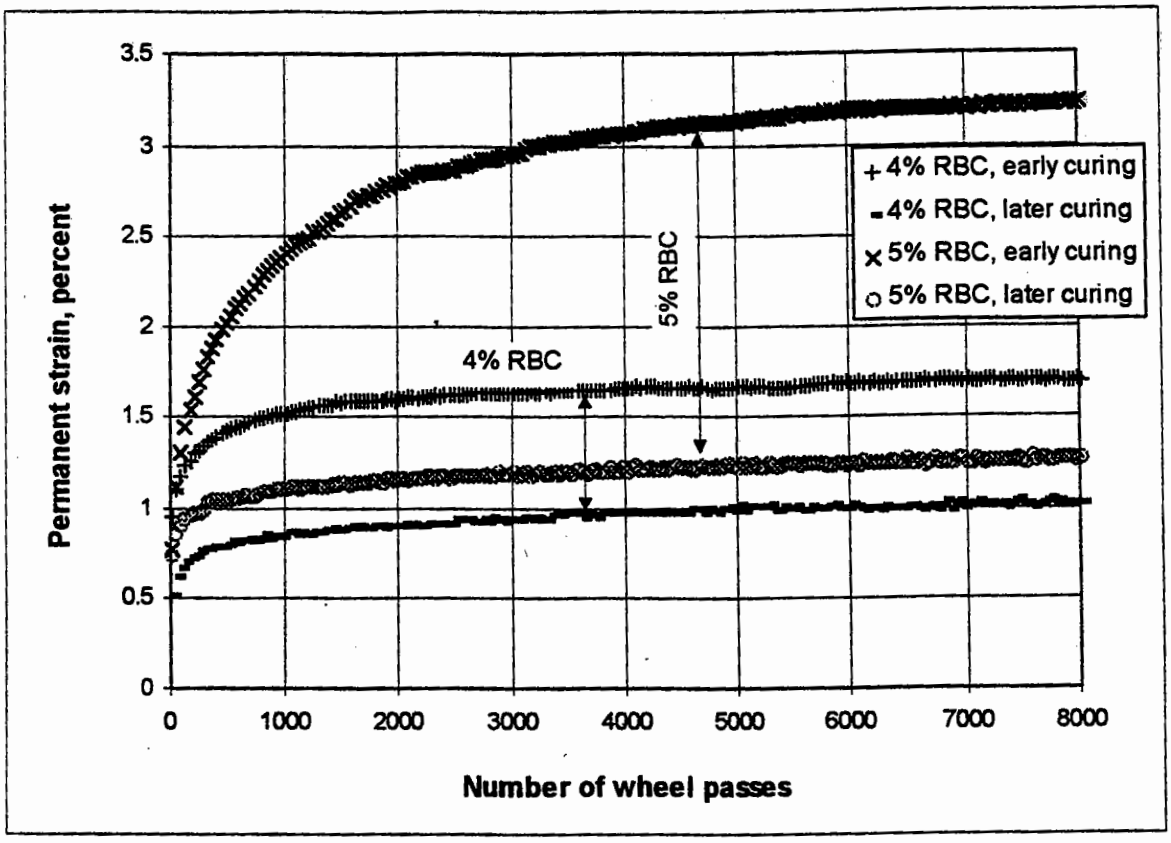


Figure 6-18 Wheel tracking test results on slabs containing 4% and 5% RBC cured for 3 days and 36 days in the mould (test temperature 20° for 3 day curing and 40°C for 36 days)

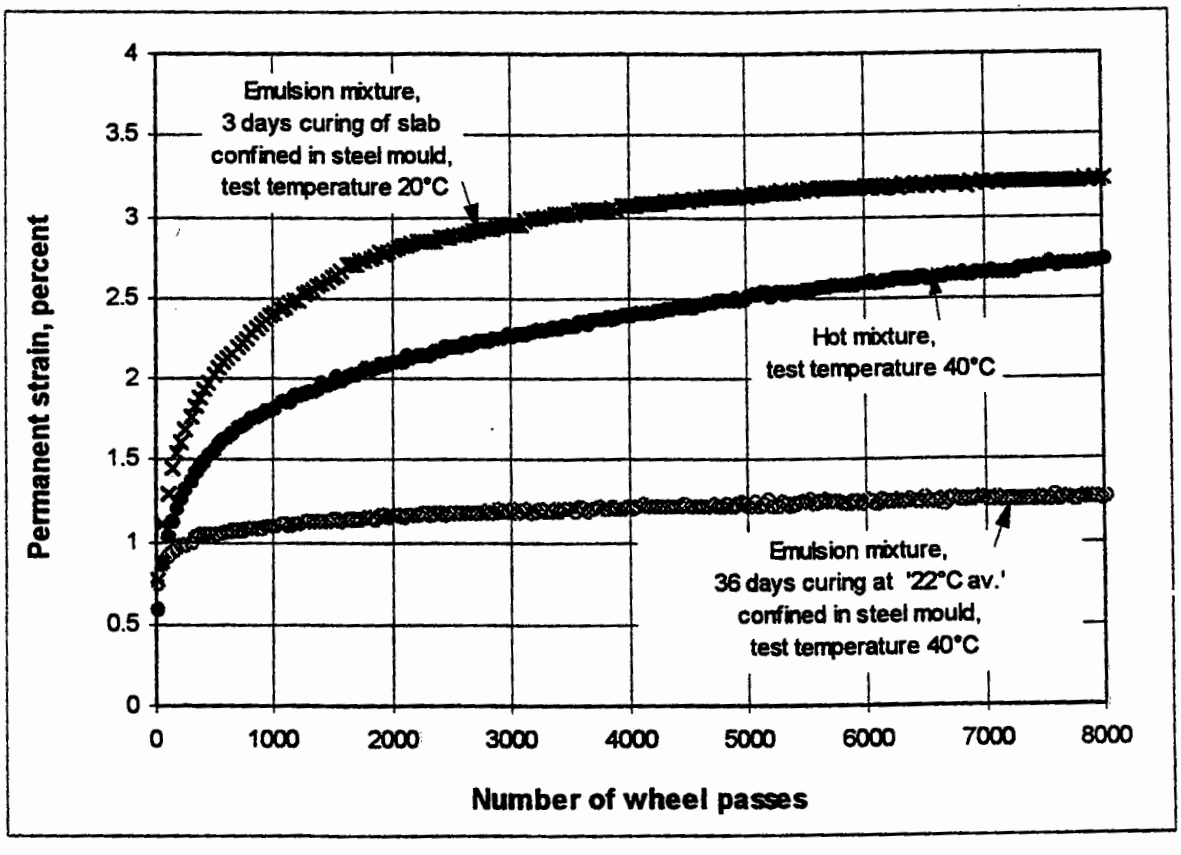


Figure 6-19 Wheel tracking test results on K-emulsion mixtures containing 4% RBC compared to results from hot bituminous mixture containing 4% BC

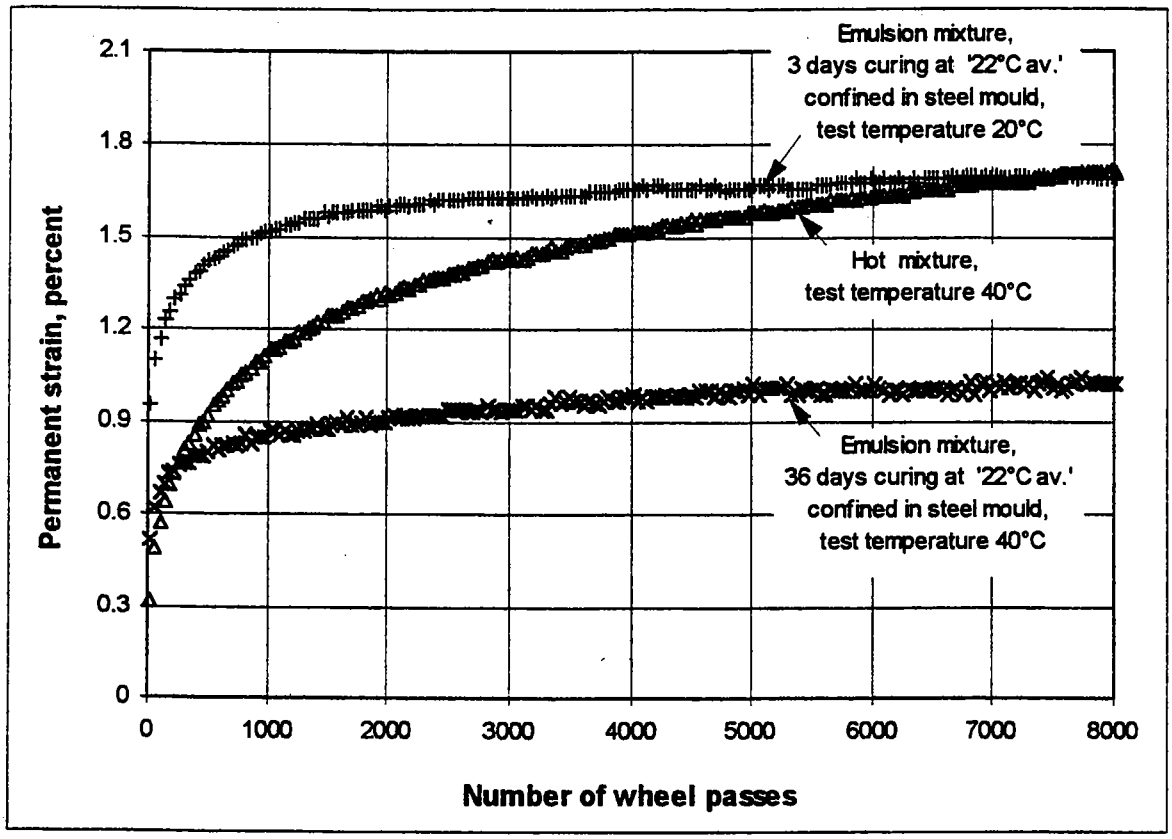


Figure 6-20 Wheel tracking test results on K-emulsion mixtures containing 5% RBC compared to results from hot bituminous mixture containing 5% BC

On the basis of the findings reported herein, it would appear that emulsion mixtures have better resistance to deformation than the corresponding hot mixtures, provided that sufficient curing to the material is achieved. Any permanent deformation problem in emulsion-aggregate mixtures will come mainly from its performance at early curing stages. Since the deformation resistance of such mixtures will be affected by the deformation occurring at early life, realistic deformation parameters could be found by combining both early and later deformations.

Given that performance of emulsion aggregate mixtures is influenced by the overall response during curing, the deformation performance of the material relative to hot mixtures will be dependent on the residual bitumen content. Using a lower RBC, e.g. 4 % RBC, an emulsion mixture deforms much more than a hot mixture during the initial phase of testing, resulting from densification of the material. But, because of its lower strain rate

at later stages relative to the hot mixture, the overall deformation will be less. On the other hand, in emulsion mixtures containing higher RBC, e.g. 5 % RBC, the deformation will be much higher than that of hot mixtures over the whole life of the material. Thus, using a lower RBC in emulsion aggregate mixtures is beneficial, as it may mitigate the problem of permanent deformation.

The above findings are based on the wheel tracking testing. Testing in the NAT showed a rather different trend of deformation characteristics, as there was similarity in the minimum strain rates of both types of mixtures, depending less on the RBC and curing time. Nevertheless, the overall strains in emulsion mixtures were higher than in hot mixtures, being affected by the response during the initial phase of the test. The reason for the difference between the results from the wheel tracker and the NAT may however relate to the confinement level. The more the confinement the greater the advantage of emulsion mixtures, because of their higher internal frictional resistance and reduced lubrication from the binder.

6.5 SUMMARY

Permanent deformation of an emulsion-aggregate mixture is dominated by the contained water content. At early stages of curing, the determined mean strain rate was high, mainly related to the performance of the material during the first phase of the test, in which densification and shear flow occur. During the second phase, the strain rates of K-emulsion mixture specimens, from the repeated load axial and triaxial testing were similar, for all curing levels and at different emulsion contents. On the other hand, results from the wheel tracking test showed different strain rates during the second phase of the test, depending on the emulsion content used. The overall performance of the material, in all test methods, was however affected by its response during the early stages of curing. Accumulation of permanent deformation during the curing period is therefore important and should be considered in mix design purposes. Considering the permanent deformation accumulation, a lower RBC in a mixture is beneficial, as it may reduce the overall permanent deformation relative to that of hot mixtures.

Emulsion-aggregate mixtures exhibit higher internal frictional resistance than hot mixtures. Triaxial testing with mounted LVDTs and an appropriate level of confining pressure (20 kPa is preferred) is therefore a suitable tool for assessing the material's resistance to permanent deformation, and to minimize the effect of the end constraints which inevitably develop.

The performance of this material in a larger wheel tracking test was also investigated in this research and will be discussed in Chapter 9.

CHAPTER

7 FATIGUE CHARACTERISATION IN THE INDIRECT TENSILE FATIGUE TEST

7.1 DEFINITION

It is recognised that cracking of bituminous mixtures can be categorised into two groups: load-associated and non-load-associated. The principal class of load-associated cracking has been described as fatigue cracking, the phenomenon of fracture under repeated or fluctuating stress having a maximum value less than the tensile strength of the material. However, the fatigue process usually occurs in two stages:

1. Crack initiation, defined as the merging of microcracks to form a macro-crack which then propagates. This stage is usually characterised using simplified laboratory tests representing the type of load experienced in pavements. Generally, the number of load applications to initiate fatigue cracking N_f is described as a function of the maximum tensile strain in the mixture as:

$$N_f = a\left[\frac{1}{\varepsilon_t}\right]^b$$

where:

ε_t is the maximum value of applied tensile strain.

a and b are factors depending on the composition and properties of the mixtures.

2. Crack propagation, the growth or propagation of a macro-crack. Less has been carried out in the laboratory on this stage of fatigue characteristic.

7.2 LABORATORY TEST METHODS

Fatigue of bituminous mixtures is generally characterised in repeated load tests on prepared specimens, either using a constant applied load or stress (termed controlled stress) or constant deflection or strain (termed controlled strain). In controlled stress type testing, the

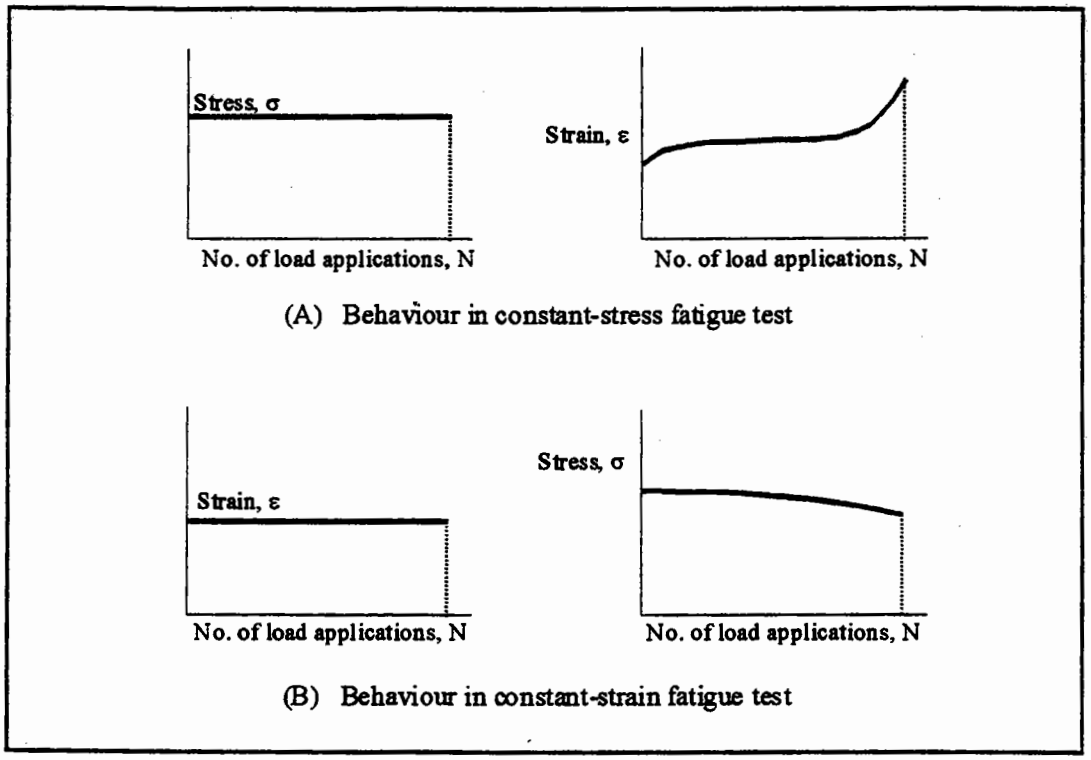


Figure 7-1 Variation of stress and strain in both strain and stress controlled fatigue tests

maximum load or stress is held constant during the test and the resultant strain or deformation increases until failure occurs. In contrast, for tests of the constant strain type, the maximum strain is maintained constant until fracture is reached. In this type of test, the stress or load decreases as the test progress, because of the stiffness reduction of the material that occurs associated with the progressive damage within the material during testing. Figure 7-1 shows the variation of the stress and strain in both modes of testing.

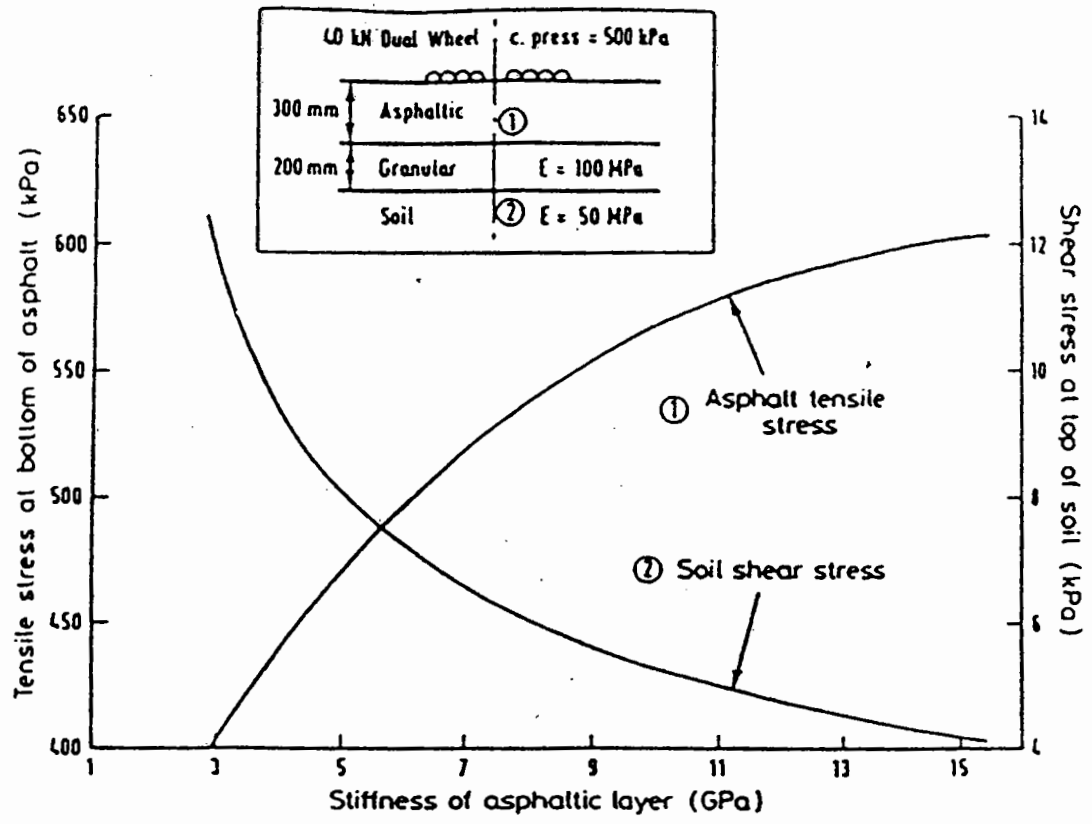
Many researchers have reported differences in the strain-life relationships from stress and strain controlled modes of testing. It has generally been reported that failure of specimens occurs very rapidly after initiation of a crack in a stress controlled test. However, a significant period of crack propagation is associated with strain controlled tests. The reason for that was explained by Brown (1979). The rate of crack propagation depends on the tensile stress intensity at the crack tip. The higher the stress intensity the more rapid the failure of a specimen after crack initiation. In controlled strain tests, the stress gradually decreases at the crack tip, leading to a significant time for cracks to propagate before failure.

However, in a pavement structure, the tensile strains generated in the bituminous layer are generally greatest at the bottom of the layer. According to Brown (1988), as indicated in Figure 7-2, the induced tensile strain at the bottom of the asphalt layer decreases as stiffness increases which, in turn, retards crack initiation. In contrast, stiff material attracts to its underside large tensile stresses which, in turn, result in a rapid crack propagation. In support of this, through laboratory work on crack propagation in bituminous mixtures, Read (1996) showed that the life of a specimen to crack propagation is dependent on its initial stiffness. A greater resistance to crack propagation was found for materials with low initial stiffness. Accordingly, materials with low elastic stiffness values exhibit more rapid crack initiation and a longer process of crack propagation but possess poor load spreading qualities.

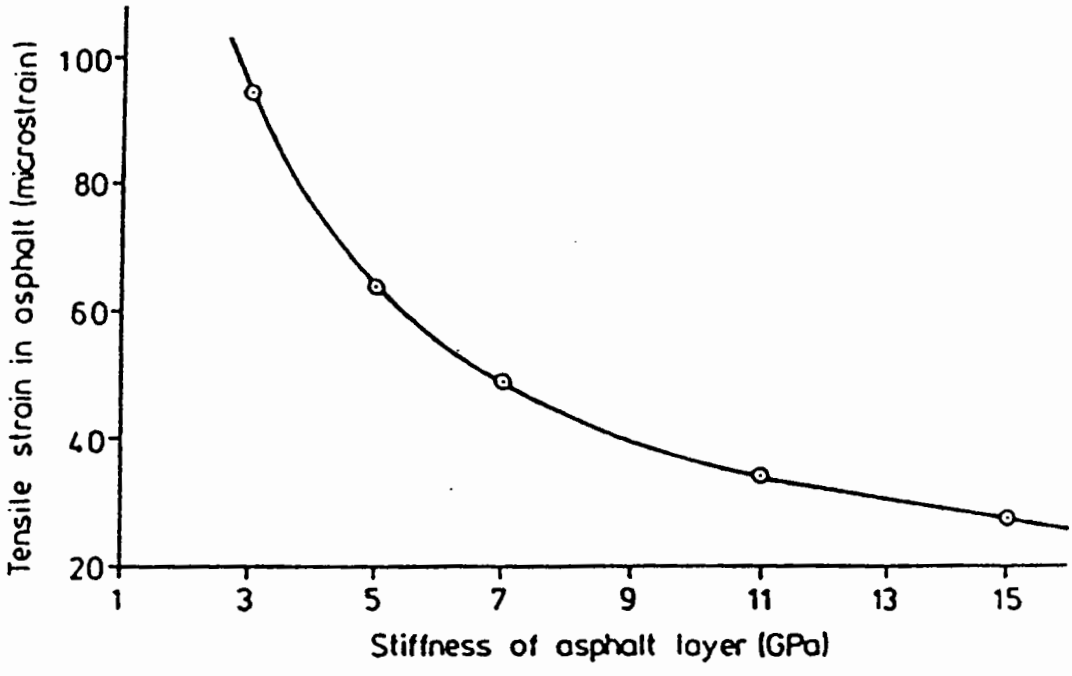
Comparative evaluation of stress and strain controlled tests taken from Rao Tangella et al (SHRP project report, 1990) is presented in Table 7-1 and various fatigue test configurations used for characterising bituminous mixtures are described in Table 7-2.

Table 7-1 Comparative evaluation of stress and strain controlled fatigue tests (reproduced from Rao Tanglla et al, SHRP project, 1990)

Variables	Controlled stress (load)	Controlled strain (deflection)
Thickness of asphalt concrete layer	Comparatively thick asphalt bound layers	Thin asphalt-bound layer; < 3 inches
Definition of failure; number of cycle	Well-defined since specimen fractures	Arbitrary in the sense that the test is discontinued when the load level has been reduced to some proportion of its initial value; for example, to 50 percent of the initial level
Scatter in fatigue test data	Less scatter	More scatter
Required number of specimens	Smaller	Larger
Simulation of long-term influences	Long-term influences such as ageing lead to increased stiffness and presumably increased fatigue life	Long term influences leading to stiffness increase will lead to reduced fatigue life
Magnitude of fatigue life, N	Generally shorter life	Generally longer life
Effect of mixture variables	More sensitive	Less sensitive
Rate of energy dissipation	Faster	Slower
rate of crack propagation	Faster than occurs in situ	More representative to in-situ conditions
Beneficial effects of rest periods	Greater beneficial effect	Lesser beneficial effect



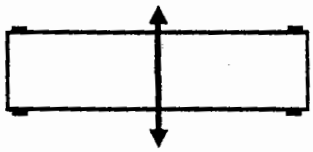
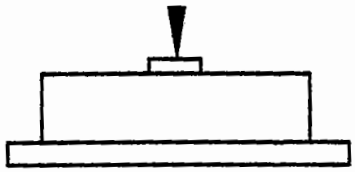
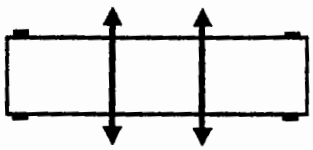
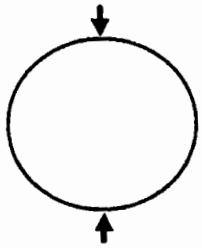
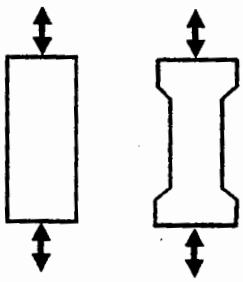
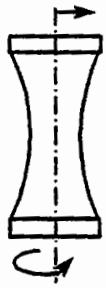
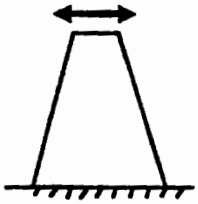
(a) Critical stresses



(b) Asphalt strain

Figure 7-2 Influence of asphaltic layer elastic stiffness (after Brown, 1988)

Table 7-2 Various test configuration used in Fatigue characterisation

Test	Loading Configuration / Stress state	Test	Loading Configuration / Stress state
Beam test (three point bending)	 Uniaxial	Beam on elastic foundation	 Uniaxial
Beam test (four point bending)	 Uniaxial	Indirect tensile	 Biaxial
Direct tension	 Uniaxial	Rotating bending beam	 Uniaxial
Trapezoidal beam (two point bending)	 Uniaxial		

7.3 FAILURE CRITERIA

Definitions of failure in stress and strain controlled tests are different. In a stress controlled test, it is generally taken to be the condition at which either the specimen has fractured or when the stiffness has reduced to less than 10% of its initial value. However, failure in a strain controlled test is often taken as the point when the stiffness has decreased to 50% of its initial value.

Rowe (1996) presented another way of defining fatigue life to the point of crack initiation for both testing modes, using the dissipated energy concept. This simply involved plotting the number of load cycles against the dissipated energy ratio. This was originally proposed by Hopman et al (1989) to define the number of cycles to crack initiation in a controlled strain test. The energy ratio is defined as:

$$R = n w_o / w_i \qquad \text{where:}$$

n is the cycle number,

w_o is the dissipated energy in first cycle,

w_i is the dissipated energy in cycle i.

Since bituminous mixtures behave in visco-elastic manner at ambient temperature, energy dissipates during loading and unloading. The area within the resulting hysteresis loop will be equivalent to the amount of energy dissipated for a single cycle of loading. In a purely elastic material, the relationship between stress and strain is linear and, consequently, the energy is stored in the system and no dissipated energy occurs. In a sinusoidally loaded bituminous mixture, the area within the stress/strain loop or rather the dissipated energy per loading cycle will be:

$$w_i = \pi \sigma_i \varepsilon_i \sin \delta_i \qquad \text{where:}$$

w_i is the dissipated energy in cycle i,

σ_i is the stress amplitude in cycle i,

ε_i is the strain amplitude in cycle i,

δ_i is the phase angle between the measured stress and strain in cycle i.

The energy ratio can then be rewritten as:

$$R = \frac{n(\pi \sigma_o \varepsilon_o \sin \delta_o)}{(\pi \sigma_i \varepsilon_i \sin \delta_i)}$$

By eliminating all constants in the above equation, which will not alter the shape of the life-energy ratio relationship, and change in sin δ which is very small, the resulting energy ratio will be as follows:

- *In strain controlled test*

R_ε will be proportional to $\frac{n\sigma_o}{\sigma_i}$, which can be rewritten as $R_\varepsilon \propto \frac{n(\varepsilon_0 E_o^*)}{(\varepsilon_i E_i^*)}$,

then $R_\varepsilon \propto \frac{n}{E_i^*}$ where E_i^* is the complex stiffness modulus in cycle i

- *In stress controlled test*

R_σ will be proportional to $\frac{n\varepsilon_o}{\varepsilon_i}$, which can be re-written as $R_\sigma \propto \frac{n(\sigma_o / E_o)}{(\sigma_i / E_i)}$

then $R_\sigma \propto n E_i^*$

Plotting the relationship between the number of cycles and the equivalent energy ratio according to the mode of test, reveals a change in the response at a number of cycles Ni, the point of initiation of crack.

7.4 AIM OF THE INVESTIGATION

Fatigue cracking has been reported to be another type of distress associated with emulsion mixtures (Ishai 1975, Khosla 1983, and Sabita 1993). On the other hand, Santucci (1983) and Lafon et al (1993), from the point of view of experience, stressed that emulsion mixtures with a resilient modulus less than 4000 MPa do not fail in fatigue.

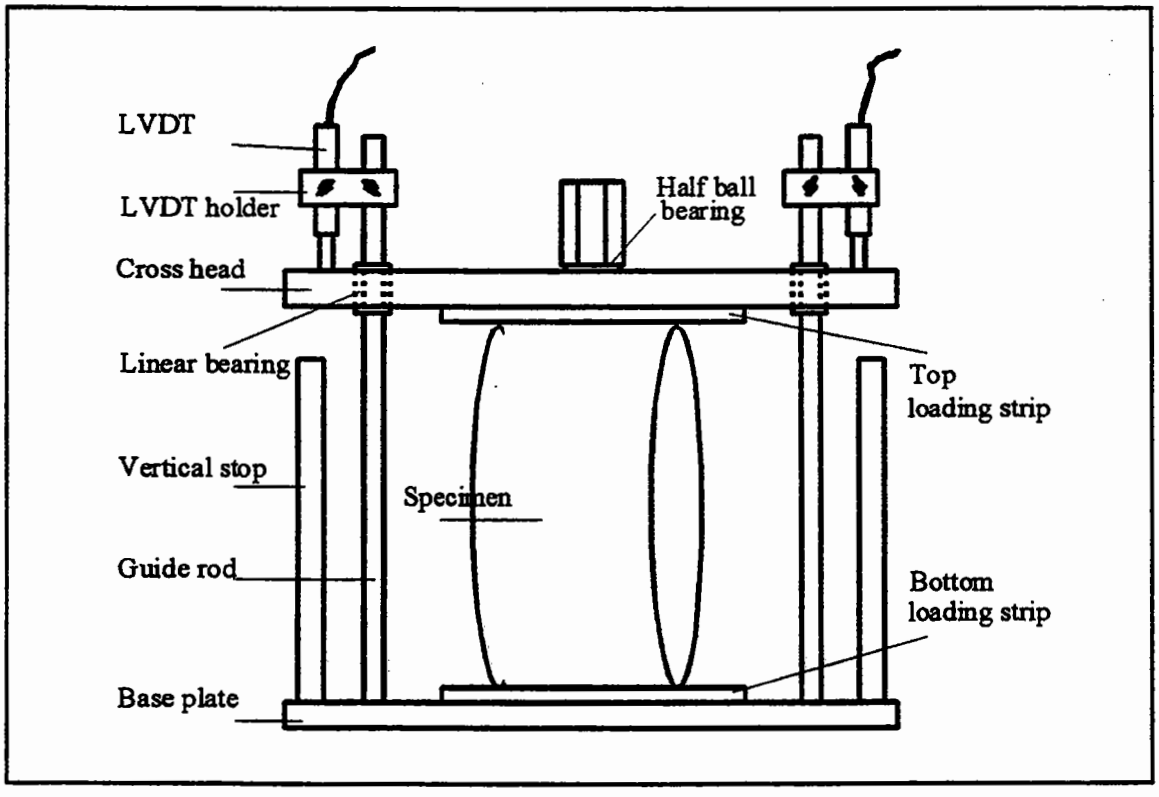
In this study, fatigue testing was conducted in the indirect tensile fatigue test 'ITFT' under controlled stress mode, to investigate the fatigue performance of K-emulsion mixtures at different curing times. Variables were residual bitumen content, curing time at 20°C, and density.

According to work carried out at the University of Nottingham on ranking materials using this configuration of test in the NAT, which was reported by Brown and Cooper (1993), it

can provide a quick and reliable assessment of fatigue characteristics. They reported good correlation for a DBM base course between results from the repeated load indirect tensile test and the trapezoidal bending test, which is one of the standard tests developed in research work. This finding was supported by Rowe (1996) and Read (1996). Also, Kim et al (1991) have shown test results of dense-graded asphalt concrete which were sensitive to test temperature and mixture variables, providing further evidence for the test's capacity to rank materials. Figure 7-3 shows a configuration of the ITFT assembly for testing in the NAT.

In addition, there are advantages to this test method relative to the other test configurations described in Table 7-2:

1. The test is simple to conduct.
2. Failure is initiated in a region of uniform tensile stress.
3. Specimen fabrication is simple.
4. Curing of specimens can be controlled.



Fatigue 7-3 Schematic diagram of the indirect tensile fatigue assembly for testing in the NAT

7.5 TEST PROCEDURE

It has been shown that mechanical properties of emulsion mixtures change over the curing period. Moreover, the material appears to have a significant variation in stiffness modulus depending on the applied load magnitude, resulting from not only the rheological response of the binder, or rather the non-linear viscoelastic nature of bitumen, but also from the occurrence of micro-structural damage, which dominates the material response. However, healing of the material occurs during the curing process leading to an increased stiffness. Nonetheless, it does not reduce the stress dependency and the material is greatly influenced by the applied stress level even after a long curing period.

Since fatigue testing in the ITFT mode in the NAT is carried out under controlled stress, this stress dependency of the material should significantly influence the test procedure. According to the British Standard (first Draft for Development, June 1996), which was developed for testing hot bituminous mixtures, calculations of strains are made by averaging stiffness moduli for different stress levels, corresponding to horizontal deformations up to 20 microns (see also Brown et al, 1995[a] & 1995[b], and Read, 1996). However, in testing emulsion aggregate mixture specimens, using an average value of stiffness modulus is no longer valid due to the significant effect of load magnitude. The stiffness at each stress level should therefore be determined prior to commencing the tests. This can be done by testing specimens for stiffness modulus in the NAT under stress control rather than the current horizontal deformation control. Another alternative is to carry out the test at different controlled deformations and to determine the resulting horizontal stresses, which can then be used in fatigue testing. Thus, the procedure used was as described in the flow chart presented in Figure 7-4.

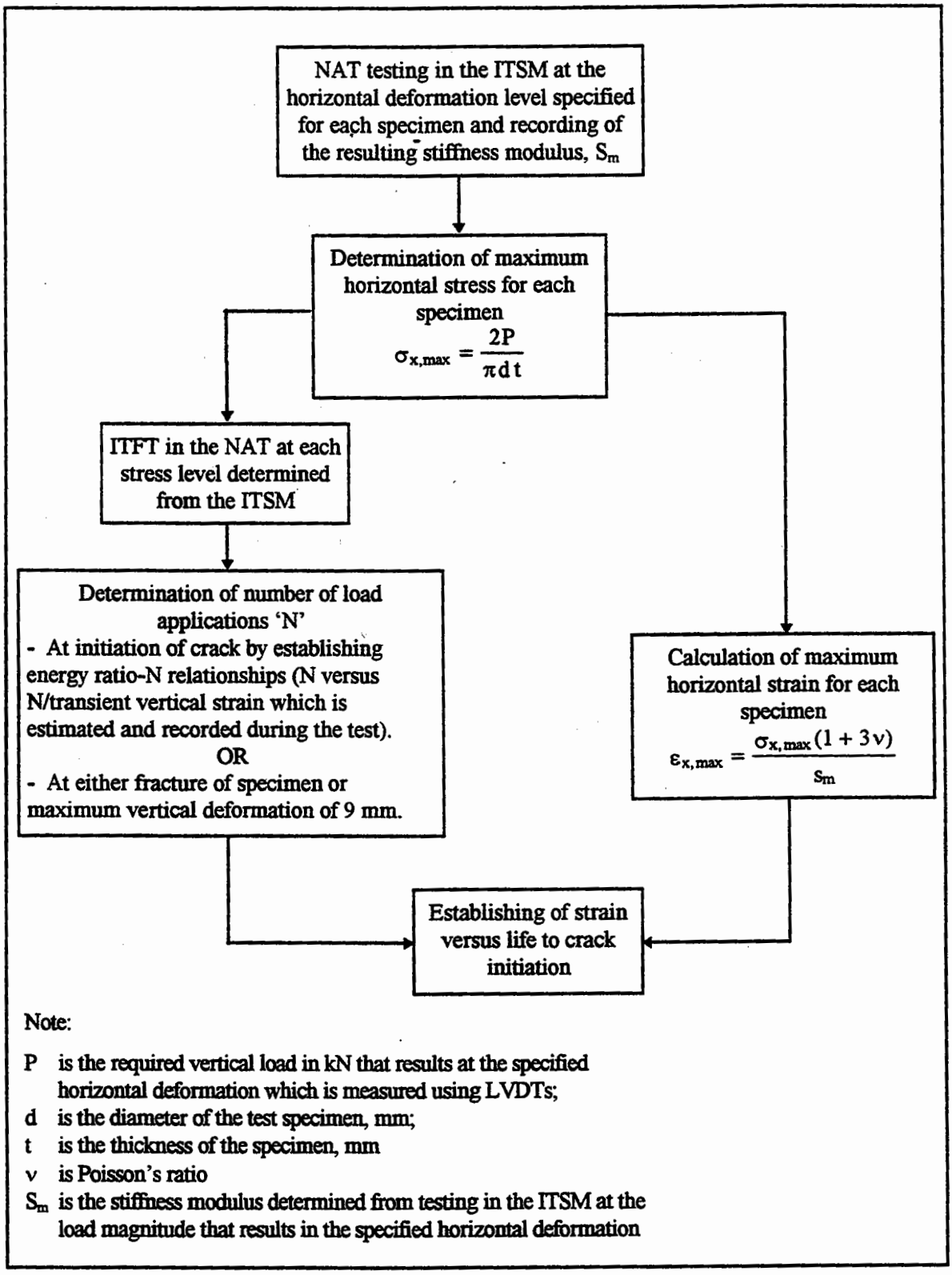
Different definitions of failure in the indirect tensile fatigue test have been reported. Kim et al (1991) reported a definition used by Scholz (1989) that, failure of cold recycled mixtures occurs when the permanent horizontal deformation reaches between 0.28 inch (7.1 mm) and 0.36 inch (9.1 mm). Kim et al (1991) found a dramatic increase in horizontal deformations after 0.1 inch for dense-grading asphalt mixtures

and reported that 0.1 inch (2.5 mm) maximum total horizontal deformation is appropriate. On the other hand, specimen rupture or a maximum vertical deformation of 9 mm was recommended by Brown et al (1995[b]) and Read (1996).

Using the permanent deformation of specimens as a failure criterion leads, of course, to considerable crack propagation, particularly in specimens containing higher residual bitumen content and in lightly cured specimens. To compare the fatigue performance of different mixture combinations at similar states of damage, defining fatigue life to the point of crack initiation is preferred. Therefore, relationships between energy ratio and number of load applications were established to enable determination of the point of crack initiation (N_i) of the tested specimens, the peak of energy ratio.

N_i was difficult to determine for some test results, on some mixture combinations, as it was not clearly defined. Since the tests in the ITFT were performed in the controlled stress mode, the remaining lives associated with crack propagation were relatively small. Typical plots are presented in Figures 7-5 and 7-6.

On the basis of the above discussion, the tests were carried out with a rise time of 120 ms at one load level for each specimen. In other words, testing using different load levels on the same specimen was avoided, as results would have been influenced by the higher load, as explained in Chapter 5. All tests were carried out until a maximum vertical deformation of 9 mm had been reached or fracture of the specimen had occurred.



Note:

P is the required vertical load in kN that results at the specified horizontal deformation which is measured using LVDTs;
d is the diameter of the test specimen, mm;
t is the thickness of the specimen, mm
ν is Poisson's ratio
S_m is the stiffness modulus determined from testing in the ITSM at the load magnitude that results in the specified horizontal deformation

Figure 7-4 Flow diagram of the procedure used in assessing the fatigue resistance

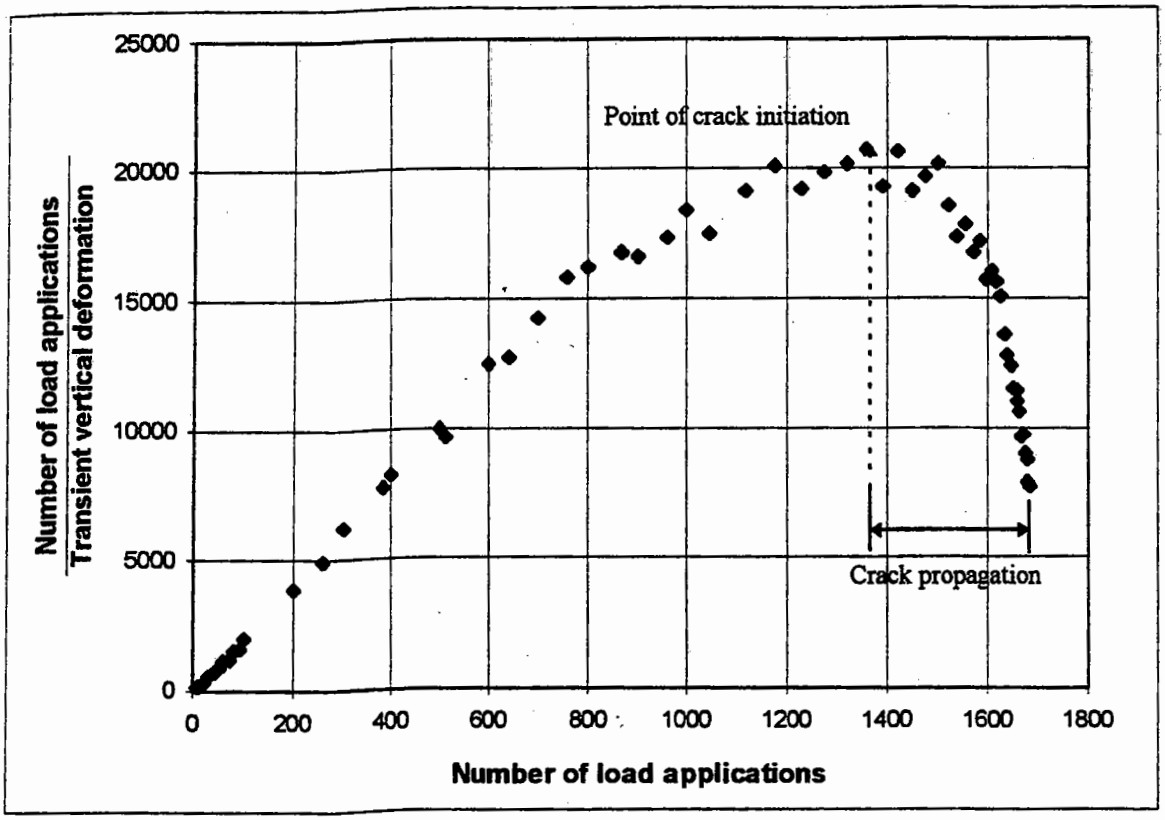


Figure 7-5 Crack initiation of specimens containing 5.2 % RBC of K-emulsion (early curing, test horizontal stress 50 kPa)

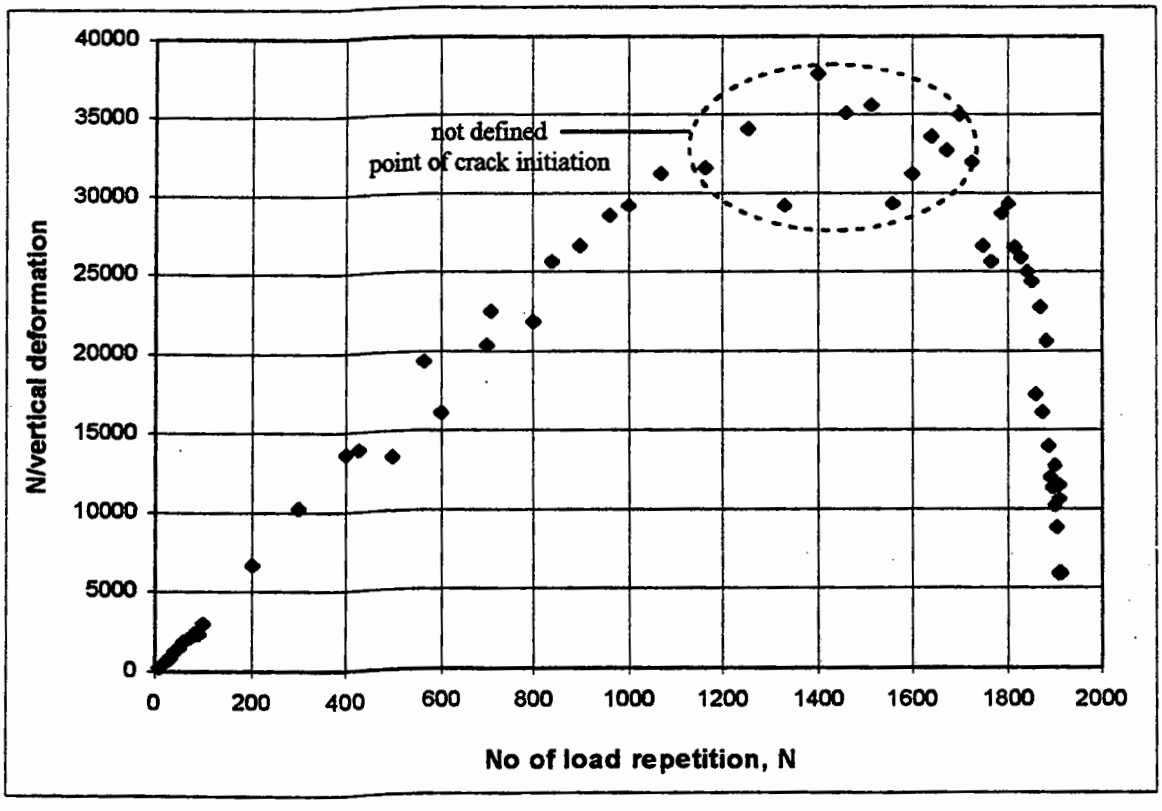


Figure 7-6 Crack initiation of specimens containing 4.2 % RBC of K-emulsion (early curing, test horizontal stress 50 kPa)

7.6 EFFECT OF RESIDUAL BITUMEN CONTENT

Specimens of K-emulsion mixtures with different RBC at mid-DBM grading were prepared in the vibrating compactor. The target voids content was 10 %. Tests were then conducted in the ITFT at 20°C as previously explained, after a short period of curing at 20°C, as shown in Figure 7-7, which presents the results as a function of initial strain ε. Regression analysis of the data was conducted using the general linear model: $\log \varepsilon = \log a + b \log 1/N$.

It can be seen that the resulting slope of the fatigue line is steeper for the mixtures containing a higher RBC. Generally, mixtures with higher RBC showed longer fatigue life at higher strain levels. At lower strain levels, which are more likely in the field, no significant influence of RBC on fatigue performance of the material could be distinguished. This result is not in agreement with the general concept of the effect of increasing bitumen content on the fatigue characteristic of bituminous mixtures reported by Pell (1974), Pell and Cooper (1975), and Rao Tangella et al (SHRP project 1990). This concept is shown in Figure 7-8, which indicates that increasing bitumen content leads to longer fatigue life, governed by crack propagation, illustrated by shifting of the fatigue line (log ε/log N) to the right, the shifting greater at lower strain levels.

This lack of agreement with work on hot mixtures may be attributed to the effect of water content incorporated within the mixtures, being higher in specimens containing a higher RBC. After testing, the fractured specimens gave the appearance of the bitumen having stripped from the coarser aggregate particles. It was then realized that the adhesion between the aggregate particles and the binder was not sufficient to resist the stress concentrated at the aggregate binder interface. Probably, the inevitable higher void content of this type mixture is another factor which may dominate the fatigue response of the mixtures, leading to lower influence from the binder content.

It is however expected that higher water contents and lower adhesion of binder and aggregate particles are associated with the increase of residual bitumen content in emulsion aggregate mixtures.

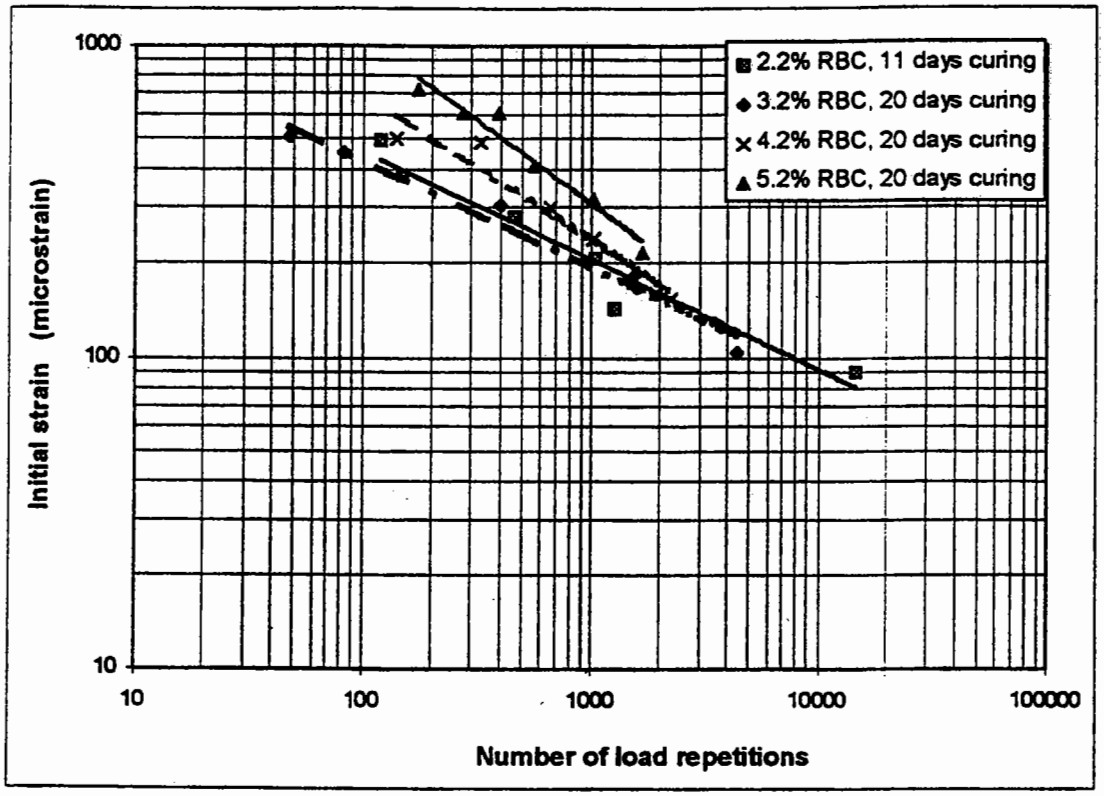


Figure 7-7 The effect of residual bitumen content on the fatigue resistance of emulsion-aggregate mixtures (Testing in the ITFT, test temperature 20°C)

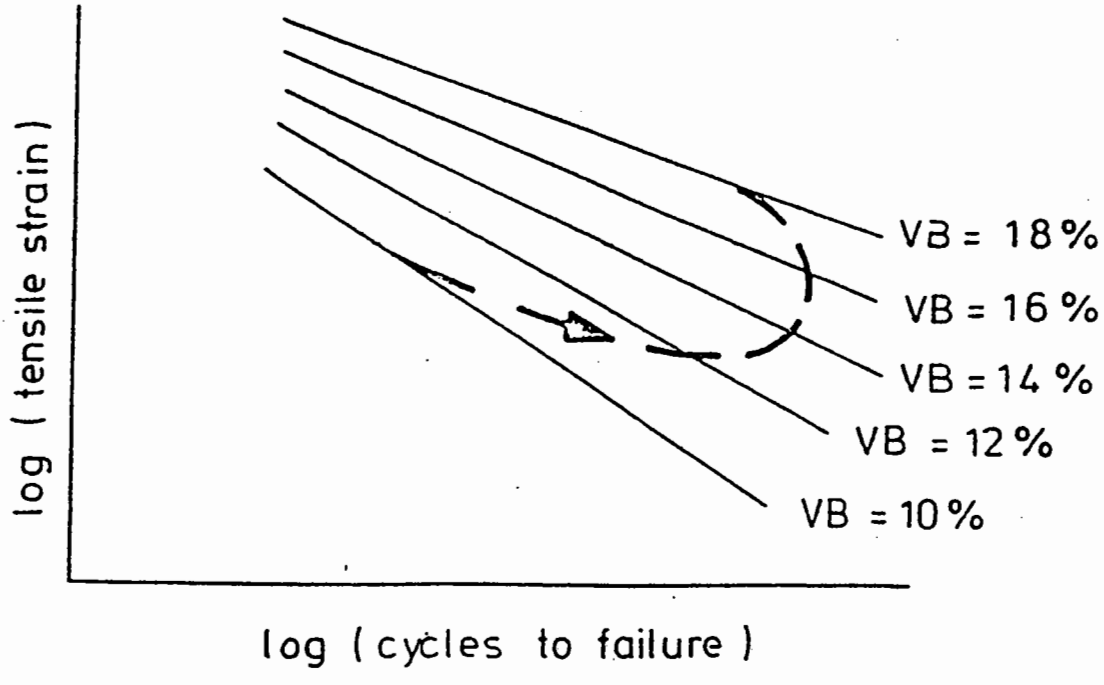


Figure 7-8 Effect of binder content on fatigue life (after Pell, 1974)

7.7 EFFECT OF VOIDS CONTENT

The qualitative influence of air void content on the fatigue response of bituminous mixtures has been the subject of much research. It has been concluded that the higher the air void content the lower the fatigue resistance of the material. By reducing the voids in a mixture, its stiffness modulus will be increased; consequently, the resulting strain will be smaller at a given stress level, leading to longer fatigue life. That is, the point representing fatigue life at a smaller strain moves down the basic $\log \varepsilon$ - $\log N$ line. Kim et al (1991) explained that, a higher air void content provides better probability of void coalescence, faster crack propagation, and therefore, a shorter fatigue life. Also, Epps and Monismith (1971) suggested the importance of the size, degree of interconnection, and shape of voids in relation to fatigue resistance.

To account for the effect of voids content quantitatively, Santucci (1977) presented the formula "$N_C = N_f \times 10^M$" based on data from fatigue test results on hot bituminous mixtures from many sources, to account for the influence of air void content in a mixture, where:

- N_C is the corrected number of repetitions to failure;
- N_f is the number of repetitions to failure of a controlled mixture (air voids, V_V = 5 %, and bitumen content by volume, V_B = 11 %), shifted from direct laboratory test results in controlled stress mode to account for crack propagation encountered in the field. A chart for the determination of N_f according to strain level and elastic modulus has been presented;
- $M = 4.84 \left(\frac{V_B}{V_V + V_B} - 0.69\right)$

The above formula has been claimed to be applicable to hot bituminous mixtures, emulsified bituminous mixtures, and cement-modified emulsified bituminous mixtures. Clearly, increasing air void content decreases the fatigue life. For example, in a mixture with bitumen content V_B = 11 % by volume, increasing air voids V_V from 5 % to 10 % will

reduce the number of repetitions to failure by a reduction factor of 0.1569, provided that both mixtures have similar elastic modulus.

However, the literature reveals no data for the influence of air voids on the fatigue performance of emulsion aggregate mixtures. The investigation in this study involved fatigue testing in the ITFT on specimens containing 5.2 % RBC and compacted to the level that results in a voids content of 8%, during which the water contained in the mixture was allowed to drain. The results were then compared with those for a similar mixture combination with higher voids of 10.5 %. The results are presented in Figure 7-9.

As has been seen, reducing the mixture void content results in an increase in the stiffness modulus of the material and therefore increase in the fatigue life, as the resulted strains were lower. Conversely, lower fatigue lives were observed at higher strain levels. It is likely that reducing the voids to 8 % has not influenced the binder-aggregate interaction, leading to similar adhesion condition between them. As a result, the points were close to the basic fatigue line of that containing higher voids.

In comparing the fatigue line of the mixture containing 5.2 % RBC and 8 % voids (Figure 7-9) with that of the mixture containing higher voids (approximately 10.5%), no noticeable influence resulted from increasing RBC or reducing the voids content to 8 %. Undoubtedly, better fatigue response of emulsion-aggregate mixtures requires reducing much of the voids to the level that squeezes out the water from the mixture and leads to a better bond between the aggregate and the binder. However, no further reduction in the voids of the mixture has been attempted, as it will not be realistic. The current practices show that field compaction of emulsion-aggregate mixtures, even under controlled conditions, leads to much higher voids than the experienced with hot bituminous mixtures.

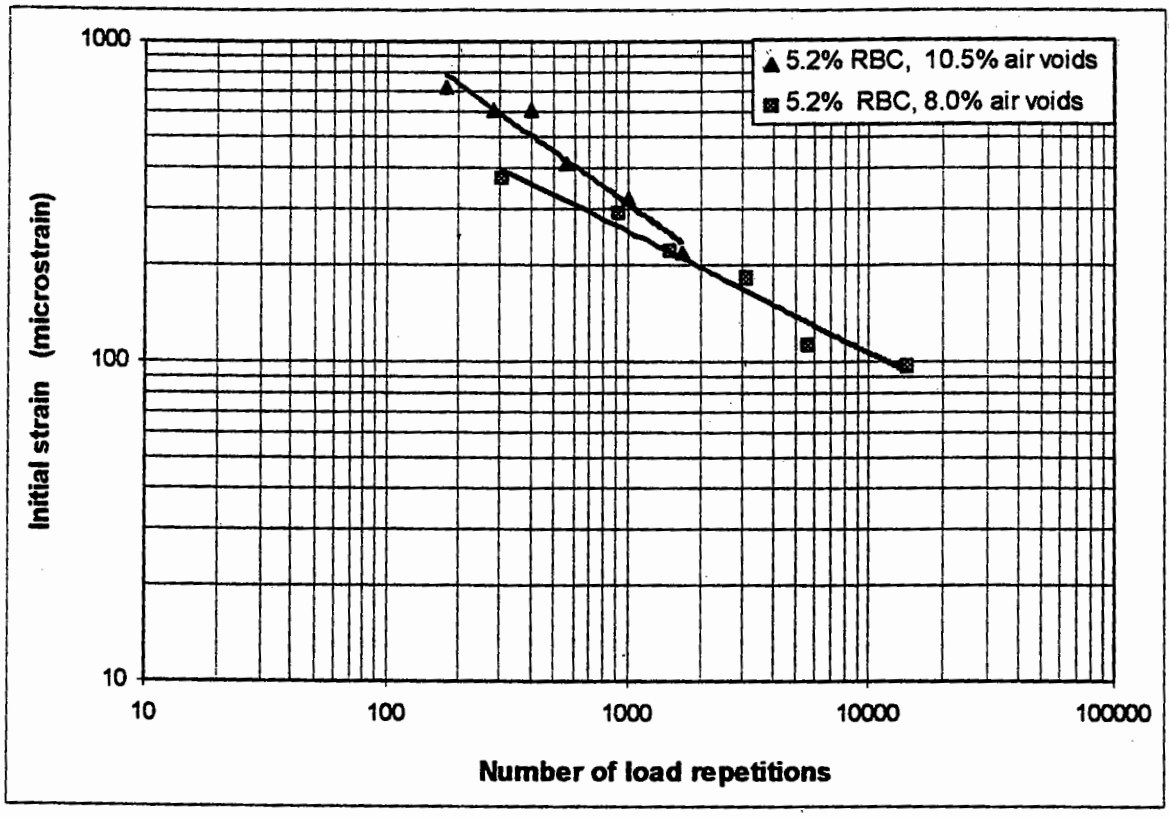


Figure 7-9 Effect of increasing compaction on fatigue response of mixtures containing 5.2 % RBC

7.8 EFFECT OF CURING

K-emulsion mixture specimens containing 3.2% and 4.2% RBC, cured for 20 and 100 days at 20°C, were tested using the NAT in its fatigue mode. The results, as a function of strain, are shown in Figure 7-10. As shown in the figure, the determined fatigue line slopes of the specimens cured for 100 days were found to be slightly less than those of the specimens cured for 20 days. In other words, curing of specimens after 20 days has limited influence on the slope of the fatigue line. Crack initiation had the major influence on the resulting fatigue lives. The results of the 100 days old specimens lay lower down the fatigue line, due to the increased stiffness of the material.

As previously discussed, with curing, water evaporates, hardening of the binder occurs and, presumably, adhesion build-up increases. Given these changes in the material's micro-structure, the fatigue lines would have been expected to shift to the right of the basic fatigue

line of the lightly cured specimens. The results reported herein seem to have been influenced by the higher voids content within specimens and imply insufficient cohesion build-up in the mixtures.

Regression analysis of the combined data of both early and later stages of curing was conducted, for each mixture combination. As shown in Figure 7-11, the correlation coefficients 'R^2' were 0.9288 and 0.96 for specimens containing 3.2 % and 4.2 % RBC respectively, which are statistically acceptable.

Thus, curing time influences the stiffness modulus of the material, resulting in lower strain at a given stress level and longer fatigue life. However, this does not influence the characteristics of the fatigue line of an emulsion mixture combination with high voids in it. Based on the findings of this research, the indirect tensile fatigue test can be conducted on emulsion-aggregate mixtures at any curing time after an equilibrium condition of water within the material is reached, regardless the stiffness state.

Residual Bitumen content (RBC)	Curing time, days	Intercept	Slope	R-square
3.2 %	20	2091	0.3428	0.975
	100	1468	0.3244	0.9763
4.2 %	20	6141	0.4716	0.938
	100	2594	0.3889	0.9583

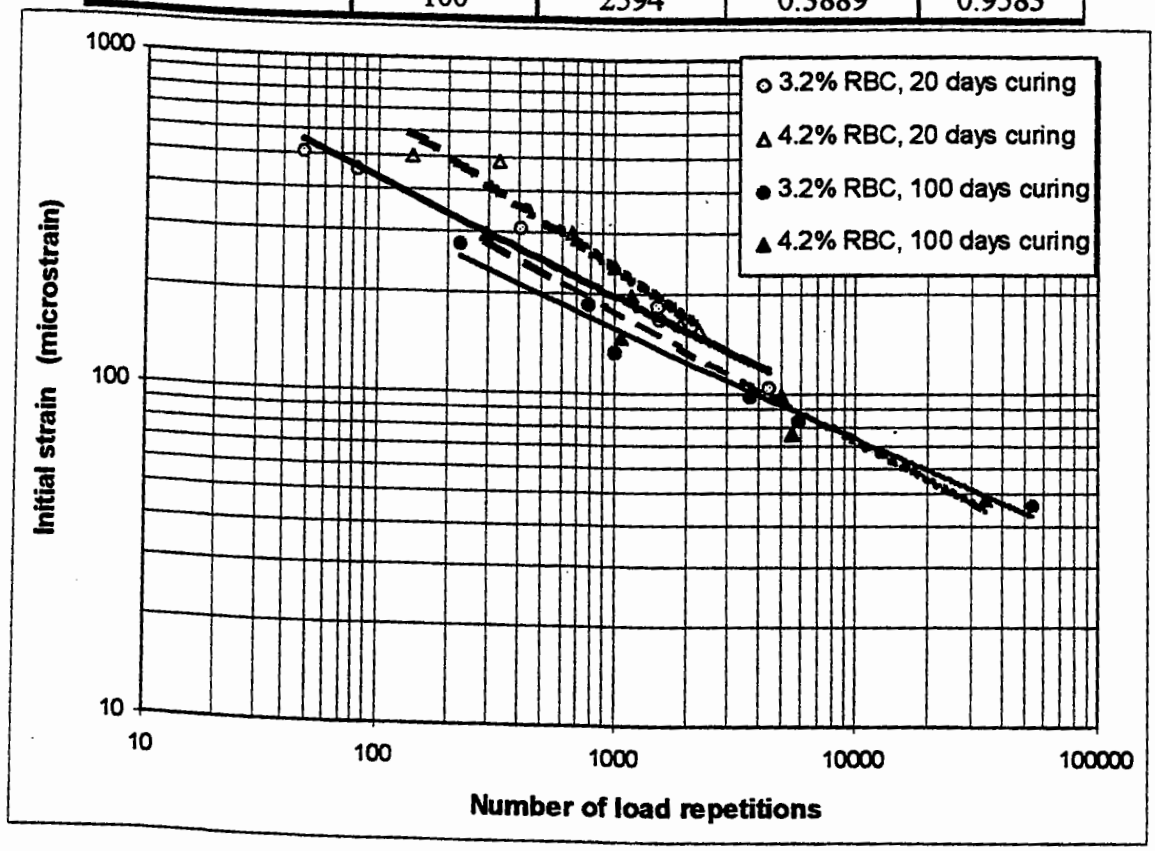


Figure 7-10 Fatigue test results of K-emulsion mixtures at two different curing times (test temperature 20°C)

Residual Bitumen content (RBC)	Intercept	Slope	R-square
3.2 %	2100	0.3584	0.96
4.2 %	5035.5	0.4586	0.9288

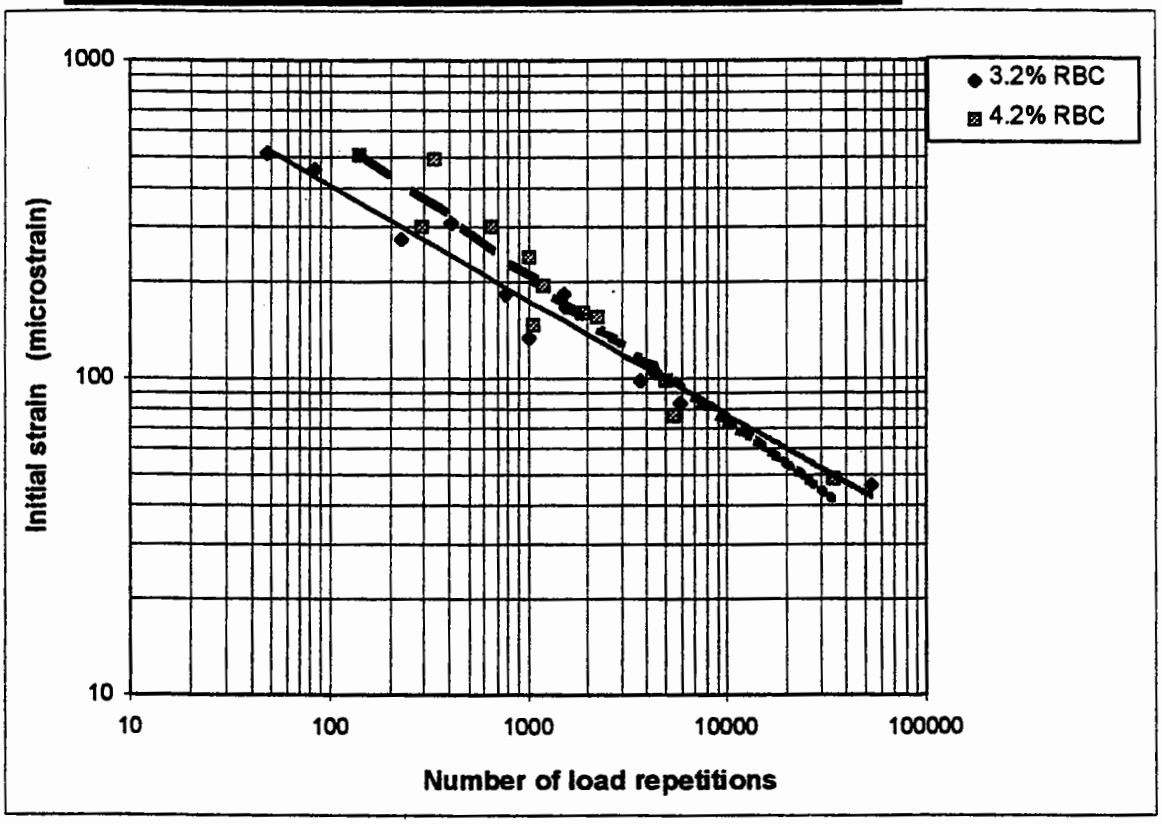


Figure 7-11 Effect of combining the early and later test results on the fatigue lines

7.9 SUMMARY

Indirect tensile fatigue testing has been reported to be sensitive to hot bituminous mix variables and to correlate well with standard tests such as trapezoidal fatigue test. The test is run in the NAT under controlled stress. This practical mode of testing was employed to study the effect of mix variables and curing time on the fatigue resistance of emulsion-aggregate mixtures containing mid-DBM grading and K-emulsion type (voids content 10.5%). Generally, the mixtures showed poor fatigue resistance whatever the level of RBC (2.2 - 5%). Reducing voids content of mixtures containing 5% RBC, down to 8%, did not change the adhesion condition between the binder and the aggregate particle, and resulted in similar basic fatigue lines. Curing increased the stiffness modulus of the material and therefore gave increased fatigue life at a given stress level, but the points still lay on the same strain versus life fatigue line. As expected, poor adhesion build up in the mixtures is the main reason for this poor fatigue performance. Unless the voids content reduces to a level at which the adhesion between the binder and the aggregate particles increases, the material's resistance to fatigue will be limited.

CHAPTER

8 WATER RESISTANCE OF EMULSION-AGGREGATE MIXTURES

8.1 INTRODUCTION

Pavement structural layer materials are exposed to various environmental factors which affect their structural integrity. Moisture is a damaging factor which leads to durability problems with emulsion aggregate mixtures. Two mechanisms may be attributed to mixture degradation due to moisture which, to a great extent, depends on curing time and condition: a) softening of the binder, or rather, loss of cohesive strength and stiffness in the bitumen film, which may be due to several mechanisms, and b) loosening of the adhesive bond between aggregate and bitumen.

Water sensitivity tests on bituminous mixtures can be divided into two categories:

- Tests carried out on loose 'uncompacted' mixtures by immersion in water, either at room temperature or brought to the boil. Assessment is then made by visual inspection of the percentage separation of bitumen from aggregate.
- Tests carried out on laboratory compacted specimens or cores by water conditioning to simulate field conditions and then determination of mechanical properties. Usually, the conditioned (or retained) to unconditioned stiffness or strength ratios are evaluated.

Most of the current test methods applied to bituminous mixtures attempt to simulate the strength loss that may occur in the field to identify the mixture combinations which are susceptible to water. Using these mixtures in a pavement causes premature distress and ultimately failure before its design life is achieved, due to moisture damage. However, for mixture design purpose, the conditioning process need not necessarily simulate field conditions but should accelerate the rate of strength loss.

Since emulsion aggregate mixtures possess different properties over the curing period, as previously discussed, the procedures currently used for assessing bituminous mixtures

should not be applied unless the material reaches a fully cured condition and behaves in a similar way to hot bituminous mixtures.

8.2 AIM OF THE INVESTIGATION

Of interest to this study was whether mixtures having a relatively high stiffness modulus and a rapid increase in strength are influenced by moisture more or less than those having lower stiffness, and whether curing regime affects this property. Additionally, the effects of aggregate gradation, emulsion type, and load conditioning of the specimen were investigated. For this, the NAT in its indirect tensile and triaxial modes was used to obtain a ratio of retained stiffness modulus to unconditioned stiffness modulus.

8.3 CONDITIONING OF SPECIMENS

For determination of the appropriate water conditioning procedure for use in assessing the water susceptibility of the emulsion mixtures in this study, different preliminary conditioning regimes were applied on lightly cured (5 days at 20°C) and oven-cured (2 days at 48°C) specimens, included:

1. Vacuum saturation at 510 mm Hg for 30 min and 1 day immersion in a water bath at both 20°C and 60°C (water head 210 mm).
2. Vacuum saturation at 355 mm Hg for both 15 and 30 min and one day soaking at both 20 and 60°C.
3. Vacuum saturation at 100 mm Hg for 1 hour as recommended by the Asphalt Institute (1979) and 1 hour soaking at 20°C.
4. Immersion in a water bath for different periods of time at 20°C.

The degrees of specimen saturation were above 50%. During testing of the conditioned specimens using regimes 1 to 3, the lightly cured specimens failed. Therefore, it was decided to use regime number '4' for the purpose of comparing the stiffness moduli of the specimens of different mixture combinations, either cured at 20°C or oven-cured at 48°C.

RESPONSE IN THE INDIRECT TENSILE MODE

Effect of Curing

The specimens, which had been cured for different times, were conditioned by immersing them in a water bath under a constant water head of 22 cm at 20°C for 24, 48, 72 and 96 hours. The results are presented in Figures 8-1 to 8-3.

The following points can be drawn:

- As expected, the retained stiffness modulus of the K-emulsion and EN998 mixture specimens increased and the absorbed water content decreased with the curing time (Table 8.1).
- K-emulsion mixture specimens exhibited little water resistance until a curing time of approximately 40 days. After 40 days of curing, the resistance to water was limited.
- Although K- emulsion mixture specimens gained some water resistance after curing at 20°C, the stiffness modulus decreased rapidly with the soaking period.
- EN998 specimens gained a resistance to moisture action at a very early stage of curing.
- A point of interest is that, even though K-emulsion specimens gained much of their final stiffness modulus at an early stage of curing and had higher stiffness than EN998 specimens at every stage of the curing process, they failed or had very low retained stiffness modulus after being soaked. A point to note is that the percentage coating of the K-emulsion specimens was the highest of all the emulsion mixtures used.

It is thought that the water absorbed by K-emulsion specimens has recombined again with the emulsifying agent which may have remained between the bitumen droplets and on the aggregate surface, which in turn has caused both bitumen softening and adhesion loss.

The reason why the EN998 emulsion mixture specimens have a much better water resistance, despite the fact that the stiffness modulus of such mixtures is less than the K-emulsion specimens, may be attributed to the residual bitumen distribution. Based on the percentage coating of the specimens and the above findings, it is believed that EN998

emulsion may be distributed in globules during the mixing process, which plugs up the voids between large particles, hence 'water-proofing' the mixture.

In addition, it may be noticed that oven curing emulsion mixture specimens at 48°C for 2 days improved their water resistance dramatically, even though the unconditioned stiffness moduli of such specimens and of those cured at 20°C were similar. This may be related to the effect of temperature on the interconnection between bitumen droplets resulting in a more continuous film of bitumen, water-proofing the mixture and giving more cohesion build-up.

However, the above discussion gives rise to the important point that oven curing emulsion mixture specimens at high temperatures is not a representative curing method and is therefore not suitable as a curing regime in assessing mixtures for water sensitivity. Also, the findings address the need for a further study to search for an additive to be used with emulsion mixtures to improve this property effectively.

Generally, the results indicate that DBM emulsion mixtures are not water resistant and provisions must be made to prevent water intrusion when such mixtures are used as a road's structural layer.

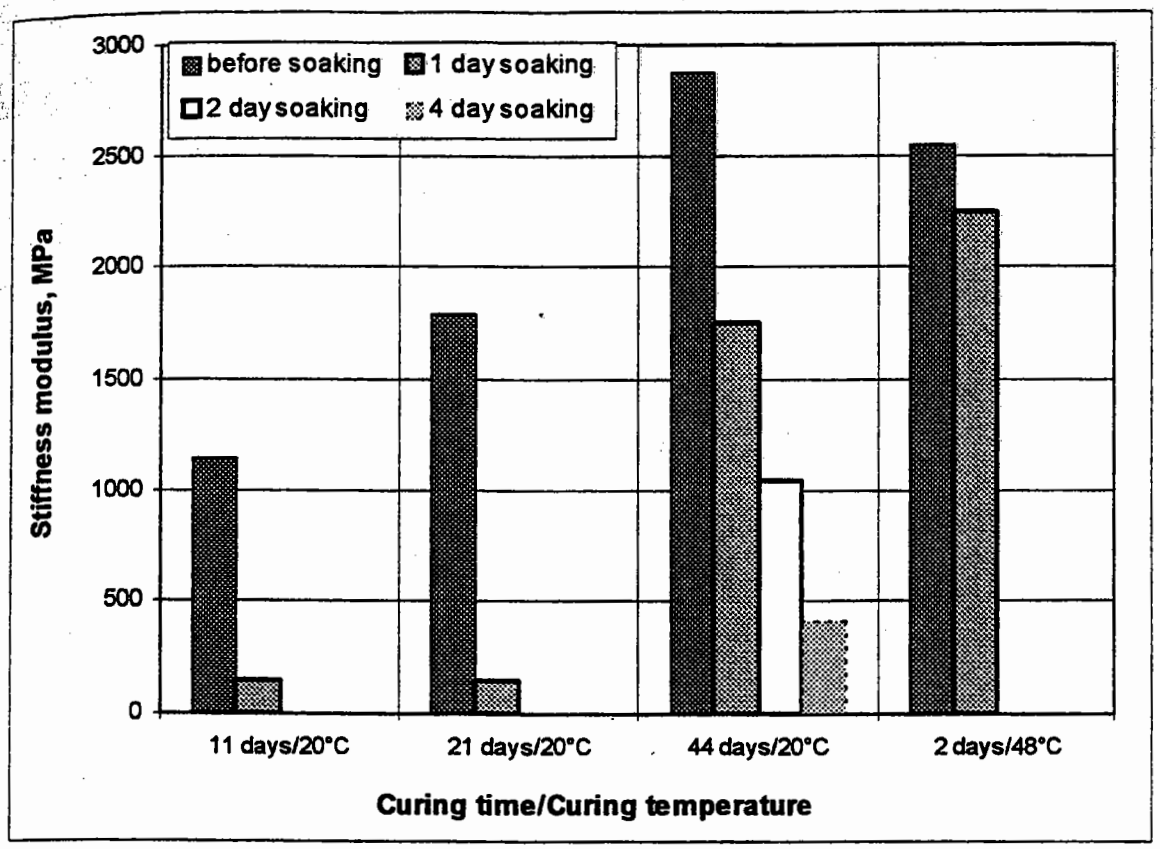


Figure 8-1 Effect of water on K-emulsion mixture specimens containing 3.2 % RBC and mid DBM grading

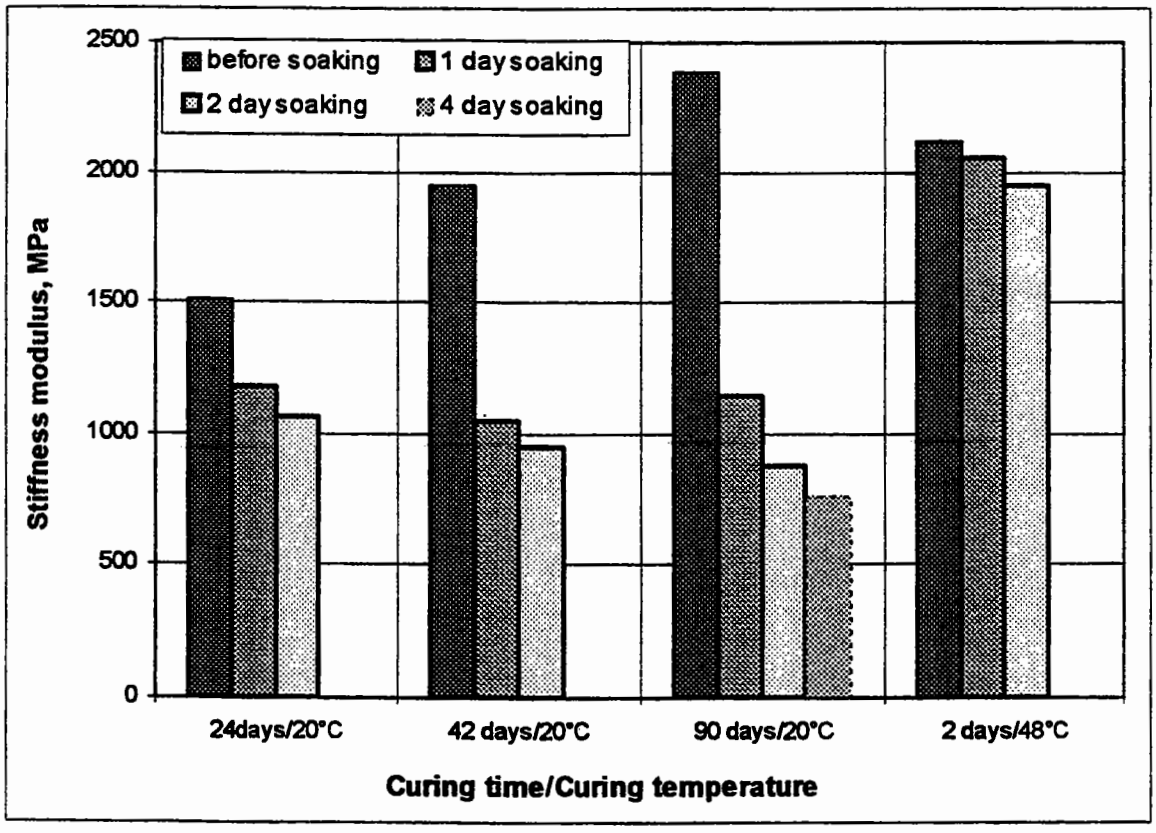


Figure 8-2 Effect of water on EN998-emulsion mixture specimens containing 3.2 % RBC and mid DBM grading

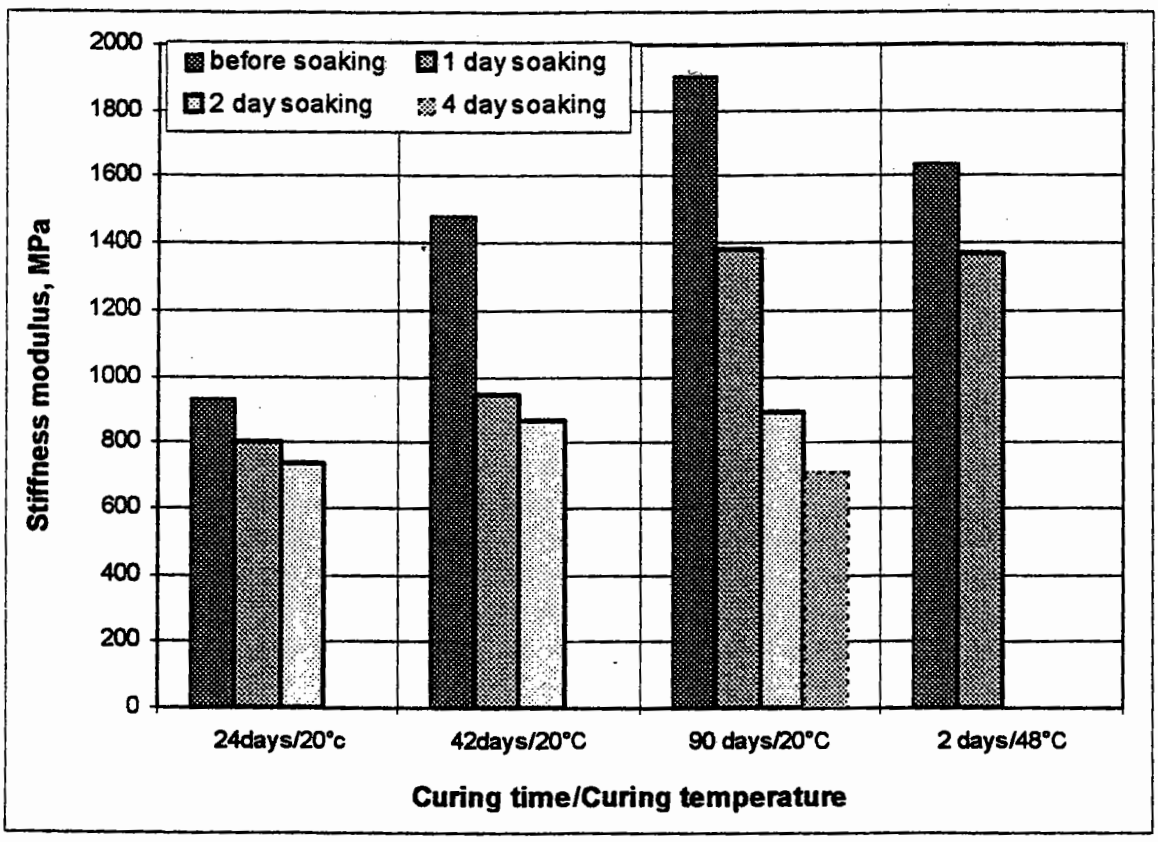


Figure 8-3 Effect of water on EN998-emulsion mixture specimens containing 4.2 % RBC and mid DBM grading

Table 8-1 Water content of specimens after one day soaking, percent

Curing time days	11	21	44	Oven curing 5 days at 48°C
K-emulsion mixtures (3.2% RBC)	2.917	1.583	1	0.72
EN998-emulsion mixtures (3.2% RBC)	2.083	2	1.67	1.08
EN998-emulsion mixtures (4.2% RBC)	1.42	1.55	1.25	0.17

8.4.2 Effect of aggregate gradation

Emulsion-aggregate mixtures have shown different stiffness responses in the indirect tensile mode of testing according to the composition used. The aggregate gradation has been shown to be a significant factor influencing the stiffness characteristic of the material. As seen in Figure 8-4, K-emulsion in a mid-DBM mixture showed a higher stiffness modulus than did the R-emulsion. On the other hand, the stiffness modulus of K-emulsion mixture containing C2-grading 'fine', relative to that of an R-emulsion mixture, was dependent on the RBC (Figure 8-5). At 5% RBC, the stiffness modulus was higher. At 6% RBC, stiffness moduli of both mixtures were to approximately similar. Generally, mixtures with C2 grading had higher stiffness than those with mid-DBM grading.

As shown in Figures 8-4 and 8-5, the resistance to water of the two mixture combinations was quite different. For mid-DBM grading, R-emulsion mixtures had higher resistance to water, according to the relative 'soaked to unsoaked' stiffness ratio, although the unsoaked stiffness moduli of these mixtures were lower. However, the C2-grading resulted in much higher relative stiffness than the mid-DBM grading. The C2-grading mixtures containing K-emulsion showed better resistance to water than those containing R-emulsion. For R-emulsion mixtures, the C2-grading did not give any improvement in the resistance to water.

This better behaviour of the C2-grading containing K-emulsion may be attributed to the material response during the compaction process (Chapter 4) and to the increased contact surface area of the aggregate particles. The benefit of using fine grading in a mixture is greatly dependent on the emulsion formulation used and its effectiveness in coating the fine particles. To put it another way, the best use of a particular emulsion type is dependent on the aggregate gradation used and this should be considered in the mix design process.

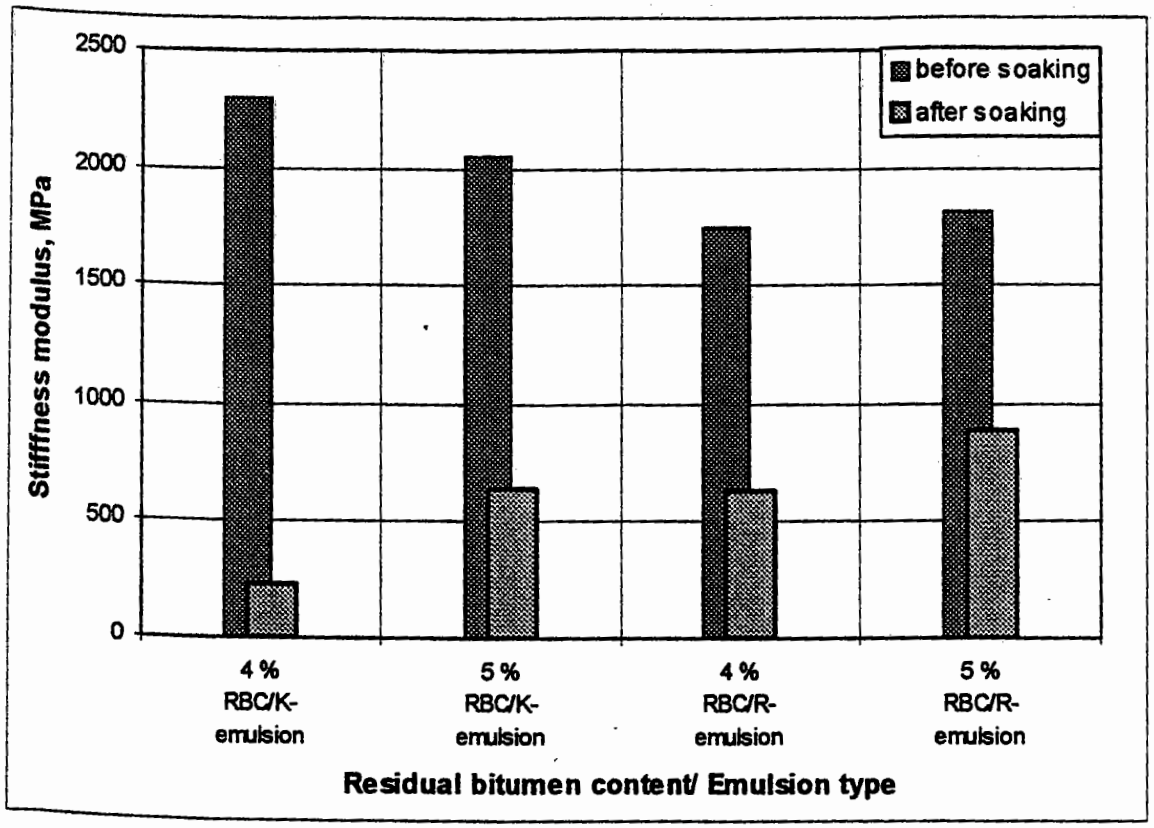


Figure 8-4 Unsoaked and soaked stiffness of mid-DBM mixtures
(curing for 54 days at 20°- soaking for 2 days at 20°C)

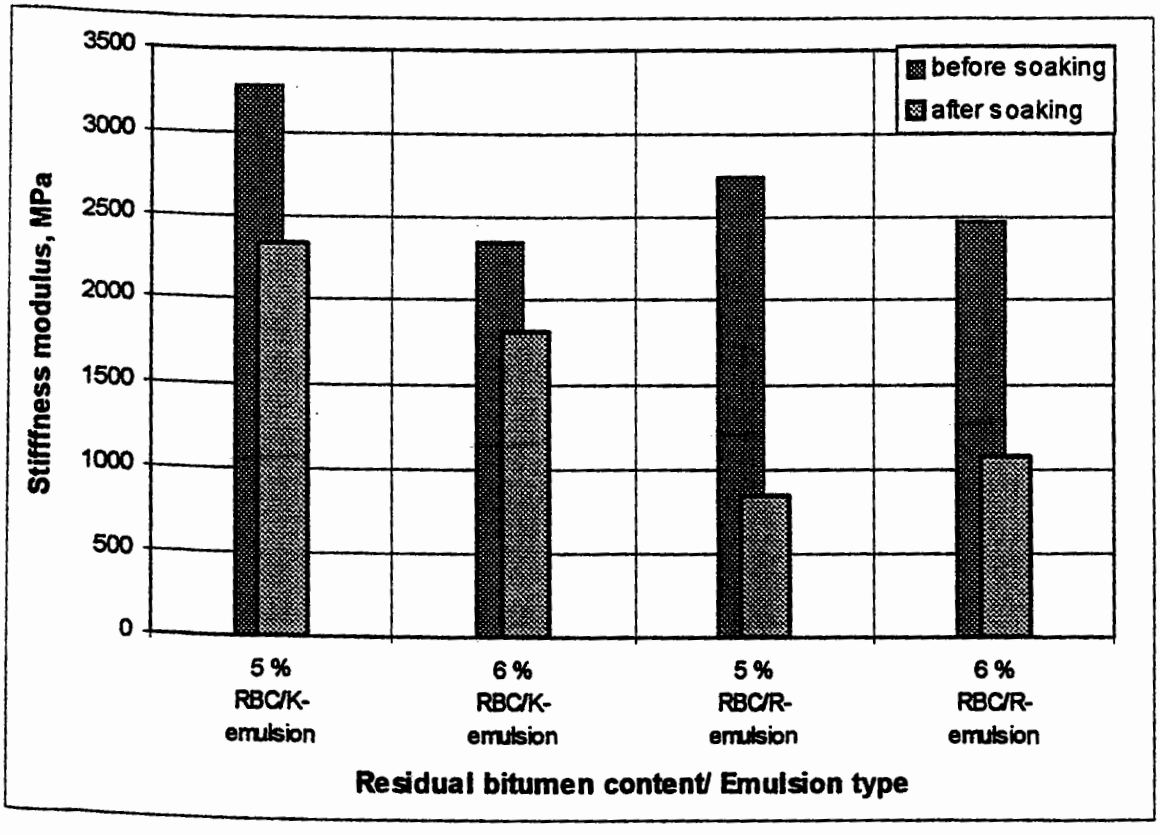


Figure 8-5 Unsoaked and soaked stiffness of C2-grading mixtures
(curing for 37 days at 20°- soaking for 2 days at 20°C)

Effect of Pre-Loading Level on Soaked Stiffness

As shown in Chapter 5 that the stiffness of emulsion mixtures is highly influenced by the applied load level. Reloading of specimens after testing them at a higher load level showed a decrease in the stiffness modulus. A possible explanation was that damage was occurring to the specimens. These specimens, however, showed a further increase in stiffness modulus during the curing process, indicating the possible occurrence of healing in the material.

To investigate this behaviour further, two different loading conditions were used in the determination of the soaked stiffness modulus as follows:

Condition A: the stiffness of specimens soaked for 2 days at 20°C was determined at a controlled horizontal deformation of 5 μm, after testing for unsoaked stiffness at similar horizontal deformation.

Condition B: specimens were tested at a controlled horizontal deformation of 5 μm for unsoaked stiffness after being loaded at higher load, resulting in a horizontal deformation of 20 μm. The stiffness of the specimen soaked for 2 days at 20°C was then determined at a horizontal deformation of 5 μm.

The soaked stiffness moduli under the two loading conditions were different (Figures 8-6 and 8-7). Loading condition 'B' showed lower soaked stiffness than loading condition 'A'. This indicates that the lower stiffness modulus, after a higher load was applied, is probably due to the formation of micro-cracks in the mixture, not only from the flow characteristics of the binder. Hence, the increase in stiffness occurring in the material during the curing time was mainly due to the curing process and evaporation of water, not due to any chemical or mechanical healing mechanism, as described for hot bituminous mixtures by Kim et al (1990).

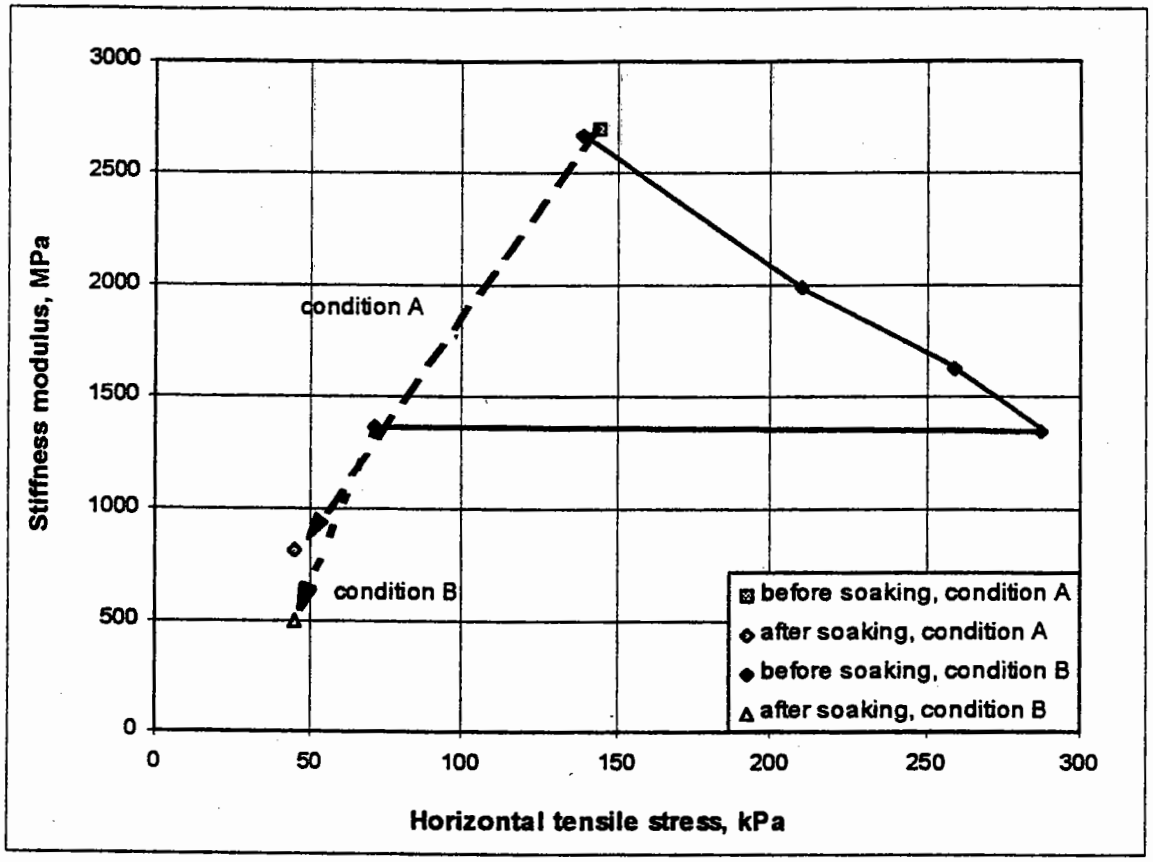


Figure 8-6 Effect of pre-loading R-emulsion mixture specimens on the measured soaked stiffness (C2 grading, 5% RBC, curing for 37 days at 20°C)

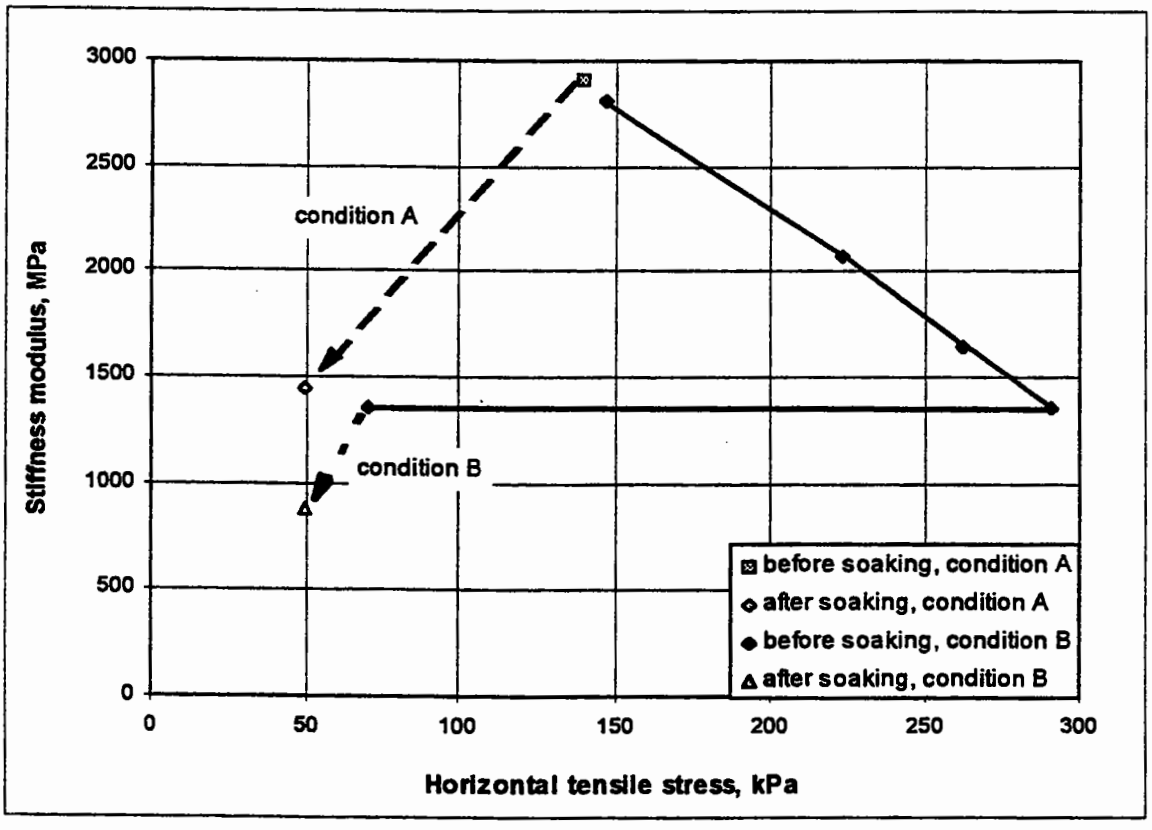


Figure 8-7 Effect of pre-loading K-emulsion mixture specimens on the measured soaked stiffness (C2 grading, 5% RBC, curing for 37 days at 20°C)

8.5 POTENTIAL OF WATER RESISTANCE ASSESSMENT IN THE TRIAXIAL MODE

To realistically assess the resistance to water of bituminous mixtures, tests should be conducted on specimens with water trapped in them. Triaxial testing, with the specimen wrapped in a rubber membrane, provides this facility. As previously stated, triaxial testing in the NAT allowed the test specimens to be soaked in water. Specimens cured for 40 days (3.7% RBC - mid DBM grading) were tested for stiffness at different stress levels, then left to soak in a water bath at 20°C for 24 hours, prior to testing once again for stiffness determination. The results, as illustrated in Figure 8-8, showed a reduction in stiffness moduli. In addition, an increase in stress dependency has been found for the soaked specimens relative to the corresponding unsoaked specimens.

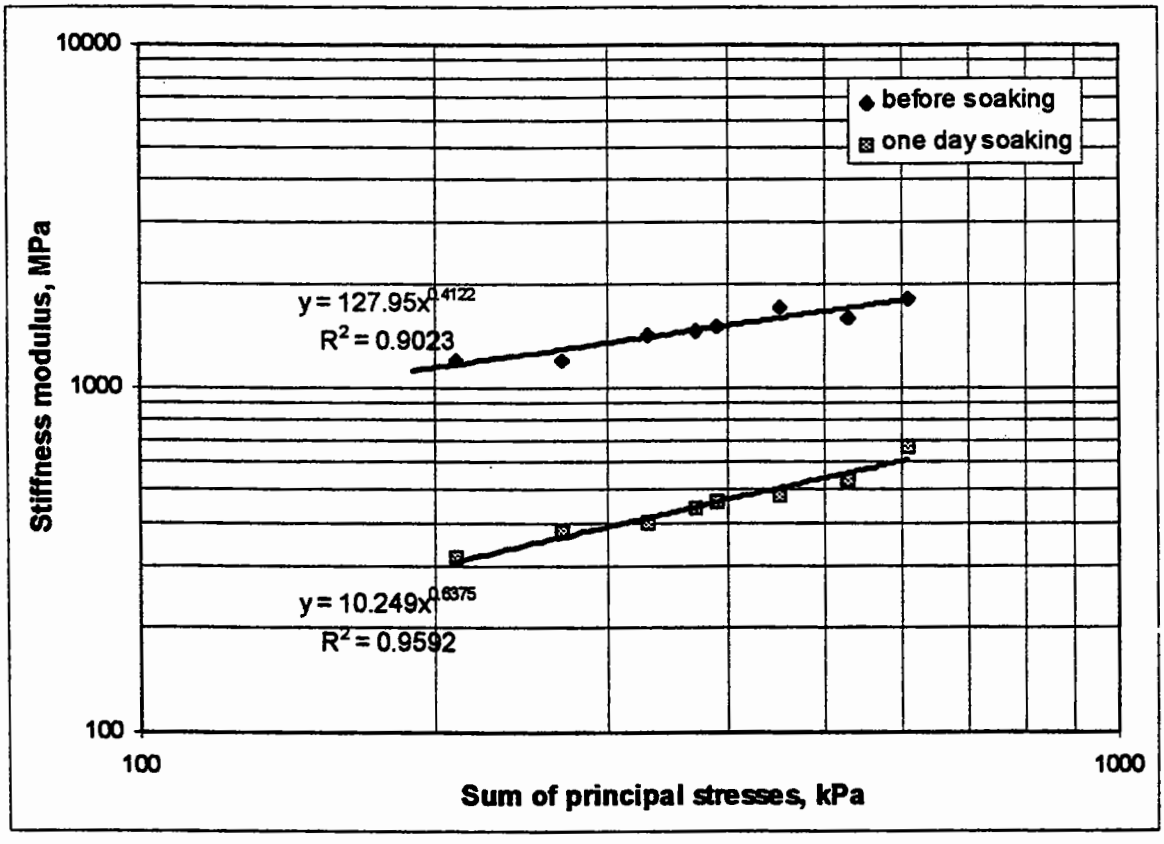


Figure 8-8 Water effect on specimens containing 3.7% RBC and mid-DBM grading, measured in the triaxial mode (curing for 40 days at 20°C)

8.6 SUMMARY

Mid-DBM graded mixtures containing K-emulsion showed poor water resistance, although coating to aggregate particles and their unsoaked stiffness moduli were the highest of all emulsion mixtures used in this study. The coating test alone is not enough for investigating compatibility of the mixture components. Mid-DBM mixtures containing R-emulsion (harder emulsion type, see Chapter 10) showed relatively better water resistance than K-emulsion mixtures, despite their lower stiffness moduli.

Use of a fine dense grading in this type of mixture, with K-emulsion, dramatically increased resistance to water effects, although the dry density and coating of aggregate particles were less than in mid-DBM graded mixtures. However, R-emulsion mixtures with fine grading did not show a change to water resistance relative to the mid-DBM grading. Thus, better resistance to water effects of emulsion-aggregate mixtures may often be obtained using fine dense graded aggregate, however the best use of a particular emulsion type is dependent on the aggregate gradation used. This should be considered in the mix design process.

CHAPTER

9 PERFORMANCE STUDY IN SLAB TEST FACILITY

As discussed in the previous chapters, emulsion aggregate mixtures behave to a great extent non-linearly. The laboratory tests on specimens highlighted 1) stress dependency of the material in relation to curing time, emulsion type, residual bitumen content, and aggregate gradation, 2) poor fatigue resistance measured in the indirect tensile fatigue test, 3) higher permanent deformation compared to corresponding hot bituminous mixtures. Also, it has been found that the behaviour and characteristics of the material are different from those of hot mixtures. Of concern to the work objectives is the investigation of the material's failure characteristics. Therefore, performance has been studied in a pilot scale wheel tracking facility. Slabs of emulsion mixtures were laid down on a base layer (sand or crushed stone) and/or a sheet of rubber. Measurements taken were surface rutting, vertical stress at the top of the base layer and tensile strain at the bottom of the emulsion mixture layer, by means of installed pressure cells and embedment strain gauges. This test arrangement is considered suitable for assessing the characteristics of the material under a moving wheel and for design validation purpose.

9.1 EXPERIMENTATION

9.1.1 Equipment Description

The Slab Test Facility 'STF' is a pilot scale facility in which a prototype representing the pavement layers under consideration is subjected to a simulated vehicle loading under controlled conditions. Figure 9-1 shows a schematic diagram of the Slab Test Facility. Two parallel steel beams are supported at both ends, acting as a lever to a moving carriage in which the wheel is mounted. The carriage is driven by means of a wire rope tensioned around a drum coupled to a servo controlled motor. Generally, the wheel speed can be controlled through an electronic control unit which sends signals to

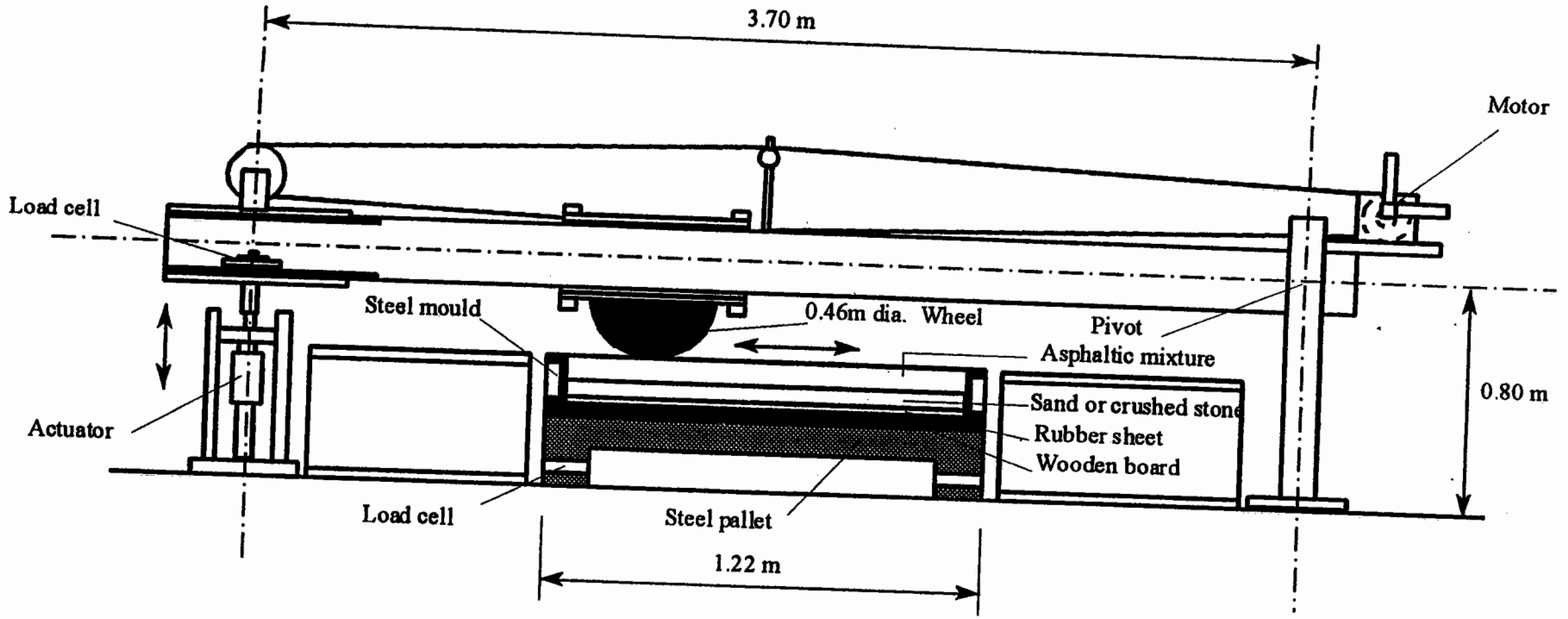


Figure 9-1 Slab test facility

a servo valve to control the motor speed. Also, the required load can be set in the electronic control unit which operates a hydraulic actuator through a servo valve. The wheel is a pneumatic tyre which can be inflated to give the required contact pressure. However, load is measured by load cells placed under corners of a steel pallet which supports the slab being tested.

A wheel load up to 8 kN and maximum contact pressure of 500 kPa can be applied. Stress and strain measurements in the materials can be obtained using installed transducers.

9.1.2 Test Programme

It is evident from the literature that little information is available regarding the performance of emulsion mixtures. Reported failure mechanisms involved: permanent deformation, disintegration, and settlement. The literature also revealed no consensus regarding the use of fatigue cracking as a design criterion for design purposes. Accordingly, testing in the Slab Test Facility was planned to study the effect of mixture density, bitumen content and wheel load on both elastic properties and damage characteristics of the material (permanent deformation and fatigue cracking). For all tests, emulsion mixture layer moduli were back-calculated from vertical stress and horizontal strain measurements. Backcalculation of moduli was made using the finite element program 'FENLAP' and the program 'MPTRN' based on linear elastic theory. The results were compared with those from the indirect tensile and triaxial modes of testing to deduce the most suitable mode of testing for use in characterizing this type of mixture.

Generally, two groups of slab arrangements were planned. The first group was of slabs laid on sand or crushed stone, with rubber sheet underneath (Fig 9-1). Measurements were the horizontal strains in the surface layer and the vertical stresses on the base layer as well as surface rutting. The other group was of slabs resting directly on the rubber sheet. In this test group, wheel load was controlled to a level leading to horizontal strains similar to that for slabs resting on unbound and rubber sheet layers.

Measurements were of surface rutting and horizontal strains in the emulsion mixture layer. Table 9-1 presents a description of the slabs used in this study.

Table 9.1 Slab arrangements

Slab	Layers			Dry density of emulsion mixture, g/cm^3	Curing at room temperature
	Hot mixture	Emulsion mixture	Supporting layers		
S1	-	4 % RBC, 108 mm thick.	sand, 70 mm	2.21	10 days
S2	-	4 % RBC, 107 mm thick.	crushed limestone, 80 mm and rubber sheet 5.5 mm thick.	2.285	28 days
S3	-	5 % RBC, 105 mm thick.	crushed limestone, 80 mm and rubber sheet 5.5 mm	2.29	30 days
S4	(DBM-14 mm), 30 mm thick.	4 % RBC, 100 mm thick.	Sand 70 mm, rubber 5.5 mm	2.318	22 days
S5	-	5 % RBC, 101 mm thick.	Sand 70 mm, rubber 5.5 mm	2.225	34 days
S6	-	5 % RBC, 97 mm thick.	rubber 5.5 mm	2.34	37 days

9.1.3 Slab Preparation and Instrumentation

Slabs were manufactured in a steel mould measuring 1.10 m in length and 0.90 m in width, resting on a wooden pallet. The mould depth were varied according to the required layer thickness. However, a maximum total thickness of 180 mm could be attained. The rubber sheet was 5.5 mm thick and had an elastic modulus of 5 MPa. It was overlaid by either a well graded crushed limestone or uniform fine sand of 0.6 mm maximum particle size. A pre-determined amount of material was laid down and compacted to give a minimum layer thickness of 70 mm, so as to allow installation of pressure gauges. The top layer was an emulsion aggregate mixture containing 4% or 5% residual bitumen content of K-emulsion and aggregate of 20 mm mid-DBM grading. Mixing of materials was achieved in a mixer of 200 kg capacity, originally used for concrete. However, preparation of materials was according to the method which has been discussed earlier in Chapter 4.

It should be mentioned that the 3.5 % added water content previously determined using Marshall size specimens was not suitable for preparation of such a large amount of material. It was realized that this amount of water would lead to a very sloppy mixture which could not be handled in the laboratory. Accordingly, the decision was to use less water, leading to workable and easy to handle mixtures. Generally, the added water content was 1.5% of the aggregate weight. A point to note is that 3 kg samples of the mixtures were taken before laying the material, for rice density determination.

For measuring the vertical stresses on the top of the underlying layer and the horizontal strains at the bottom of the emulsion mixture layer, pressure cells and embedment strain gauges were used. Instrumentation was installed after laying and compacting each layer.

Pressure Cells

A pressure cell comprises a thin diaphragm over a ring, freely deflecting under an applied load. This deflection, or strain on the inside of diaphragm, is measured using a transducer. A diagram of the Nottingham pressure cell (Brown and Brodrick, 1981) is shown in Figure 9-2. As shown, four strain gauges are attached to the diaphragm and arranged to measure both tensile and compressive strains.

For the purpose of this study, three cells were installed along the wheel path, 300 mm apart. The pressure cells were placed in holes in the sand layer which were cut with a spatula. Care was taken to ensure minimum disturbance around the instruments. In the case of crushed limestone, holes were excavated at the pressure cell locations and the cells were placed in a pre-packed condition, where fine sand having 0.6 mm particle size (less than 1/50 of the diaphragm diameter) was held in position over the diaphragm with a thin plastic film.

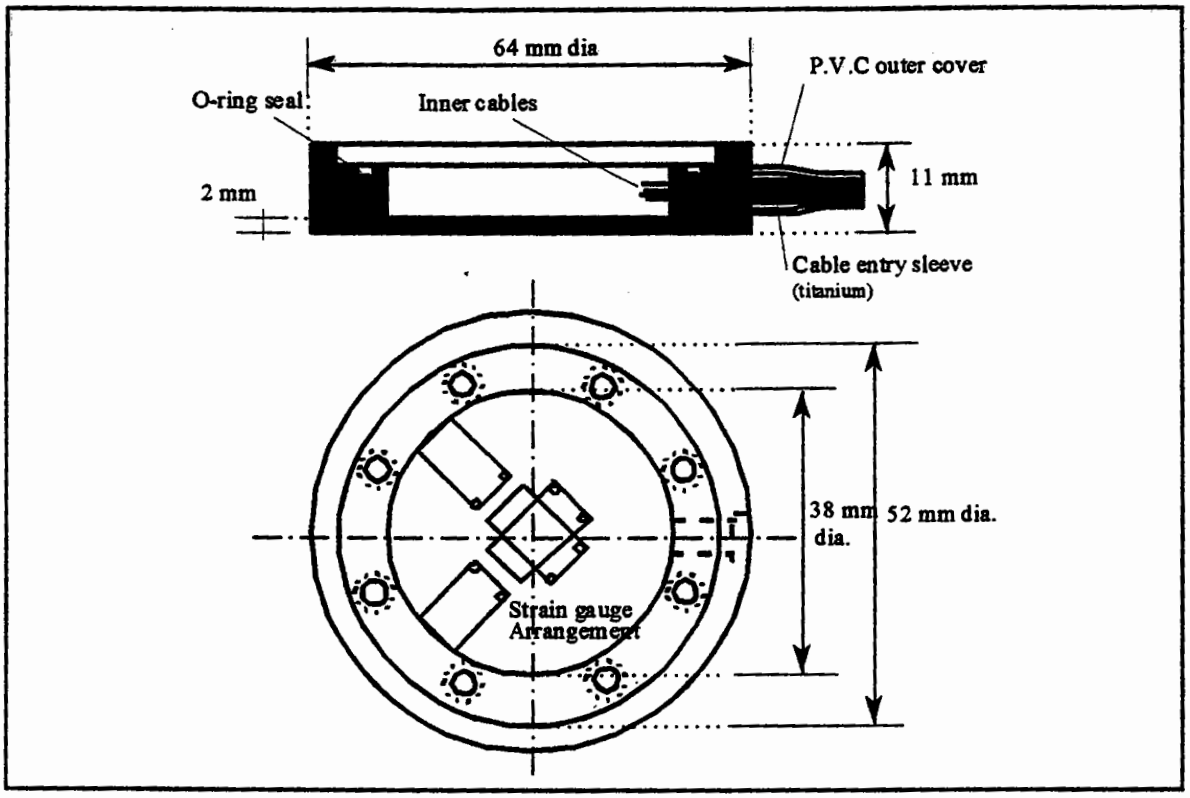


Figure 9-2 Nottingham pressure cell (after Brown and Brodrick, 1981)

Embedment Strain Gauges

Embedment strain gauges were found to be a convenient tool for the measurement of the horizontal strains at the bottom of the emulsion mixture layer. Strain gauges with a gauge length of 60 mm were used. For better adhesion with the surrounding mixture, consideration was given to the surface roughness of the gauges.

In the installation of strain gauges, care was taken by placing them in their positions and pressing them into the emulsion mixture to ensure a uniform contact over the gauge surface area. On completion of each test, the slab was sawn for density measurements and crack location investigation. In addition, the strain gauges were broken out of the slab for visual inspection. As expected, all strain gauges were found in a uniform contact with the emulsion mixture.

The location and orientation of the pressure cells and embedment strain gauges are shown in Figure 9-3.

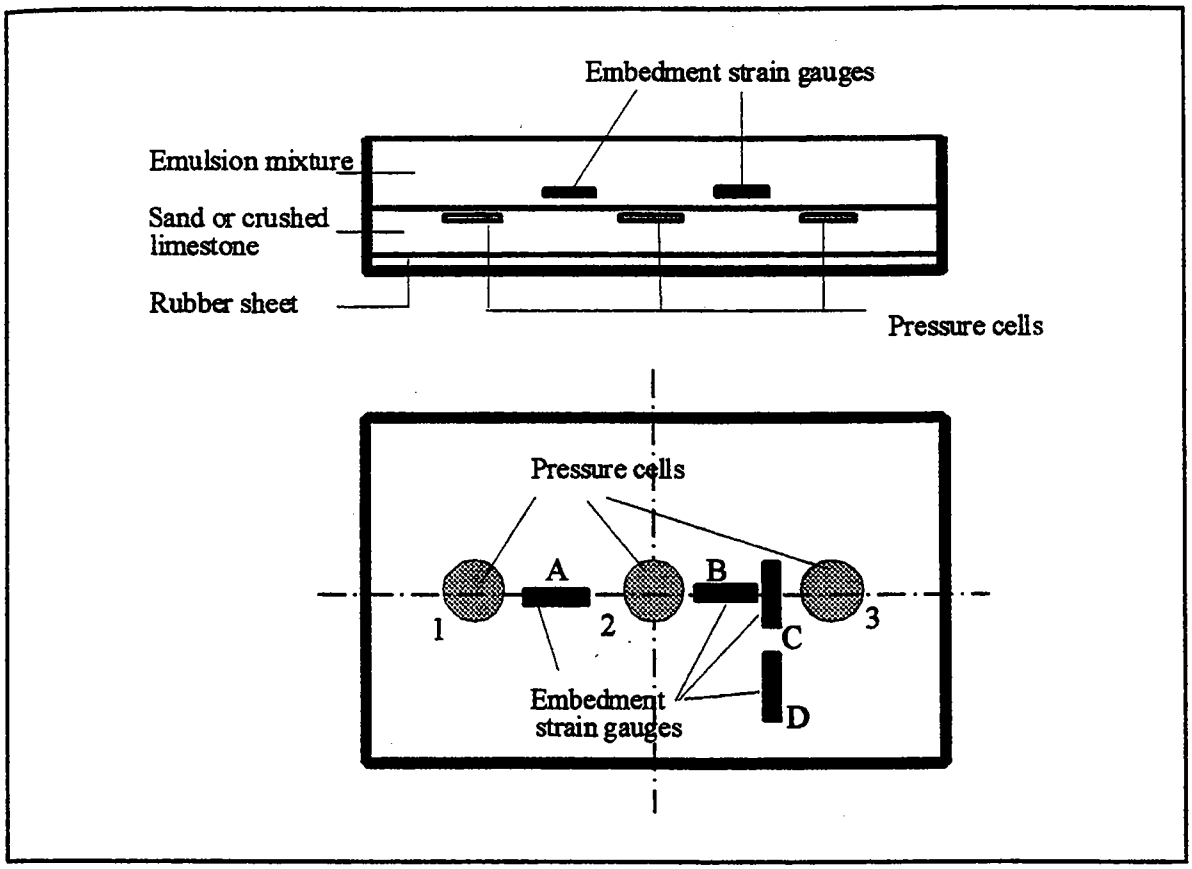


Figure 9-3 Location and orientation of pressure cells and embedment strain gauges

9.1.4 Test Procedure

The manufactured slab within the steel mould was moved by fork lift to rest on the steel pallet of the Slab Test Facility after being cured. The steel pallet with the slab was then lifted and placed in position for testing, resting on load cells at each corner. After that, all cables and wires of the pressure cells and strain gauges were connected to amplifiers which were attached to an analogue/digital (A/D) converter and computer for monitoring the outputs in volts of each channel. Measurements were the applied wheel load, wheel position, vertical stresses, and horizontal strains. The test procedure was as follows:

- The hydraulic pump and the electronic control unit were switched on, when the wheel position was off the slab and both the speed and the load readings were zero.

- After moving the wheel to the middle of slab, the speed control unit was set at a reading leading to the required wheel speed. The speed was controlled to be 40 passes per minute for all tests.

- After warming up the equipment, the cycle counter was reset to zero, and the required load was applied using the load control unit. For the slab resting directly on the rubber sheet, load control was by turning the control unit until the desired horizontal strain was achieved from the transverse strain gauges.

- Measurements from the pressure cells and the embedment strain gauges were monitored and recorded as a function of the number of wheel passes.

Tests were stopped after the occurrence of surface cracking or severe rutting.

9.1.5 Instrument Calibration

Since the output of the above described arrangement of tests is in voltage, both pressure cells and embedment strain gauges were calibrated against a known level of measurement.

Calibration of Pressure Cells

Calibration of pressure cells was done by placing each in a calibrator after being connected to the amplifier used in the experiment. Known different pressure levels were applied to the cell and the amplifier readings were monitored. Plots of voltage output from the amplifier and the applied pressure led to a factor for converting recorded measurements into pressure. A typical voltage conversion factor was 850 kPa per volt.

Calibration of Strain Gauges

Calibration of an embedment strain gauge necessitates using a special technique, since measurements are influenced greatly by the surrounding material. A slab of emulsion mixture 28×40×12 cm, with an installed strain gauge, was fabricated in the Nottingham roller compactor to a density similar to that of slabs tested in the STF. After a similar

period of curing, a prism 30×12×12 cm was then taken, including the strain gauge, for calibration.

Figure 9-4 shows a diagram and photograph of the procedure used. As shown, two calibrated LVDTs mounted on .the prism walls were used to correlate their measurements with those from the strain gauge. Upon applying load in tension, output from the LVDTs was monitored using an oscilloscope, whereas outputs of the embedment strain gauge were through the amplifier used in slab testing. A plot of the output has led to a factor for converting slab test measurements to microstrain.

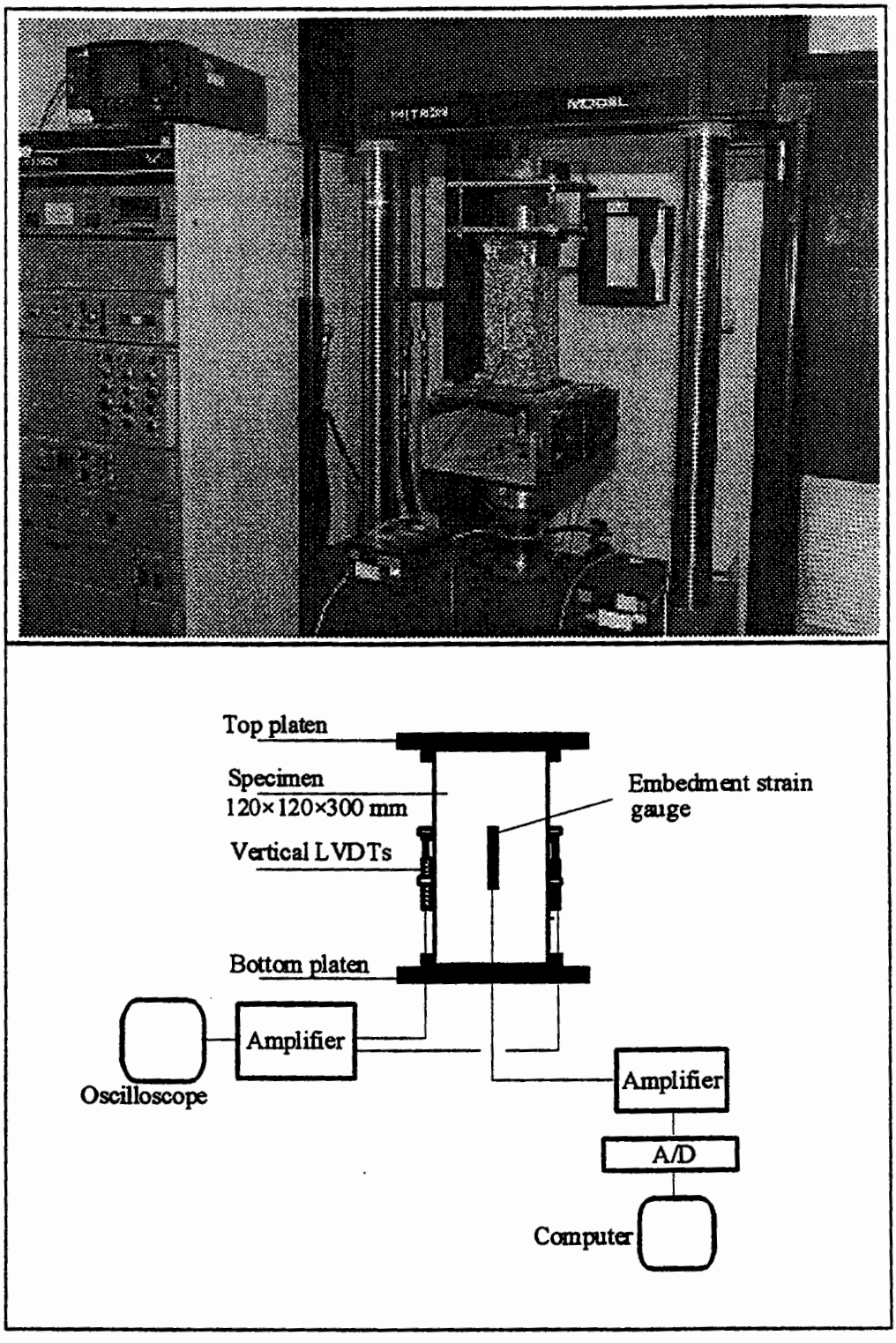


Figure 9-4 Photograph and diagram of the calibration procedure for embedment strain gauges

9.2 PRESENTATION AND ANALYSIS OF RESULTS

In this section, measurements of surface rutting, horizontal strains and vertical stresses are presented. The effect of wheel load, mixture density, residual bitumen content and curing time are discussed. For validation of laboratory test results from the NAT in indirect tensile and triaxial modes of loading, comparisons are presented with backcalculated moduli using the slab measurements. In addition, possible failure mechanisms associated with this material are highlighted.

9.2.1 Stress and Strain Measurements

Different types of stresses and strains are developed in pavement layers under the passage of a wheel, resulting in a variety of pavement damage. Fatigue cracking in particular, as a result of horizontal tensile strains at the bottom of the bituminous layer, is of concern. Nevertheless, in using emulsion mixtures in pavement layers, both fatigue cracking and permanent deformation are currently points of dispute in pavement design methodology.

In this study, strain gauges were therefore installed in the locations and directions illustrated in Figure 9-3, for measuring and monitoring longitudinal and transverse strains. Typical strain measurements are presented in Figures 9-5a and 9-5b. As seen, as the wheel approaches the strain gauge, compressive strains are developed, followed then by tensile strains. Transversely, only tensile strains are developed. On the other hand, compressive strains are the only mode measured by strain gauges off the wheel path. Generally, the transverse tensile strains were higher for all tested slabs, in line with that reported by Huhtala et al (1990) and Rowe and Brown (1997).

It is clear that any change in the measured tensile strain level as a function of the number of wheel passes could be an indication of localised distress, with a consequent change in the material properties. However, there are two possible distress locations. Distress located at the strain gauge positions results in increasing measured strains, whereas distress located next to the gauge results in decreasing measured strains due to gauge relieve. The measured horizontal strains of various test slabs are presented in

table 9-2. As can be seen, the measured strains were almost constant over the test period, indicating no sign of local distress; although, longitudinal surface cracking occurred, accompanied to rutting. The first three slabs tested (slabs S1-S3) were therefore sawn (dry) for visual inspection. Surprisingly, cracks were only apparent over the top quarter height of the slabs, next to the wheel path. Generally, emulsion mixture layers seemed to crack due to shear, either because the tested slab was in direct contact with the wheel tyres and shear resulted from single tracking, or the applied wheel load was high.

Table 9-2 Test measurements

Slab	Test temperature °C	Applied wheel load [A] kN	Transverse horizontal strain [B] microstrain	Vertical stress [C] kPa
S1	21	1.5	186	128
S2	20	3.5	96	-
S3	23	3.2	128	85
S4	21	3.3	136	54
S5	27	1.0	97	-
		2.1	143	-
		3.0	215	-
		4.0	296	-
S6	20	2.15	227	-

[A] the applied load monitored using load cells located at the pallet corners of STF (0.1 volt = 1 kN)

[B] the maximum tensile strain at the bottom of the emulsion mixture layer, measured using embedment strain gauges located transversally under the wheel path

[C] the average vertical stress at the top of the crushed limestone or sand layer measured using pressure cells located under the wheel pass.

Accordingly, two tests were carried out. The first (slab S4) was wheel tracking on a slab comprising similar layers (rubber sheet, sand, emulsion mixture) and covered by hot asphaltic mixture, as described in table 9-1. Longitudinal cracking, with rutting, and steady horizontal strains over the test period were the results. However, on sawing the slab, it was revealed that permanent deformation in the emulsion mixture layer was the failure mechanism. It was believed once again that the applied load level was the reason. Based on that, a second test (slab S5) was carried out by applying different wheel load levels 'multi-step loading' on a similar slab arrangement. A wheel load of 1 kN was applied for 35000 passes, then increased to 2.1 kN, as measured by the load cell, for 300 passes, 3 kN for 300 passes, and 4 kN for approximately 13000 passes, and finally decreased to 3 kN until completion of the test, during which the horizontal strains, vertical stresses, and surface rutting were monitored. The measured strains were also constant for the applied load levels used. Rutting was moderate when a lower load level (up to 2 kN) was applied, and severe under the 4 kN wheel load.

It is thought that surface settlement due to material softening under the wheel load is a reason for the observed surface cracks (see also Ibrahim and Thom, 1998). If damage occurred in the material due to fatigue, both the measured horizontal strains and the vertical stress would have been changed over the applied number of wheel passes. However, re-applying a lower wheel load to the slab after being tested at higher load did not show any variation in the measurements (see Figure 9-6).

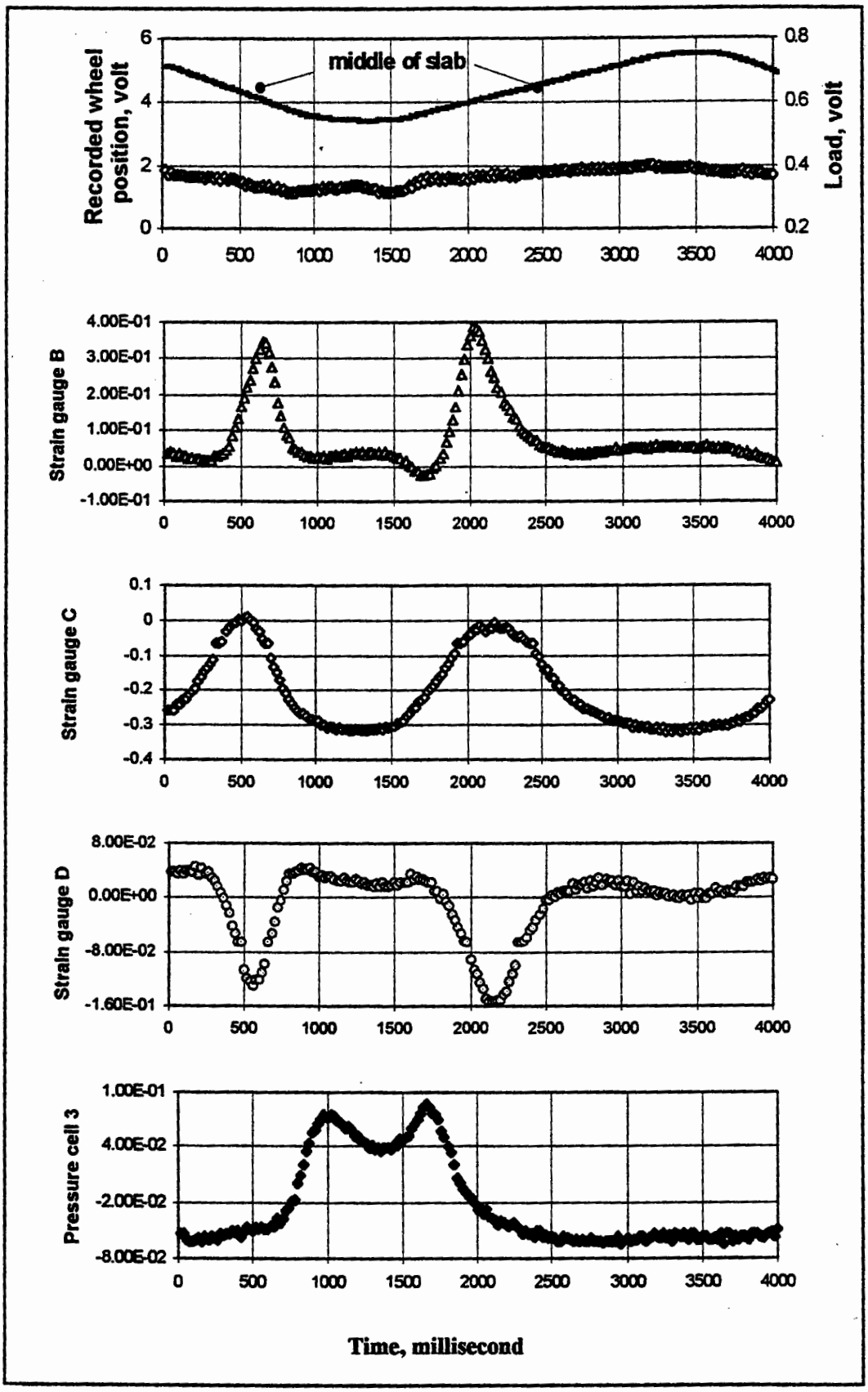


Figure 9-5a Typical output of embedment strain gauges and pressure cell in both directions of wheel travel, for slab rested on crushed limestone

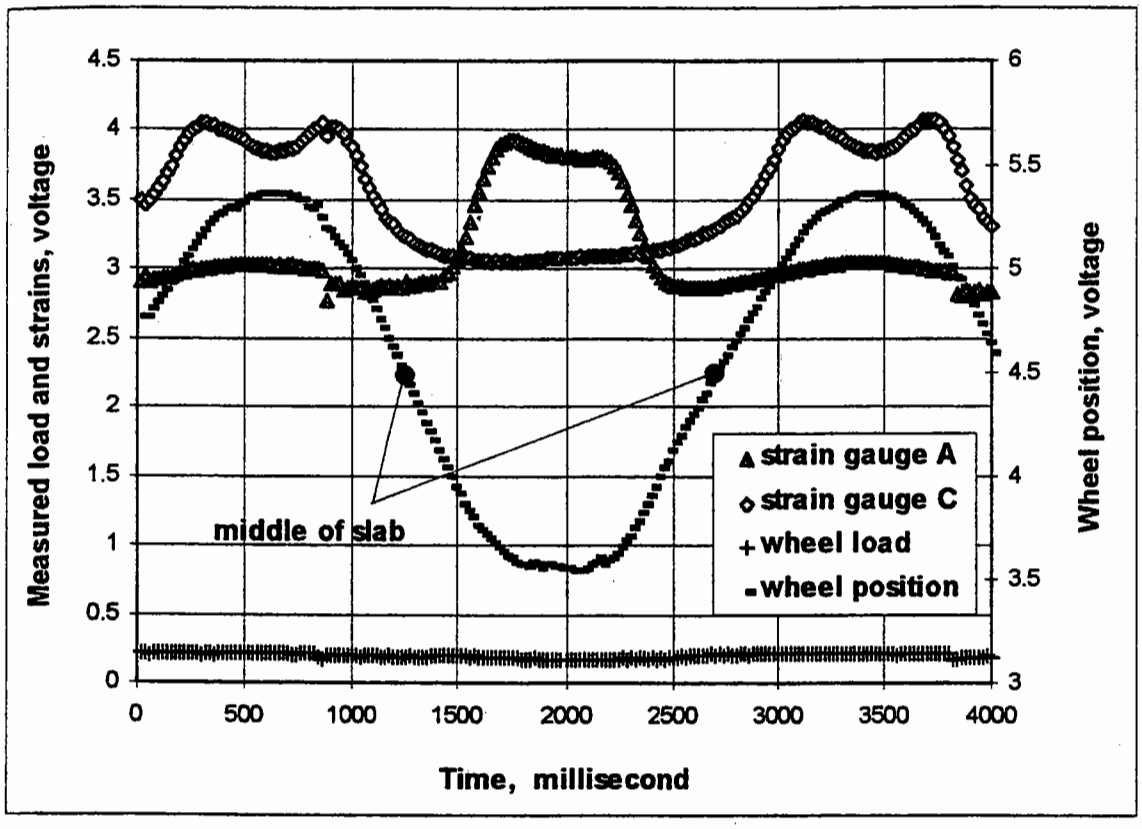


Figure 9-5b Typical output of strain gauges of slab rested directly on rubber sheet (slab S6)

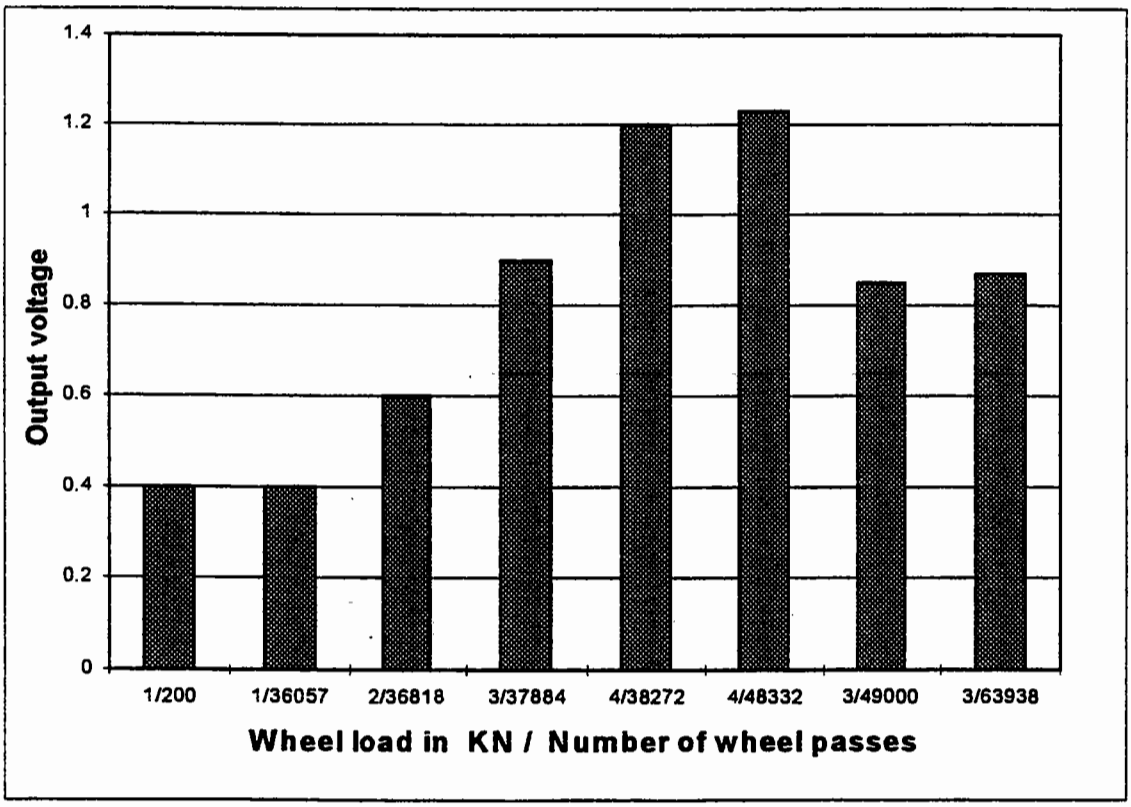


Figure 9-6 Effect of wheel load level on strain measurements (slab S5)

However, a test on a slab of emulsion mixture resting directly on a rubber sheet was also carried out. It was aimed to apply a lower wheel load, resulting in a horizontal tensile strain level higher or at least similar to that of the slab S5, when applying 4 kN. A wheel load of 2.15 kN was used, resulting in a tensile strain of approximately 227 microstrain. The test in this arrangement is a wheel tracking fatigue test, as well as inducing rutting. Therefore, the tested slab was visually investigated for surface cracking, strain measurements were taken using transverse strain gauges and the number of wheel passes was recorded. The test results are presented in Figure 9-7.

The figure shows reasonably constant strains until a number of wheel passes of approximately 77500 followed by a gradual decrease in strain measurements until 145000 passes. This decrease in measured transient strains may indicate local distress next to the strain gauge location. Visually, the start of hairline longitudinal cracking was observed after 90000 passes. The measured rutting depth was approximately 1 mm after completion of the test, see Figure 9-10. As can also be noted in Figure 9-7, after 145850 wheel passes, some recovery of the output strain was recorded following a break in the test of two weeks, after which a rapid decrease in the measured strain and failure occurred. Clearly, the results presented in the top part of Figure 9-7 show a significant relief in the strain gauge, indicated by sudden drop in the output voltage. Probably, breaking of the bond between the aggregate particles, in a shape of disintegration and loosening of the material occurred.

Although the resulting tensile strain at the bottom of the emulsion mixture layer due to the 2.15 kN wheel load was higher, the number of recorded wheel passes causing cracking was also much higher. On the other hand, the resulting surface rutting was much less than that when a high wheel load was applied. However, this measured rutting will be discussed in detail in section 9.2.3.

It can be concluded that the cracking associated with applying a wheel load of 4 kN was not a fatigue phenomenon. Nor did it result from structural permanent deformation. It was a case of deformation within the layer surface due to material softening, which created high tensile stresses at the surface, next to the wheel path.

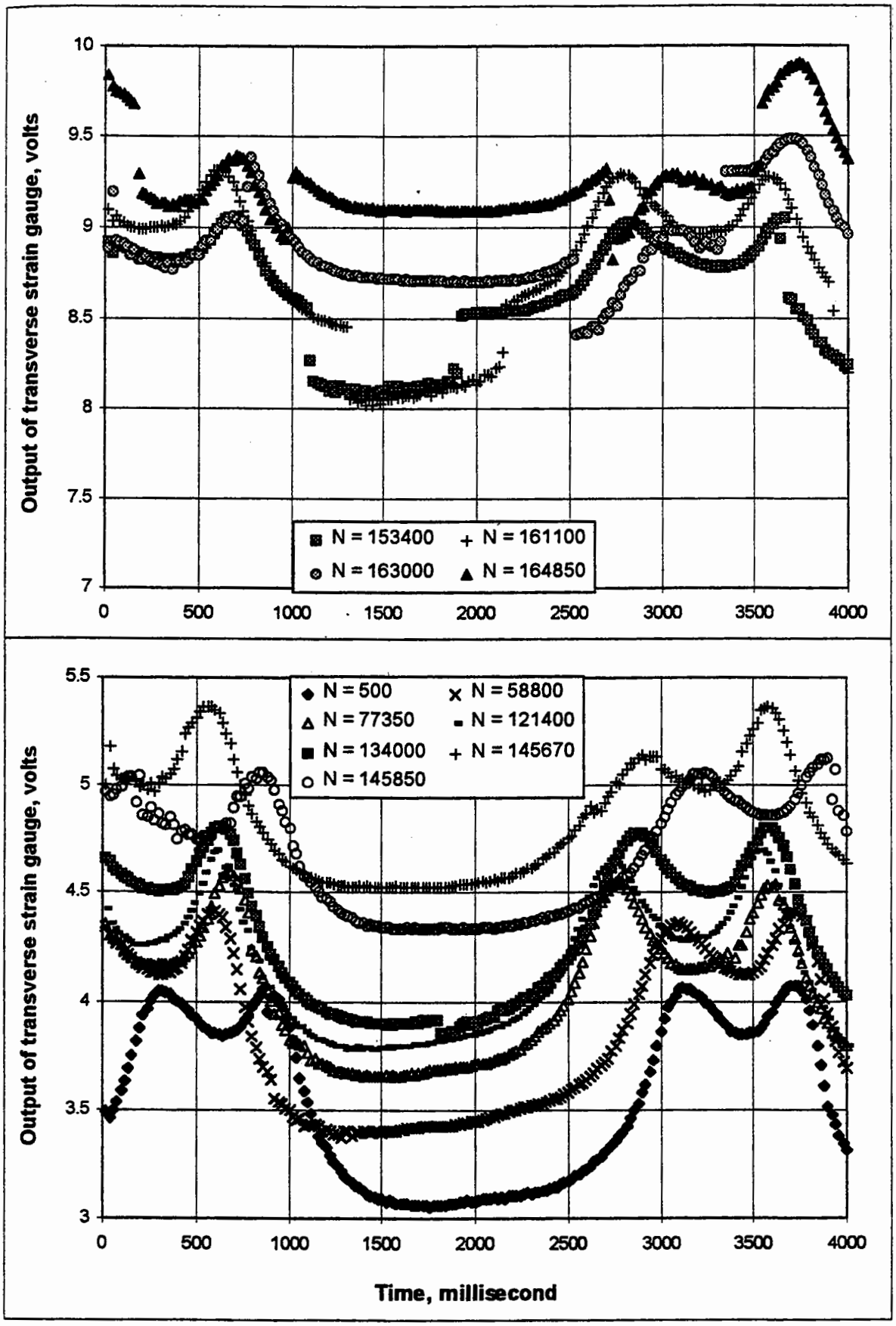


Figure 9-7 Output of transverse embedment strain gauge in slab S6 as a function of the number of wheel passes

9.2.2 Comparison of Moduli

Characterising the resilient modulus or rather stiffness of the emulsion aggregate mixtures is rather complicated in that their responses in laboratory test equipment are different. The significance of some variables affecting the behaviour of this material has been discussed in Chapter 5. Discrepancies in the effect of applied stress level and the determined moduli from the indirect tensile and the triaxial mode of loading have been found to be quite significant. Hence, the need for determination of a suitable method for characterizing the modulus of the material is paramount. For that purpose, the elastic modulus response of the material was studied in the wheel tracking pilot scale tests. However, moduli of the tested slabs described in Table 9-1 were back-calculated using both FENLAP (Finite Element Non-linear Analysis of Pavements) and MPTRN (linear mode of response) and compared with those determined using the NAT in the indirect tensile and the triaxial mode of loading.

Back-calculated Moduli using FENLAP and MPTRN

Whether the material behaves linearly or nonlinearly is an important parameter in a pavement analysis system, especially when using the material as surface and/or base layer. These modes of response for the upper layer materials significantly affect the calculated stresses and strains in pavement layers, more so than do the foundation layer materials. Generally, emulsion mixtures have been found to behave non-linearly from the laboratory tests on small size specimens. The material was therefore investigated in the linear and non-linear response modes in the backcalculation process using FENLAP.

FENLAP is a computer program written in the FORTRAN 77 language by Almeida (1993), at the University of Nottingham. It performs a finite element calculation of an axi-symmetric solid and analyse pavement structures. In the study presented herein, rectangular elements were used. The mesh used had 8 columns and 10 rows. For the non-linear analysis, the K-θ model (Hicks and Monismith, 1971) was used for the emulsion mixture layer, considering three parameters: Poisson' ratio and model constants k1& k2. A typical output is presented in Figure 9-8. However, the calculation was as follows:

1. Moduli determination of the rubber sheet, sand and crushed limestone. Values were 5, 50, 200 MPa respectively (the last two by estimation).
2. Assume a stiffness modulus of the emulsion mixture layer, based on whether the material behaves linearly or nonlinearly.
3. Calculate of stresses and strains.
4. Compare the calculated and measured stresses and strains.
5. Repeat steps 2 to 4 until coincident values of both stresses and strains are obtained.
6. Report the stiffness modulus, optimizing the calculations.

Table 9.3 presents an example of the calculated values.

```
 PROGRAM FENLAP : Finite Element Non-Linear Analysis of Pavements
 TITLE OF JOB : Typical Reduced Output

 MESH WITH 8 COLUMNS AND 10 ROWS ( 63 ELEMENTS)
 COLUMNS RADII: 0.000 0.030 0.055 0.100 0.180 0.260 0.350 0.450
 ROWS DEPTHS: 0.000 0.010 0.030 0.050 0.070 0.090 0.105 0.130 0.150 0.190
 APPLIED VERTICAL PRESSURE= 330.000 LOAD INNER RADIUS= 0.000 LOAD OUTER RADIUS= 0.055
 WATER TABLE LEVEL= 0.150 WATER UNIT WEIGHT= 10.0000
 3-LAYER PAVEMENT
 LAYER 1 --> DEPTH= 0.105 UNIT WEIGHT= 21.0000 SUCTION= 0.000 Ko=1.000 COHESION= 0.000
       K-O MODEL with v=0.400 K1= 40000. and K2=0.4000
 LAYER 2 --> DEPTH= 0.190 UNIT WEIGHT= 21.0000 SUCTION= 0.000 Ko=1.000 COHESION= 0.000
       LINEAR ELASTIC MODEL with E= 200000. and v=0.400
 LAYER 3 --> DEPTH= 0.196 UNIT WEIGHT= 1.6000 SUCTION= 0.000 Ko=1.000 COHESION= 0.000
       LINEAR ELASTIC MODEL with E= 5000. and v=0.500
 INFINITE ELEMENTS VERTICALLY WITH E=20000000. and v=0.100
 LATERAL BOUNDARY WITH ROLLERS AT RADIUS 0.450
 No. OF LOAD INCREMENTS= 1 ADMISSIBLE ERROR=0.0001 Emin= 0.1*min(Ei)

 TRANSIENT DISPLACEMENTS TO BE PRINTED AT ALL ELEMENT CORNER NODES LOCATED BETWEEN DEPTHS 0.000 AND
0.000
 TRANSIENT STRAINS, STRESSES AND MODULI TO BE PRINTED AT SELECTED ELEMENT CORNER NODES

 LOAD INCREMENT 1 ITERATION 1 --> MODULUS ERROR=0.6949 STRESS ERROR=0.0000
 LOAD INCREMENT 1 ITERATION 2 --> MODULUS ERROR=0.0191 STRESS ERROR=0.0000
 LOAD INCREMENT 1 ITERATION 3 --> MODULUS ERROR=0.0022 STRESS ERROR=0.0000
 LOAD INCREMENT 1 ITERATION 4 --> MODULUS ERROR=0.0009 STRESS ERROR=0.0000
 LOAD INCREMENT 1 ITERATION 5 --> MODULUS ERROR=0.0008 STRESS ERROR=0.0000
 LOAD INCREMENT 1 ITERATION 6 --> MODULUS ERROR=0.0008 STRESS ERROR=0.0000
 LOAD INCREMENT 1 ITERATION 7 --> MODULUS ERROR=0.0008 STRESS ERROR=0.0000
 LOAD INCREMENT 1 ITERATION 8 --> MODULUS ERROR=0.0001 STRESS ERROR=0.0000
 ***** CONVERGENCE ACHIEVED *****

          TRANSIENT DISPLACEMENTS
  RADIUS     DEPTH     VERT.DISP.    RAD.DISP.

   0.000     0.000     0.8041E-04    0.0000E+00
   0.030     0.000     0.7502E-04    -.2538E-05
   0.055     0.000     0.5632E-04    -.4822E-05
   0.100     0.000     0.1945E-04    -.3460E-05
   0.180     0.000     0.2249E-05    0.1203E-05
   0.260     0.000     -.5894E-06    0.1794E-05
   0.350     0.000     -.5479E-06    0.1041E-05
   0.450     0.000     -.4205E-06    0.0000E+00

                    TRANSIENT STRAINS,STRESSES AND MODULI
 RADIUS DEPTH  L  Ezz      Szz       Err       Srr       Ett       Stt       Ezr       Szr       Mr        Pr

   0.000  0.105  1  0.462E-03 0.110E+03 -.194E-03 -.774E+01 -.194E-03 -.774E+01 0.400E-05 0.338E+00 0.252E+06  0.400
   0.000  0.105  2  0.517E-03 0.111E+03 -.194E-03 0.892E+01 -.194E-03 0.892E+01 0.343E-05 0.245E+00 0.200E+06  0.400
   0.000  0.190  2  0.144E-03 0.580E+02 -.614E-05 0.366E+02 -.614E-05 0.366E+02 -.714E-06 -.510E-01 0.200E+06  0.400
```

Figure 9-8 Typical reduced output from FENLAP program.

Table 9-3 Comparison between calculated and measured stresses and strains in slab S3

mode of response		linear				non-linear k1/k2				
assumed stiffness		300	500	700	900	9e4 / 0.4	9e4 / 0.5	6e4 / 0.5	6e4 / 0.4	4e4 / 0.6
calculated stress	MPTRN	85.4	70.7	61.3	54.5					
	FENLAP	101	87.5	78.6	71.8	84	54	83	97	114
calculated strain	MPTRN	181	150	129	113					
	FENLAP	180	142	118	102	139	106	121	166	81
measured stress = 85 kPa, measured strain = 128 microstrain										
stiffness (ITSM)		approximately 1200 MPa								
stiffness (Triaxial)		k1 = 90000 and k2 = 0.4 after 30 days curing sided wrapped at 20°C								

Assuming a linear response for the material, the calculated stiffness modulus that leads to a similar measured vertical stress at the top of the base was approximately 500 MPa, from which the calculated horizontal strain was 142 microstrain, based on the finite element program FENLAP. Assuming a non-linear response, the best estimates of K-θ parameters were found to be k1= 9e4 and k2= 0.4 or k1= 6e4 and k2=0.5. The measured and calculated values of stresses and strains using the finite element program are approximately similar. On the other hand, none of the calculated values using MPTRN is close to the measured values. Based on the linear program MPTRN, the calculated strains were higher than those measured; conversely, the calculated stresses were lower. Clearly, the finite element program is more suited for use in analysis of pavements incorporating an emulsion mixture layer, and more accurate than the linear elastic programs. Also, assuming the response of the material to be non-linear leads to more accurate values of stresses and strains.

As previously mentioned, an agreed test method for determination of emulsion mixtures' stiffness does not yet exist. Currently in the UK, it is usually characterised in

the indirect tensile mode, following the procedure for hot asphaltic mixtures. Unfortunate, the behaviour of emulsion mixtures and hot asphaltic mixtures are completely different based on the work of this study. However, calculated values of stiffness based on the pilot scale wheel tracking test measurements presented in Table 9-3 show proximity to the corresponding values from the triaxial mode. Hence, transmission of the wheel load to the underlying layer is more influenced by the stiffness in compression.

9.2.3 Rutting

Two mechanisms of rutting development in flexible pavements have been recognised; rutting caused by permanent deformation within the bituminous mixtures and/or that caused by deformation at depth in the pavement structure. Often, formation of shoulders at the edge of the ruts is associated with deformation within the bituminous mixture due to lateral displacement of the material. However, for investigating rutting mechanisms in emulsion mixtures, transverse measurements of the surface levels of the above described slabs were taken before running the test and at different numbers of wheel passes. The measured rutting profiles were then compared with permanent deformation measurements from the repeated load axial and wheel tracking tests (at the same load level) presented in Chapter 6. Measured surface profiles are presented in Figures 9-9a and 9-9b.

Typically, rut profiles show an increase in slab surface level at the rut edges, indicating rutting occurring within the emulsion mixture layer for slab S5. At a wheel load level of 1 kN, the maximum rut depth was 1.8 mm after applying 18230 passes. Generally, when applying a low level of wheel load, up to 2 kN, measured rutting depth indicated lower strains compared to those measured in the laboratory at similar stress levels on small size specimens (Chapter 6). But, increasing the wheel load to 4 kN resulted in severe ruts. Measured rut depth was approximately 7 mm for slab S5 and 12 mm for slab S2. A comparison of the measured ruts for slab S2, the permanent deformation measured in the triaxial mode at a similar stress level, and the wheel tracking test results can be seen in Figures 9-10 to 9-12. However, a steep strain rate was always associated with tests at applied load levels of 3 to 4 kN and the measured rut depth

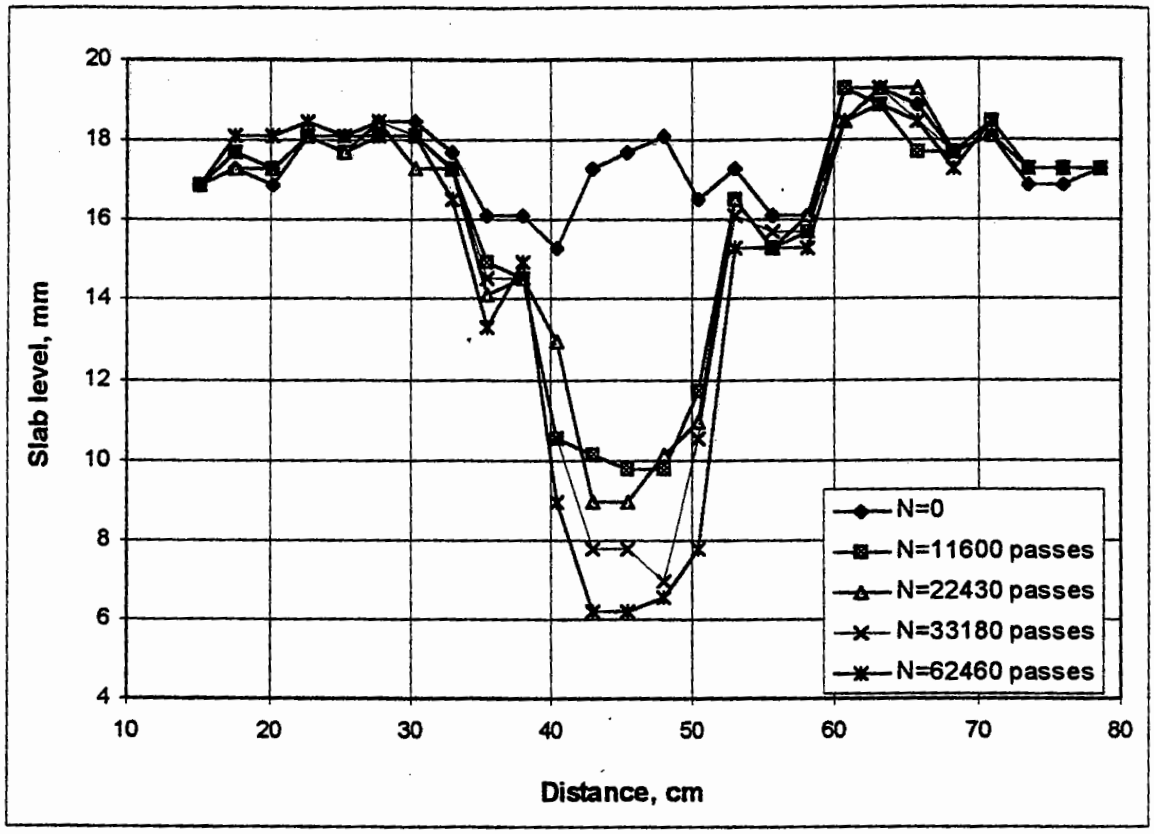


Figure 9-9a Rut profiles of wheel tracking in the STF on slab S2

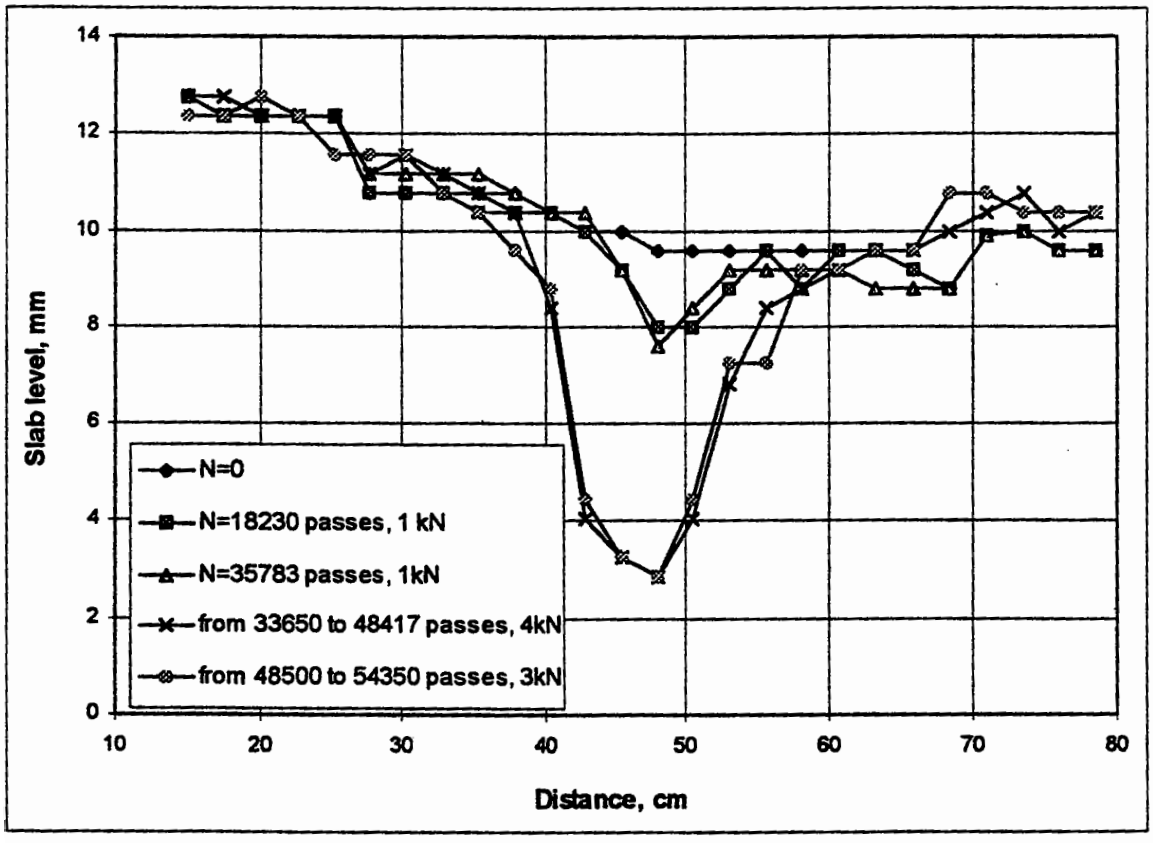


Figure 9-9b Rut profiles of multi-stage wheel tracking in the STF on slab S5

is not in line with predictions from small size specimens. The thought was that severe rutting could be a result of severe settlement in the underlying layer, since only limited formation of shoulders occurred at the rut edges, or rather only a small increase in the slab level was observed.

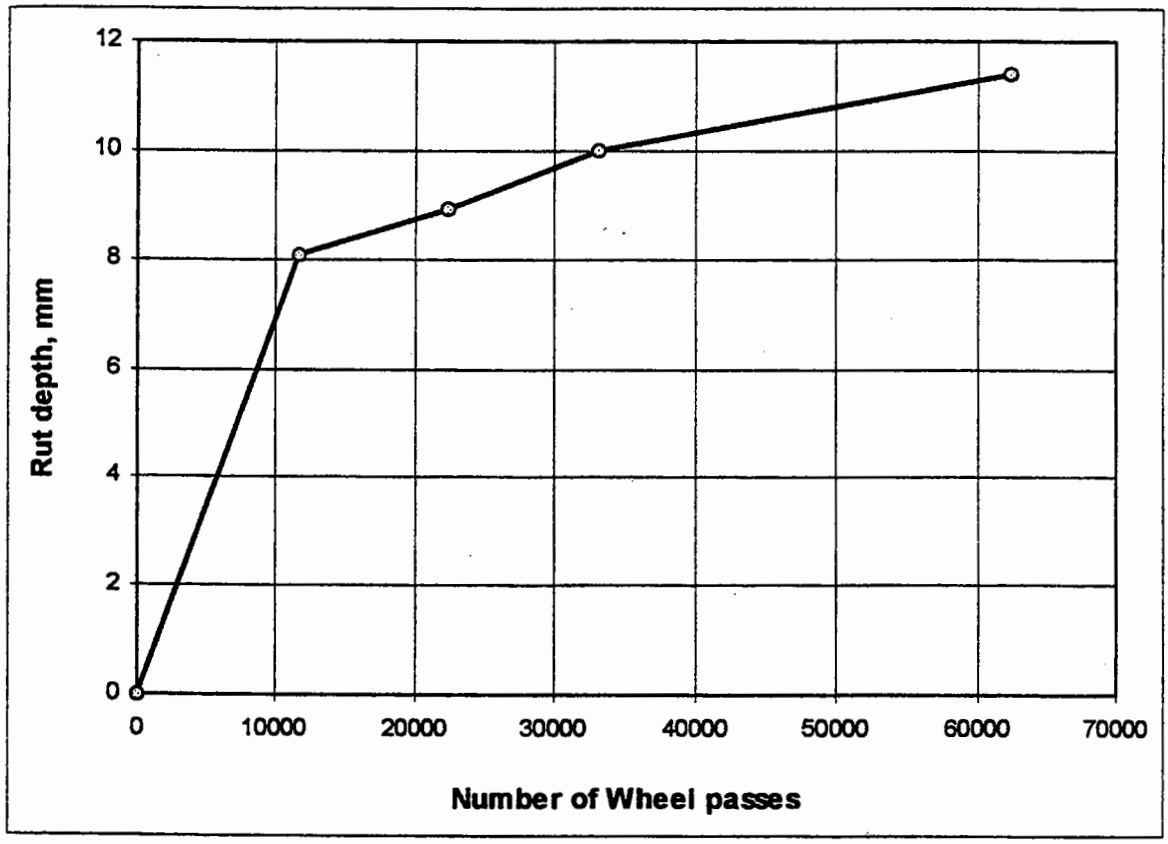


Figure 9-10 Rut depth of wheel tracking on Slab S2 in the STF as a function of wheel passes

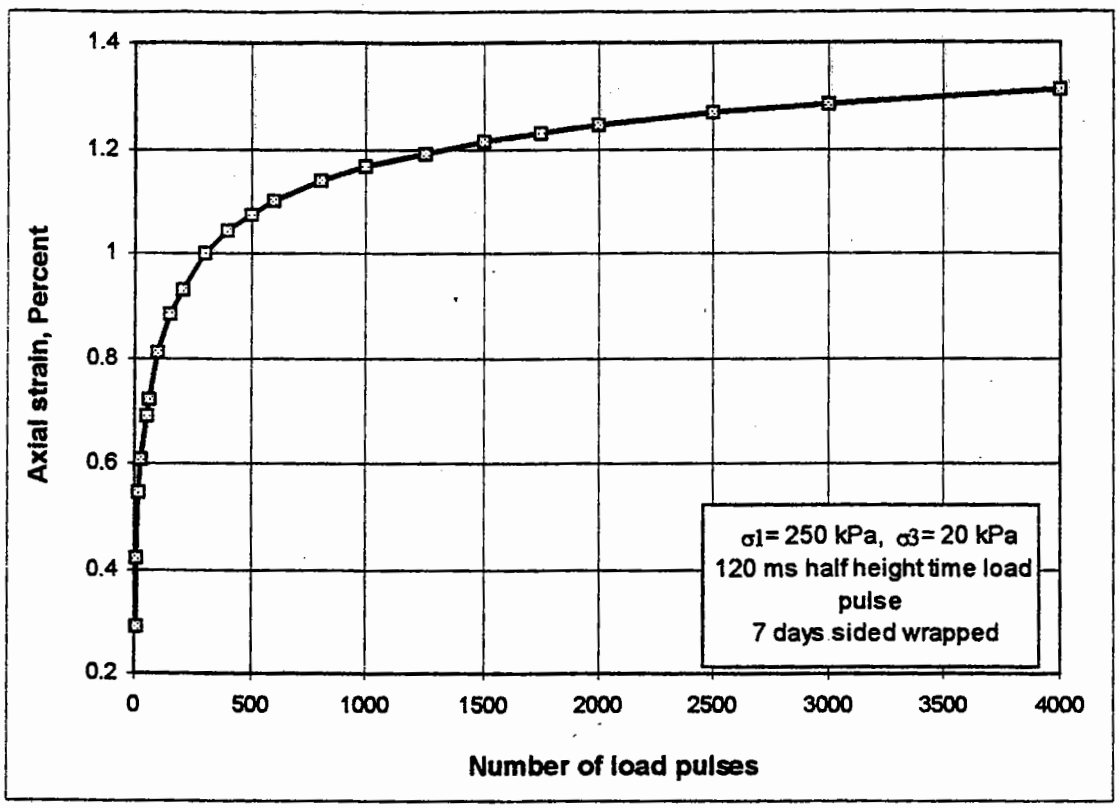


Figure 9-11 Permanent axial strain of redicote specimens, containing 12.1 % void content, in the triaxial mode of the NAT

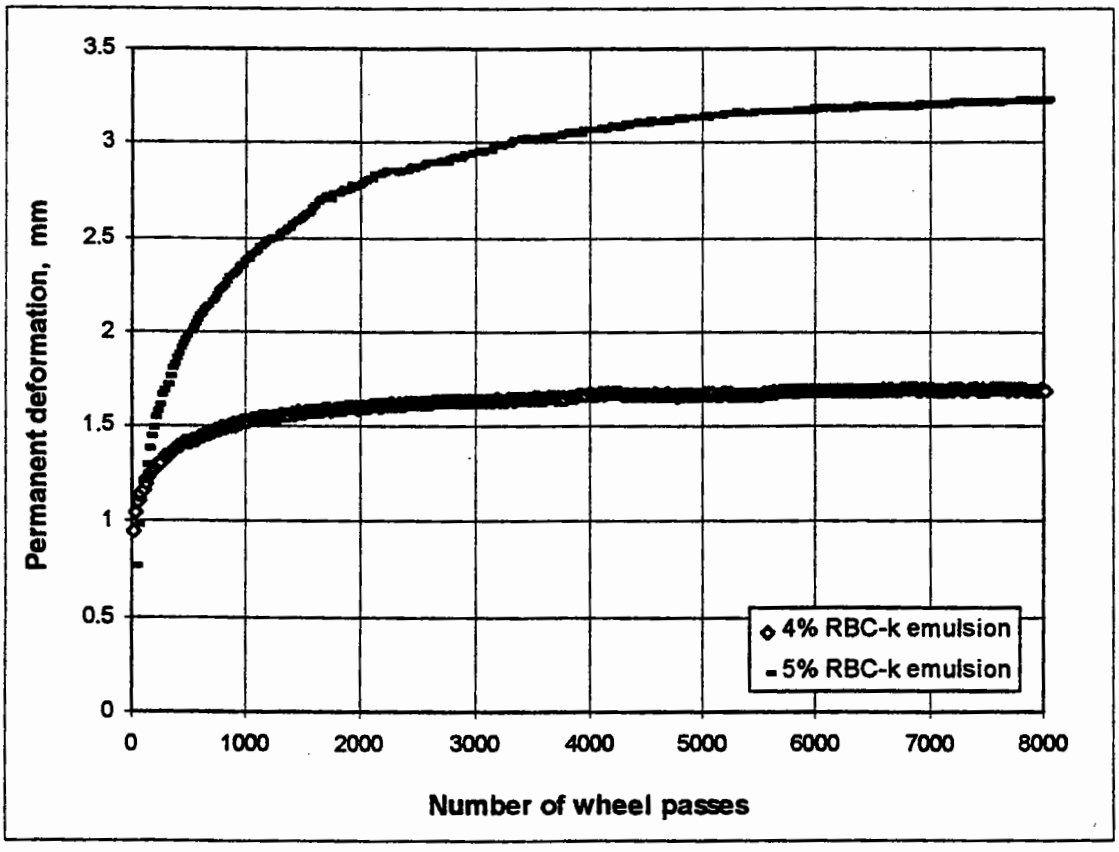


Figure 9-12 Permanent deformation of redicote slabs containing 4 and 5 % RBC, in the wheel tracking test (curing for 4 days at room temperature, and tested at 20°C)

Of course, as a consequence of settlement in the supporting layer, the overlaid layer will bend and an increase in the horizontal strains occurs. As long as no change in the horizontal strain gauges was recorded, structural deformation was not occurring. Nevertheless, the slabs were sawn laterally after testing, for visual inspection of the crack formation, location, and orientation. In addition, thickness and levels of the layers were measured under and off the wheel path. Having investigated the sawn slabs, the following were observed:

- Cracks were visible at the edges of ruts, penetrating from the surface to a quarter depth of the slabs.
- No crack was observed at the bottom of the emulsion mixtures.
- Thickness reduction was only evident within the emulsion mixture layers.

It is therefore expected that the severe rutting in emulsion mixtures was due to softening in the material under the high applied wheel load which may be related to a lack of bond between aggregate particles. This result was confirmed by testing a slab resting directly on a thin rubber sheet (slab 6), see Figure 9-13.

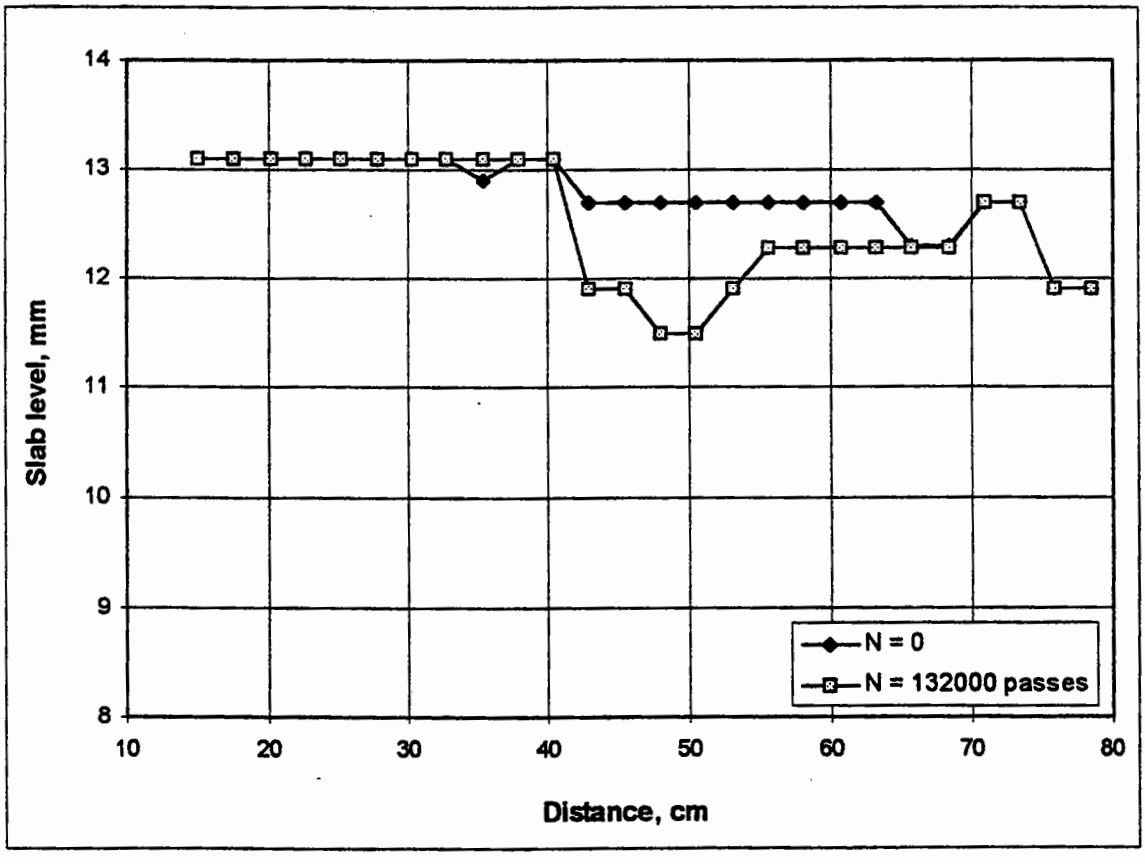


Figure 9-13 Rut profile of slab S6 in the slab test facility, wheel load 2.15 kN

As found in Chapter 6, permanent deformation of emulsion mixtures is mainly from densification of the material. The strain rate during the second stage of permanent deformation is low compared to hot mixtures, which may be a result of higher internal friction. Applying high wheel load may then break down that frictional resistance, leading to excessive deformation in the emulsion mixture layer.

9.3 SUMMARY

The level of wheel load is a significant factor affecting performance of this material. Excessive load might lead to deformation in the surface of the emulsion mixture layer which is considered to be due to a loss of cohesion, leading to less tensile stress resistance and occurrence of cracks at the layer surface. Based on the above discussion, two cases associated with emulsion mixtures can be distinguished. When applying a low wheel load, there is little rutting and reasonable fatigue resistance, but the failure is prone to be in fatigue rather than in rutting . When applying high wheel load, excessive rutting is expected and the failure will be in rutting rather than in fatigue.

It is apparent that emulsion mixtures behave in a similar way to granular materials rather than hot asphaltic mixtures, even after significant curing.

CHAPTER

10 BINDER RHEOLOGY AS A FUNCTION OF CURING

Undoubtedly, properties of emulsion mixtures depend greatly on the binder characteristics that develop over the curing period. At early stages of curing, a lower stiffness modulus, high permanent strain rate, and low water resistance have been observed, all related to the mixture water content, which influences both binder characteristics and mixture cohesion. At later stages, as the water content of the mixture approaches an equilibrium state, better responses have been reported. In comparison with the hot mixtures, the material shows different behaviour. The water content of the material is a significant factor influencing the binder properties and, as a consequence, the mixture response.

In this chapter, the effects of water content on the flow characteristics of the binder, and filler content on the flow characteristics of the bitumen-filler mastic are presented. Characterisation of emulsion residue compared to the base bitumen is also highlighted. Experiments were carried out in the dynamic shear rheometer (DSR). Modification to the rheometer base plate to allow testing of emulsion at different curing times is also described.

10.1 RHEOLOGICAL MEASUREMENTS

Bitumen is a temperature susceptible material in that it behaves as a viscous fluid (flow under shear loading) at very high temperatures, as an elastic solid at very low temperatures, and in a viscoelastic manner at intermediate temperatures, the typical conditions experienced in pavements. Consequently, bituminous mixtures behave viscoelastically, being both time and temperature dependent. Therefore, both time of loading and temperature are considered in characterising the flow properties of the material.

Two groups of tests are used in measuring the flow properties of bitumen. Tests used for grading bitumen according to its consistency, such as the penetration test, softening point 'ring and ball' test, and viscosity measurement tests. Such tests are conducted at different regions of the bitumen temperature response (penetration for semi-solid range, softening point for beginning of fluidity range, and viscosity for fluidity range). Grading of bitumen using these tests therefore is largely based on measured empirical parameters and hence unsuitable for characterising the viscoelastic behaviour of bitumen. A second group of tests measure fundamental rhelogical properties of viscosity and stiffness of bitumen, enabling characterisation of the viscoelastic behaviour of bitumen, such as the dynamic shear rheometer and the bending beam rheometer. Viscosity measurement is generally used to characterise bitumen emulsion for mixing requirements.

In this study, the dynamic shear rheometer was utilized to determine complex modulus, viscosity, and phase angle of emulsions with different water contents in them (including emulsion residues, zero water content) and emulsion-filler mastics.

10.2 DYNAMIC SHEAR RHEOMETER

This test is used to measure the viscoelastic properties of bitumen in the linear region. Two modes of test can be conducted, strain controlled in which sinusoidal strain is applied to a bitumen sample (i.e. oscillating the spindle) and the resulting stress is recorded, and stress controlled in which a sinusoidal varying stress is applied and the strain response measured. Testing in the linear region of viscoelasticity necessitates keeping strains small, the strain controlled mode of testing therefore is commonly used. The main components of the dynamic shear rheometer are presented in Figure 10-1 and the stress-strain functions are shown in Figure 10-2.

In the dynamic shear rheometer, or rather the oscillatory shear test, a bitumen sample is placed between a fixed base plate and a spindle. The required gap 'h' that defines

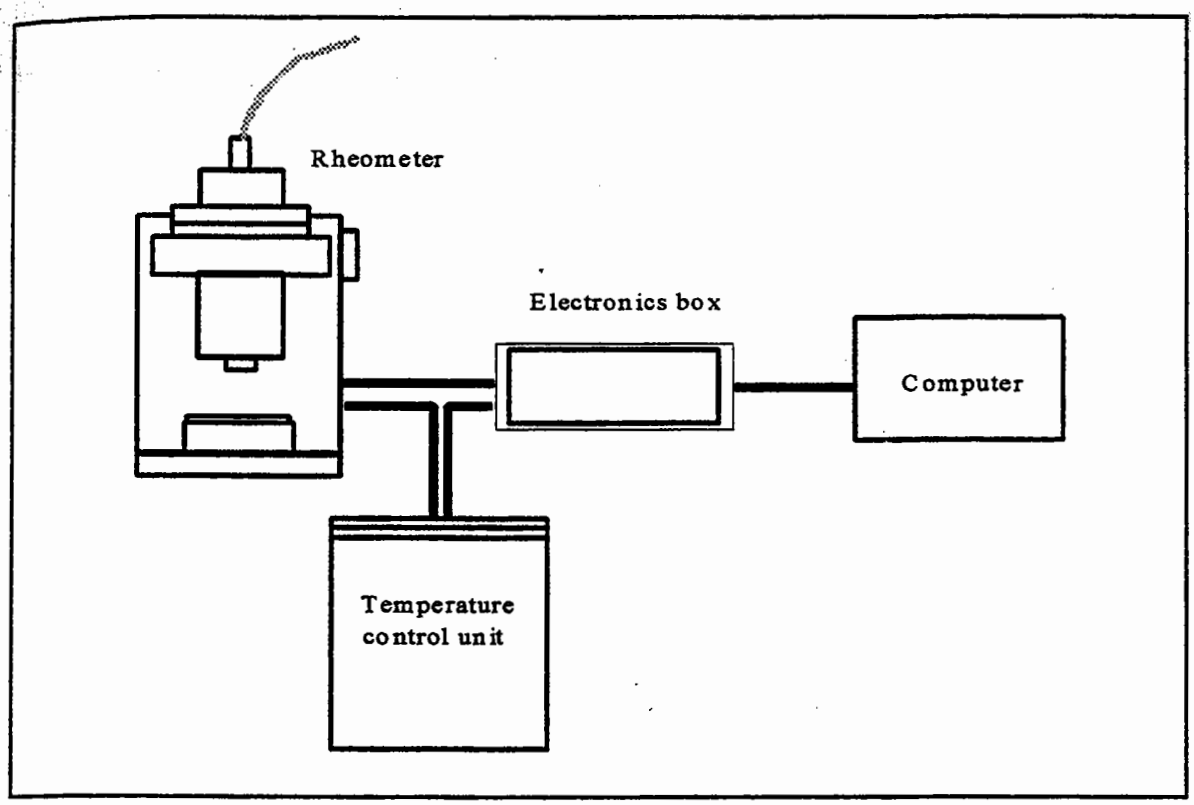


Figure 10-1 Main connections of the dynamic shear rheometer

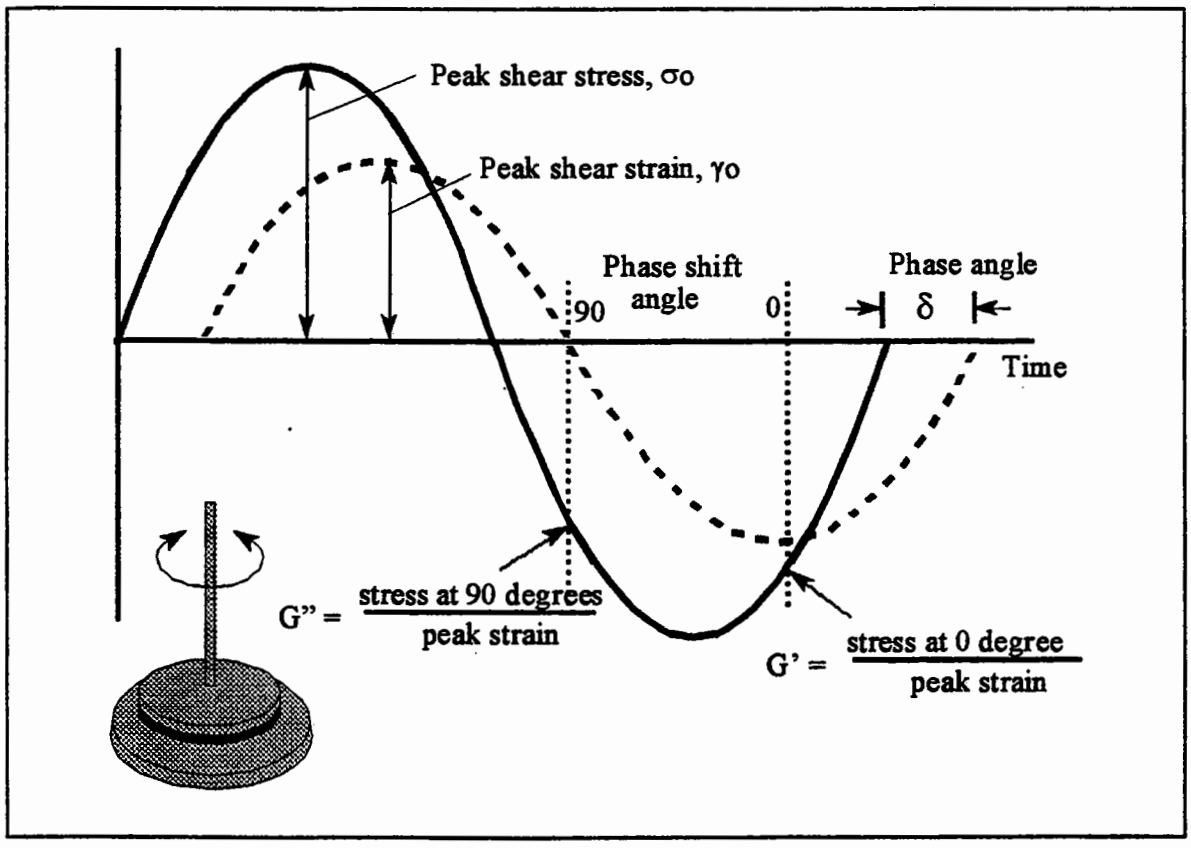


Figure 10-2 Dynamic oscillatory stress-strain functions and test outputs

the sample thickness can be set using a Vernier on the top of torque motor in the rheometer. The sample is then subjected to a sinusoidal strain (constant amplitude and frequency) and the corresponding stress amplitude is measured. The shear stresses 'τ' and shear strains 'γ' are calculated from:

$$\tau = \frac{2T}{\pi r^3} \tag{1}$$

and $$\gamma = \frac{\theta r}{h} \tag{2}$$

where:

τ = shear stress, Pa

T = applied torque, Nm

r = radius of spindle, m

γ = shear strain, m/m

θ = deflection angle of the spindle, radians

h = gap setting 'bitumen thickness', m

Spindle size is chosen according to the expected stiffness of the bitumen, the higher the stiffness the lower the spindle size. The spindle size used in this study is 25 mm diameter. Gap setting is generally in the range of 0.5 to 2 mm.

10.2.1 Complex Modulus and Viscosity Determination

In a sinusoidal strain, dynamic oscillating shear strain 'γ^*' can be represented by:

$$\gamma^* = \gamma_0 e^{i\omega t} \quad \text{or} \quad \gamma^* = \gamma_0 \sin \omega t \tag{3}$$

where:

γ_0= peak shear strain

ω = angular frequency, radian/sec = $2\pi f$

f = frequency, Hz

The developed dynamic oscillating shear stress on the other hand is sinusoidal and out of phase with the applied strain. This can be represented by:

$$\tau^* = \tau_0 e^{i(\omega t + \delta)} \quad \text{or} \quad \tau^* = \tau_0 \sin(\omega t - \delta) \tag{4}$$

where:

τ^* = dynamic oscillating shear stress, Pa

τ_0 = peak shear stress, Pa

δ = phase angle, degrees

The complex shear modulus G* then can be calculated from the ratio of the resulting shear stress to the applied shear strain as follows:

$$G^* = \frac{\tau^*}{\gamma^*} = \frac{\tau_0}{\gamma_0} e^{i\delta} \tag{5}$$

or

$$G^* = \left(\frac{\tau_0}{\gamma_0}\right) \cos\delta + i \left(\frac{\tau_0}{\gamma_0}\right) \sin\delta$$

$$= G' + iG'' \tag{6}$$

The ratio of the peak stress to the peak strain τ_0/γ_0 is the absolute value of the complex shear modulus $|G^*|$. As seen in equation 6, the complex shear modulus G* which measures the total strain resistance of the material to the subjected shear stress is comprised of two components. The real part G' is designated as the storage modulus or the elastic component in which the stress is in phase with the strain and equal to $|G^*| \cos\delta$. This term represents the amount of stored energy in each oscillation. The imaginary part of the complex modulus G" is designated as the loss modulus or the viscous component in which the stress is 90 degrees out of phase with the strain and equal to $|G^*| \sin\delta$, representing the average energy dissipation rate in continuous steady oscillation.

Normally, the moduli are presented in plane Cartesian coordinates as in Figure 10-3. As seen, the phase angle or phase lag between shear stress and shear strain responses

10.2.2 Specimen Preparation and Modification of Base Plate

The present base plate configuration of the dynamic shear rheometer allows testing of base bitumen, modified bitumen or recovered bitumen from emulsion. Normally, the sample is prepared by first heating up and stirring the material in an oven or on a hot plate until it reaches sufficient fluidity for pouring the required specimen. This process ensures homogeneity and removes air bubbles. Then, after cleaning and drying the surface of both the spindle and the base plates, the pre-determined weight of bitumen is poured into the base plate. According to the Bohlin Rheometer Manual, the temperature of the base plate should be room temperature at the time of pouring the material so that the sample solidifies into an elliptical mass. On the other hand, the AASHTO TP5 (in Petersen et al, SHRP project 1994) specifies bringing the base plate to approximately 45°C prior to the mounting of the test specimen so that the bitumen may be squeezed between the plates. Generally the sample is surrounded with circulating fluid and the test temperature is controlled using a special unit and sensitive temperature sensors in contact with the rheometer base plate.

The rheological properties of bitumen emulsion with different water contents including emulsion residue recovered by evaporation at room temperature are difficult to measure using the current configuration of the rheometer base plate. Preparing an emulsion sample with a certain water content, or even after curing, gives difficulties in handling and placement, if the above procedure is followed. One of the reasons is that heating up the material causes evaporation of water and probably leads to some coalescence of bitumen droplets on to each other, consequently overestimating the stiffness and viscosity. Also, as experienced in this study in preliminary work, heating emulsion leads to foaming and inhomogeneity of the material. Another problem that might be encountered is excess flow of the liquid emulsion over the surface of the base plate. In addition, when testing partially cured emulsions, controlling sample temperature by covering with fluid may lead to re-emulsification and then liquefaction of the sample.

Consequently, modification to the base plate of the rheometer was made in this study enabling preparation and testing of the sample. Stainless steel moulds with the shape

during a test is between 0 and 90 degrees. As the value approaches 90 degrees viscous behaviour of material is dominant; on the other hand, as it approaches 0 the behaviour is elastic. Under normal temperatures, the phase angle lies in between the two axes and the behaviour is viscoelastic. Hence, the value of phase angle is an indication whether the material's complex modulus should be attributed to elastic or viscous behaviour.

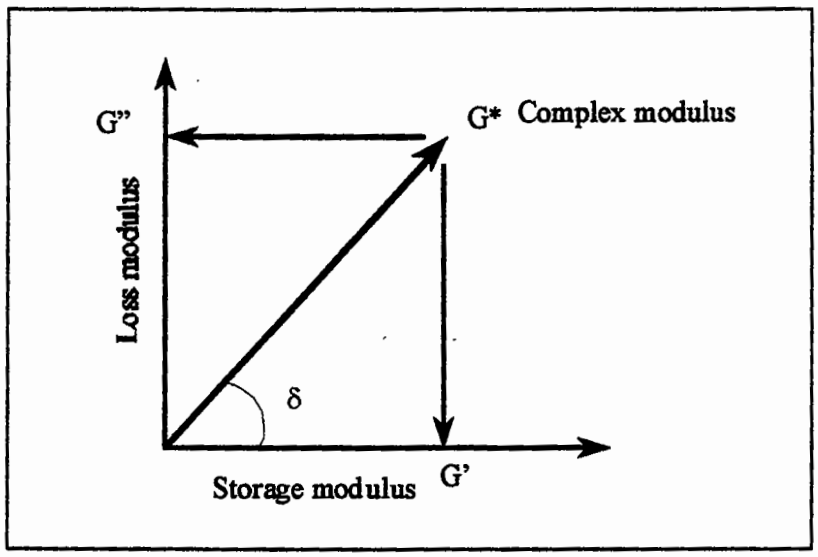


Figure 10-3 Definition of viscoelastic behaviour of bitumen

In addition, the bitumen viscosity as an important parameter in describing flow characteristics of the material can be determined from the dynamic shear rheometer, being the ratio of the complex modulus and the angular frequency. The term is then called complex viscosity η^*, comprising real and imaginary parts:

$$\eta^* = \frac{G' + iG''}{\omega}$$

The real part G'/ω is termed the dynamic viscosity η', while the imaginary part G''/ω is termed the out of phase component η'', both in Pa sec.

The complex modulus and viscosity of bitumen can be determined for a range of frequencies and temperatures.

and dimensions presented in Figure 10-4a and Figure 10-4b were manufactured. Considerable effort was made in making them easy to clamp and to hold in position below the spindle. With this arrangement, the fluid used in controlling the test temperature can be raised in the chamber around the mould without covering the sample.

Hence, with the modified base plate, samples were prepared by pouring a pre-determined weight of emulsion resulting in a sample height of 1.2 mm (required gap + 0.2 mm) into the moulds, and leaving them for the required curing time at 20°C. A point to note is that zero gap readings of each mould were taken using the vernier of the rheometer to enable proper gap setting.

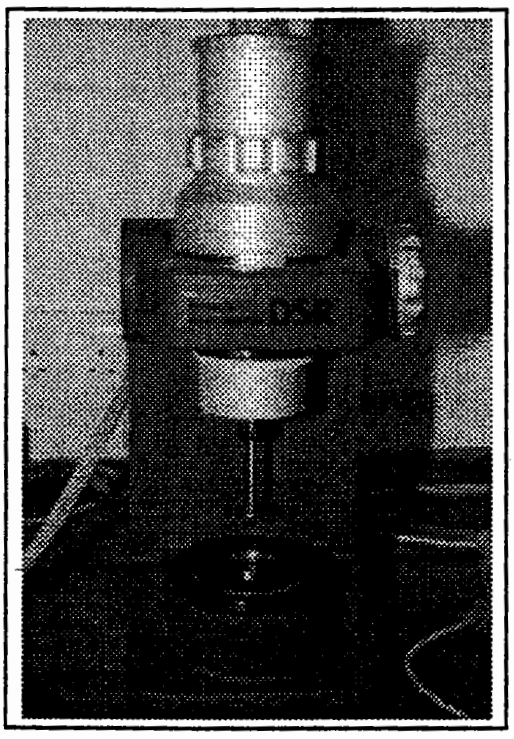


Figure10-4a The dynamic shear rheometer with the modified base plate

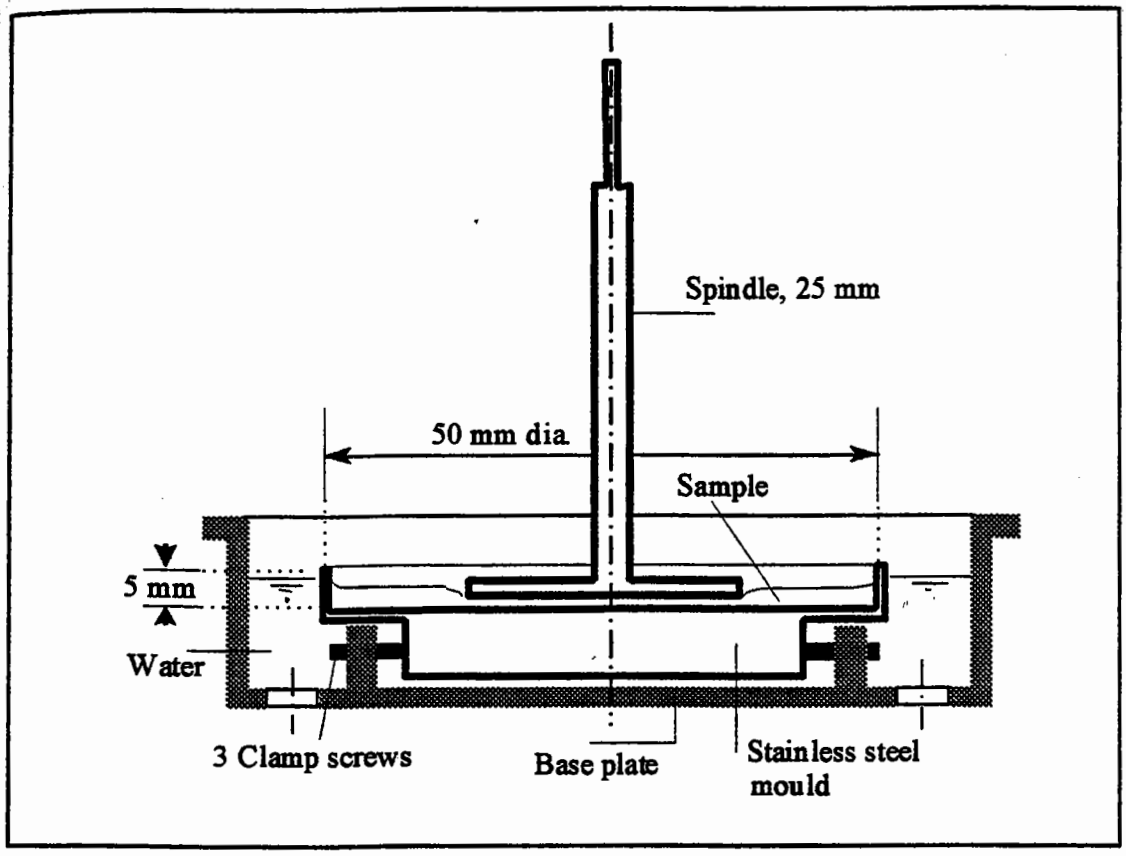


Figure 10-4b Diagram of the modified base plate used in the dynamic shear rheometer

10.2.3 Test Procedure

Prior to the test, the prepared sample being cured inside the mould was weighed for determination of water content at testing. The test procedure then was as follows:

- The vernier of the rheometer was set up at the reading that results in raising the spindle to the required gap (1 mm for most of the tests).

- The mould containing the sample was then clamped and fixed in its place below the spindle using the clamp screws shown in Figure 10-4.

- The water from the circulator connected to the rheometer was raised to a level above the sample level outside the mould. Care was given to the level of the water to avoid covering the sample. Test temperature was then controlled through the

software and the data acquisition system which control the circulator and heating system connected to the rheometer. However, when testing emulsion or partially cured emulsion, the base plate was brought to 20°C and the spindle lowered onto the sample. In contrast, when testing emulsion residue or base bitumen, the spindle was lowered after bringing the base plate to 60°C for softening and squeezing the sample and better adhesion with the plate of the spindle. Some emulsion samples containing lower water contents, being cured for one day at 20°C, were carefully brought to 40°C to avoid any hardening that may occur.

- To ensure testing in the linear region of the material's viscoelasticity, preliminary tests were conducted at different controlled strain levels. A strain level of 0.01 was found suitable for use over all test samples. The important point then was to ensure that both the measured strain and the target strain were similar; otherwise, the test had to be abandoned. Dissimilar strains were an indication of a fault in the settings; for instance, improper adhesion between the sample and the plates or an increase in the area of contact with the sample, resulting from adhesion to the perimeter of the spindle plate.

- Tests were carried out on the samples over a range of frequencies, between 0.1 to 10 Hz, and a range of temperatures between 20 to 40°C.

Typical test outputs are presented in Figure 10-5.

BOHLIN CS SYSTEM

Residual Emulsion 20/3

Oscillation test

30/09/96 16:24

P25DSR gap 1 mm

Manual temperature :

Measurement interval 1 No. of measurement 1

Shear stress 1.27E+04 Pa

Temperature 30 - 30.0 C

File name RBCK301

Time	Temp	Freq	Phase	Viscosity'	G*	G'	G"	Strain	Stress
s	C	Hz		Pas	Pa	Pa	Pa		Pa
12.3	30	0.1	77.95	5.55E+04	3.57E+04	7.45E+03	3.49E+04	9.91E-03	3.54E+02
29.9	30	0.2	75.85	4.88E+04	6.32E+04	1.55E+04	6.13E+04	1.01E-02	6.38E+02
39.5	30	0.5	73.49	4.15E+04	1.36E+05	3.87E+04	1.30E+05	9.97E-03	1.36E+03
45.6	30	0.7	72.48	3.86E+04	1.78E+05	5.36E+04	1.70E+05	1.00E-02	1.79E+03
50.7	30	1	71.25	3.58E+04	2.38E+05	7.64E+04	2.25E+05	1.00E-02	2.39E+03
55.4	30	2	67.85	3.02E+04	4.10E+05	1.55E+05	3.80E+05	1.00E-02	4.10E+03
62	30	5	60.82	2.25E+04	8.09E+05	3.94E+05	7.06E+05	1.00E-02	8.08E+03
66.7	30	10	53.59	1.62E+04	1.27E+06	7.52E+05	1.02E+06	1.00E-02	1.27E+04

Figure 10.5 Typical output from the dynamic shear rheometer in the oscillation mode on residual emulsion

10.3 PRESENTATION AND ANALYSIS OF RESULTS

10.3.1 Viscoelastic Properties of Emulsion Residue

It has been shown that when bitumen emulsion is in contact with aggregate particles, it passes through different processes, mainly due to water evaporation. Separation of the dispersed phase resulting in sedimentation of bitumen droplets, followed by closing up of the bitumen droplets forms a discontinuous film, then coagulation, forming a compact mass, occurs. Hence, the material shows different behaviour at early and late stages of curing, related to the water content.

Effect of Water Content

Tests were carried out in the dynamic shear rheometer on residues of K-emulsion, being obtained from curing at 20°C for different times. Test results are presented in Figures 10-6 to 10-8. The Figures show plots of the measured parameters (complex modulus G*, storage modulus G', loss modulus G", phase angle δ, and viscosity η) as a function of frequency Hz, for three different states of curing, as follows:

1. Curing for 2 days, resulting in zero water content, i.e., representative of the recovered bitumen.
2. Curing for 16 hours, resulting in 5.14 % water content,
3. Curing for 4 hours, resulting in a water content of 26.4 %, as a ratio of the bitumen weight.

It can generally be seen from the Figures that as the test frequency increases the parameters G*, G', and G" increase and both of the phase angle and the dynamic viscosity decrease. Clearly, the level and rate of change of the measured parameters are dependent on the sample condition. For the recovered bitumen sample, two regions of frequencies divided by frequency f_{45}, at which G' = G" and phase angle = 45 degrees, can be distinguished. Below this frequency, G" > G', the sample shows more viscous than elastic response, or rather the dissipated energy is relatively more than the stored energy and phase angle > 45 degrees. On the other hand, at higher frequencies (> f_{45}), phase angle < 45 degrees and the material response is mainly elastic as the dissipated

gy decreases significantly and the sample stores most of the energy. However, a parison amongst the test results for different curing times shows that the storage dulus G' and loss modulus G" tend to be equal at different frequencies as the phase gle decreases towards 45 degree, being higher for the less cured sample.

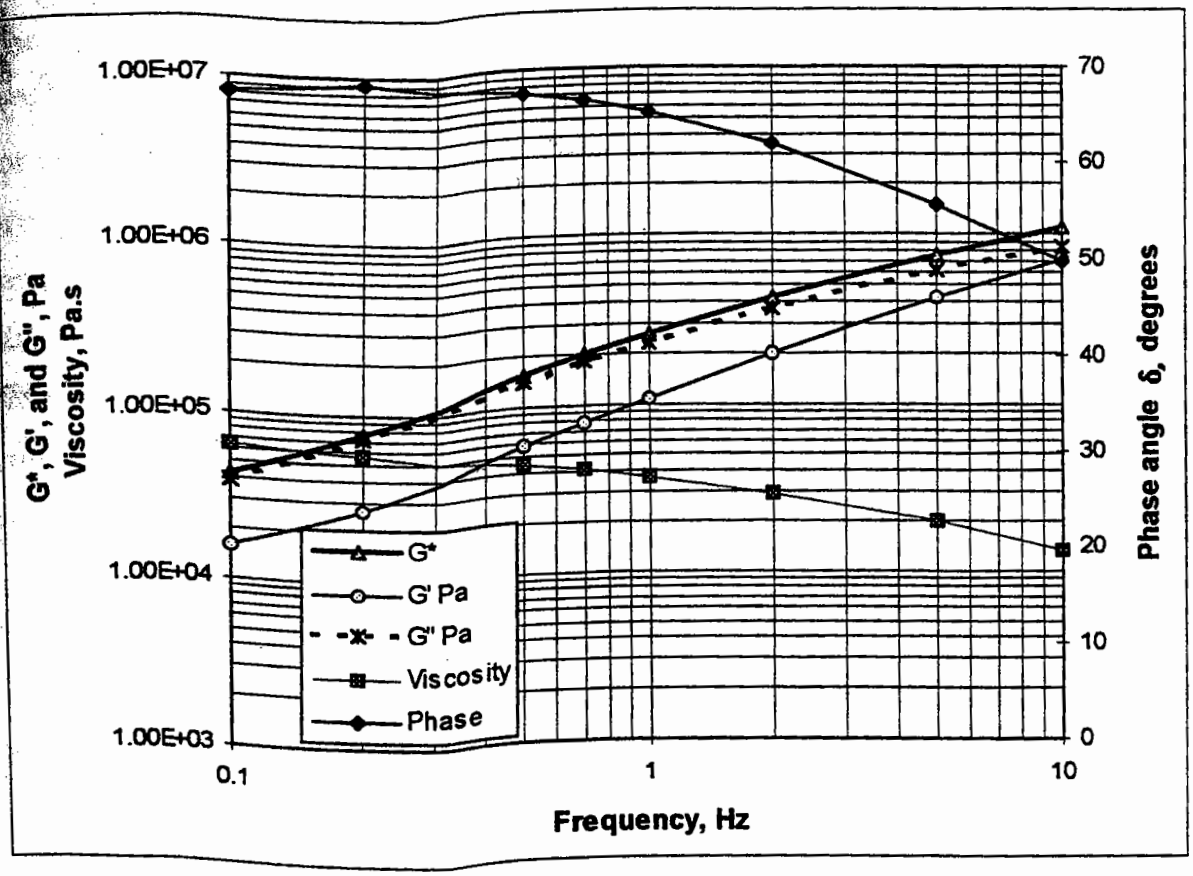


Figure 10-6 Rheological parameters of recovered binder from K-emulsion in the dynamic shear rheometer (0 % water content and test temperature 20°C)

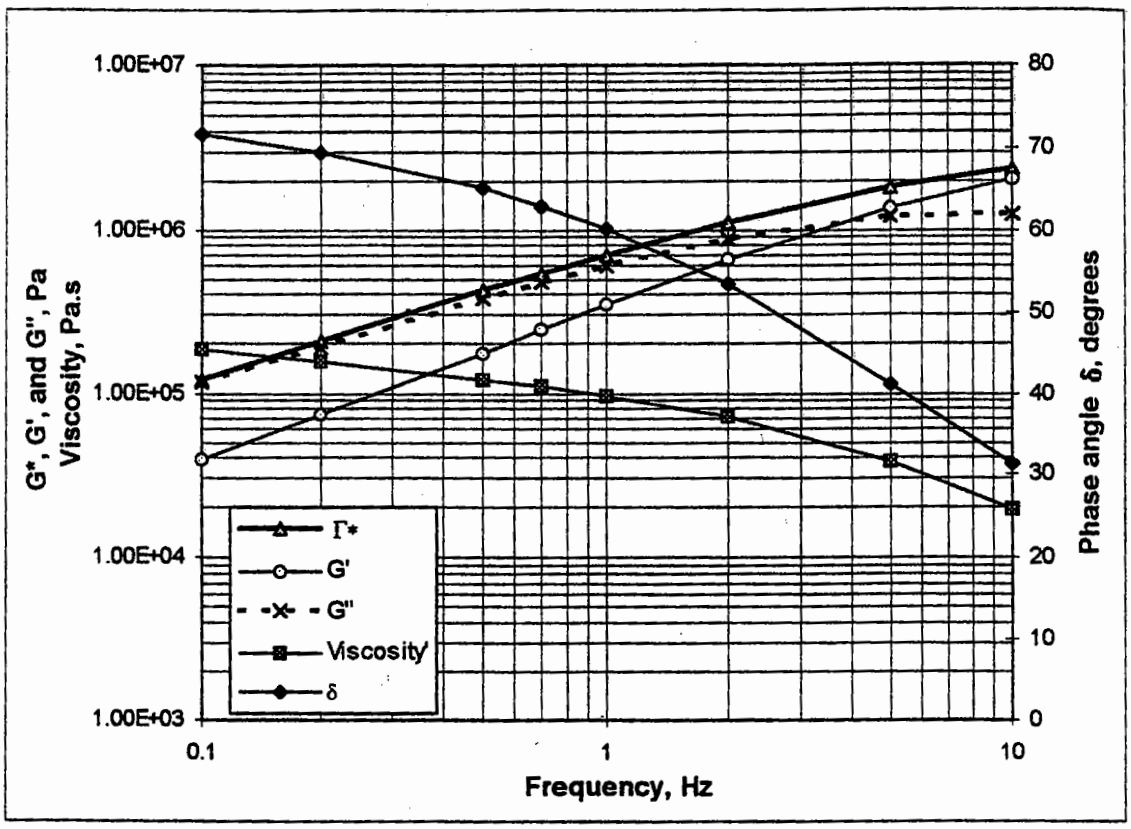


Figure 10-7 Rheological parameters of K-emulsion cured for 18 hours at 20°C in the dynamic shear rheometer (5.14 % water content and test temperature 20°C)

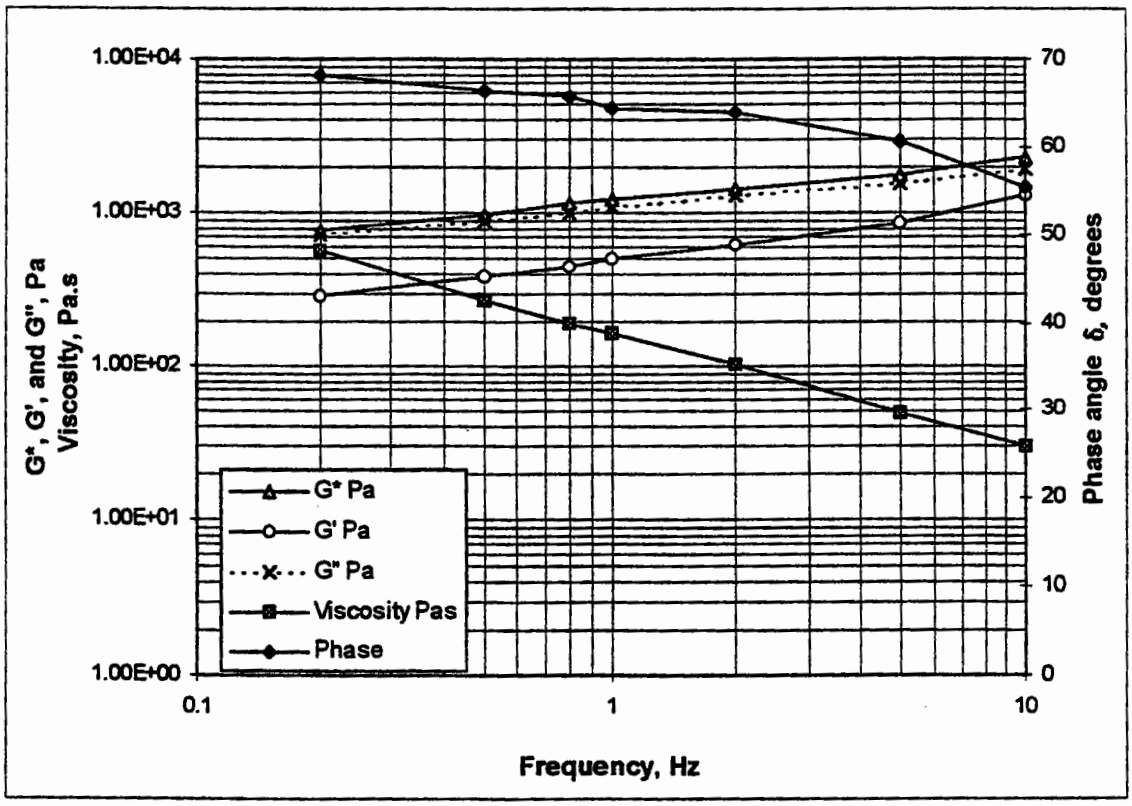


Figure 10-8 Rheological parameters of K-emulsion cured for 4 hours at 20°C in the dynamic shear rheometer (26.4 % water content and test temperature 20°C)

Clearly, as the material cured and water was lost the complex modulus increased and the rheological response generally improved. The storage modulus (elastic response) increases relative to the loss modulus (viscous response) as indicated by the frequency at which G' and G" are equal or phase angle δ equals 45 degrees. The lower the frequency at which G' = G" the more the material tends to behave elastically.

Temperature Susceptibility

The empirical measures of penetration index 'P.I', penetration-viscosity number 'PVN', and the use of bitumen test data chart described in Chapter 2, are unsuitable for use in characterisation of the temperature susceptibility of emulsion residues. As previously discussed, these methods require measurements at relatively high temperatures, e.g., softening point or viscosity which would affect the structure of the binder at a certain state of curing and alter its actual characteristics. Recovering bitumen from emulsion at normal temperatures for penetration tests was difficult. Non-homogeneity, uneven surface, and foaming (in the case of curing at high temperatures) were always present.

Therefore, the rheological parameters of the emulsion residues previously described were determined in the dynamic shear rheometer, as a function of temperature at a frequency of 2 Hz. This level of frequency, or rather test loading time, was used as it corresponds to the loading time of testing in the NAT on mixture specimens, see Chapter 5. The results are presented in Figure 10-9. Clearly, the change in the determined absolute complex modulus and phase angle of the two binders, obtained from two different curing times, are quite different. The fully recovered binder (zero water content) shows more susceptibility to temperature than the binder containing some water in it (5.14 % based on the bitumen weight). At lower temperature the complex modulus is much higher and the binder exhibits more elastic response, indicated by the phase angle. As the temperature increases the complex modulus falls to a similar value to that of the less cured binder and the response is more viscous.

However, at early curing the material is less temperature susceptible. As the material cures with time it tends to become more temperature susceptible. This lower temperature susceptibility of binder at early stage of curing might be a contributing factor to the low differences experienced in the permanent deformation of partially cured emulsion mixture specimens measured in the NAT.

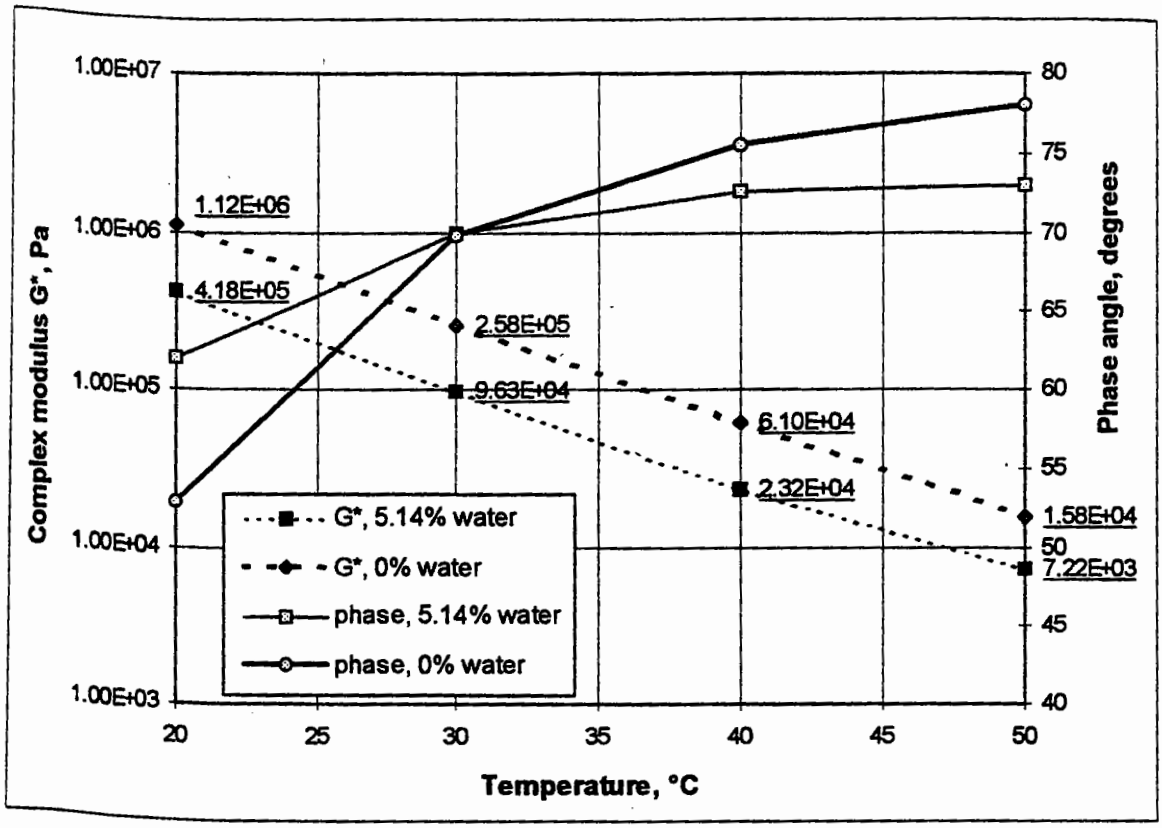


Figure 10-9 Isochrone of the complex modulus and phase angle of emulsion residues as a function of temperature and curing at 2 Hz

10.3.2 Contribution of Binder to Mixture Response

It was reported that water in an emulsion mixture decreases with time until it reaches an equilibrium condition, after which time an increase in the material stiffness continues to occur. Of reasons reported for this increase in material stiffness are aging of binder and reaction of binder with aggregate particles developed over time. Some water remains in the emulsion mixture, contributing to a limiting of the material's performance. Whether this limitation on material properties is attributable to a binder softening or a loss in adhesion with aggregate particles is a point of question.

Presented in Figure 10-10 is the determined water content contained in bitumen emulsion samples against the measured complex modulus at 2 Hz. As seen, the binder response is quite sensitive to the contained water. Just 5.14 % water within the binder, representing a water content of 0.26 % of the aggregate weight in an emulsion mixture containing 5 % RBC, reduced the complex modulus of the binder from 1.11E+03 to 4.18E+02 kPa. More water in the binder, e.g. 17.1 %, representing 0.86 % in a mixture with 5 % RBC, resulted in dramatic reduction in the complex modulus to 1.79E+01 kPa and the material generally showed a predominantly viscous response.

The results presented in Figure 10-11 are for emulsion mixture specimens containing fine grade aggregate and 5 % RBC of K-emulsion, tested in the NAT in the indirect tensile mode, as described in Chapter 5. A limited variation in water contents led to a great increase in stiffness. A decrease of water content from 0.88 to 0.58 % caused a limited increase in stiffness from 1035 to 1337 MPa. In contrast, changing in water content from 0.58 to 0.33 % led to a larger increase in stiffness, from 1337 to 3288 MPa.

The binder alone did not show a reasonable value (i.e. equivalent to pure bitumen) of complex modulus until all water had been evaporated. On the other hand, the mixtures achieved considerable stiffness modulus values, despite the contained water content. The conclusion is that most of the water is therefore not in the binder within the mixtures. Based on the binder results, with even a small proportion of water contained in the binder, the mixture specimens would have had much lower stiffness in the indirect tensile mode of test. This implies that, both binder hardening and binder/aggregate adhesion continuously build up during the early stages of curing. Once a low mixture water content is attained, little further binder hardening takes place due to water loss and increase in adhesion between the binder and aggregate is then the main factor, contributing to the considerable increase in stiffness experienced at later stages of curing.

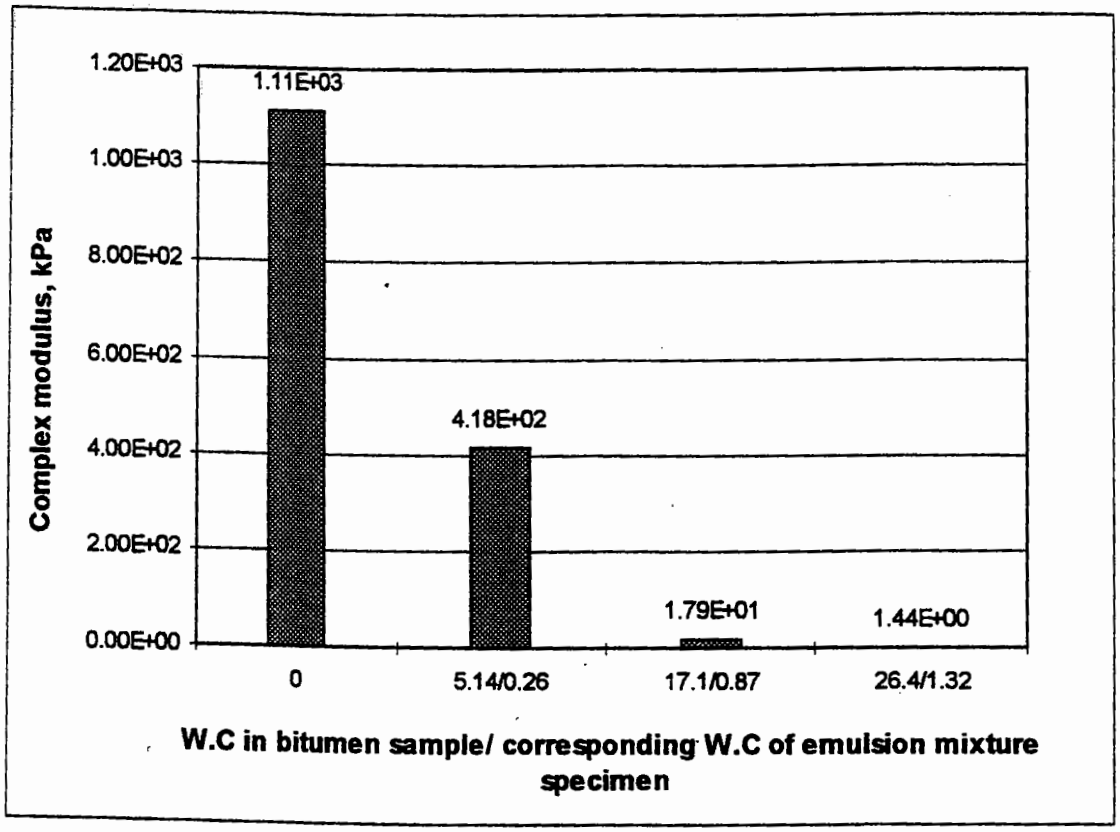


Figure 10-10 Effect of water content within binder on the measured complex modulus in the dynamic shear rheometer

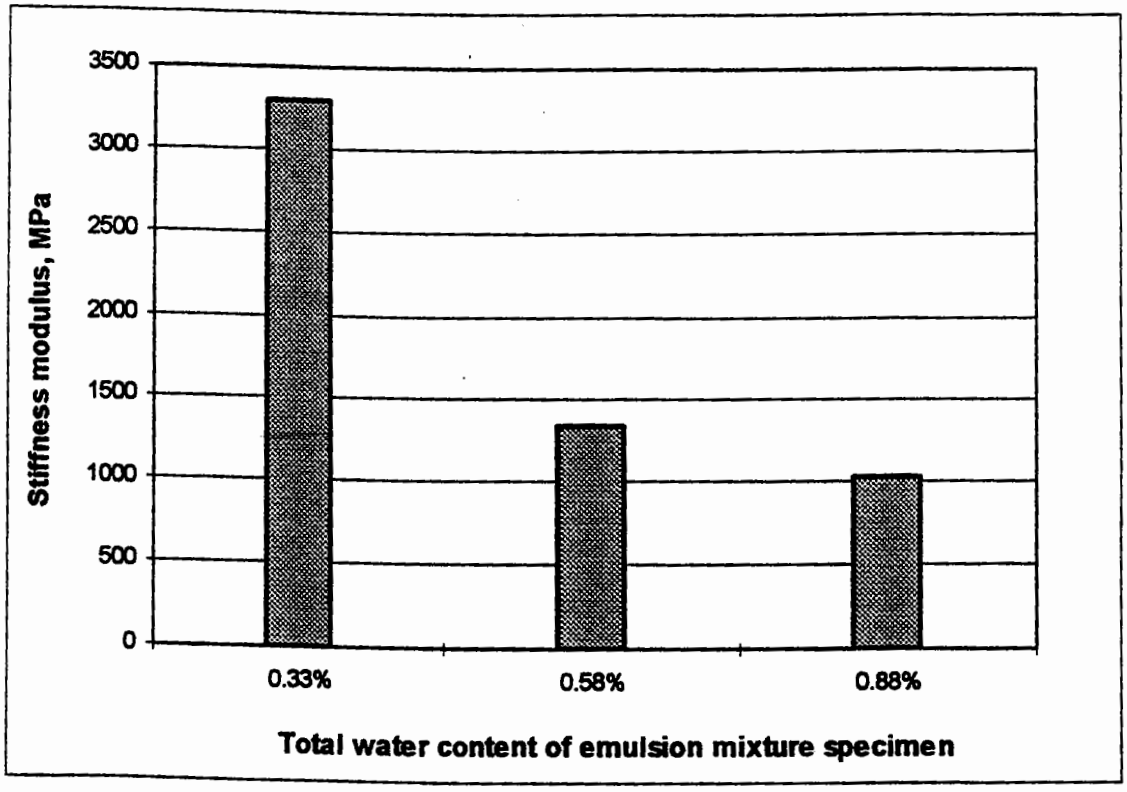


Figure 10-11 Effect of water content on stiffness modulus of emulsion mixture (from Chapter 5)

10.3.3 Recovered Bitumen versus Base Bitumen Rheology

Recovering of bitumen from an emulsion should be done in a way that does not influence its characteristics and allows it to be handled for further testing. Obtaining emulsion residues from evaporation processes rather than a distillation process has been followed by many researchers, although no concensus has been reached so far. The evaporation process generally involves either leaving a thin layer of emulsion on a fabric sheet at ambient temperature and at 50°C for 24 hours each, or storing the emulsion for several days at normal temperature after several days of stirring.

In this study, another way of recovering bitumen from emulsion was used. Emulsion residue was simply obtained by storing a thin film of emulsion within the fabricated stainless steel moulds previously described, at 20°C for just 48 hours. This way of obtaining a recovered bitumen was considered reasonable as long as the measured rheological parameters, complex modulus and dynamic viscosity, of both the recovered and original bitumens were similar over the range of frequencies and temperatures used. The results however were confirmed by running a comparable test on samples cured for 3 days at 40°C, from which similar trends of rheological response were found. The results are shown in Figures 10-12 to 10-14.

In addition, the responses of both bitumens were compared using phase angle values. Plots of phase angle versus temperature relationships are presented in Figure 10-15. In the Figure, the complex moduli of the binders are also reproduced as a function of the test temperature to enable comparison. As seen, the phase angle function shows some differences. The phase angles of the emulsion residues and the base bitumen are equal at a test temperature of 20°C. A difference then is apparent at higher temperatures. This difference increases as the temperature increases. In general, the phase angle of the base bitumen was higher over the test temperatures used. In terms of the complex modulus, no appreciable difference can be noticed.

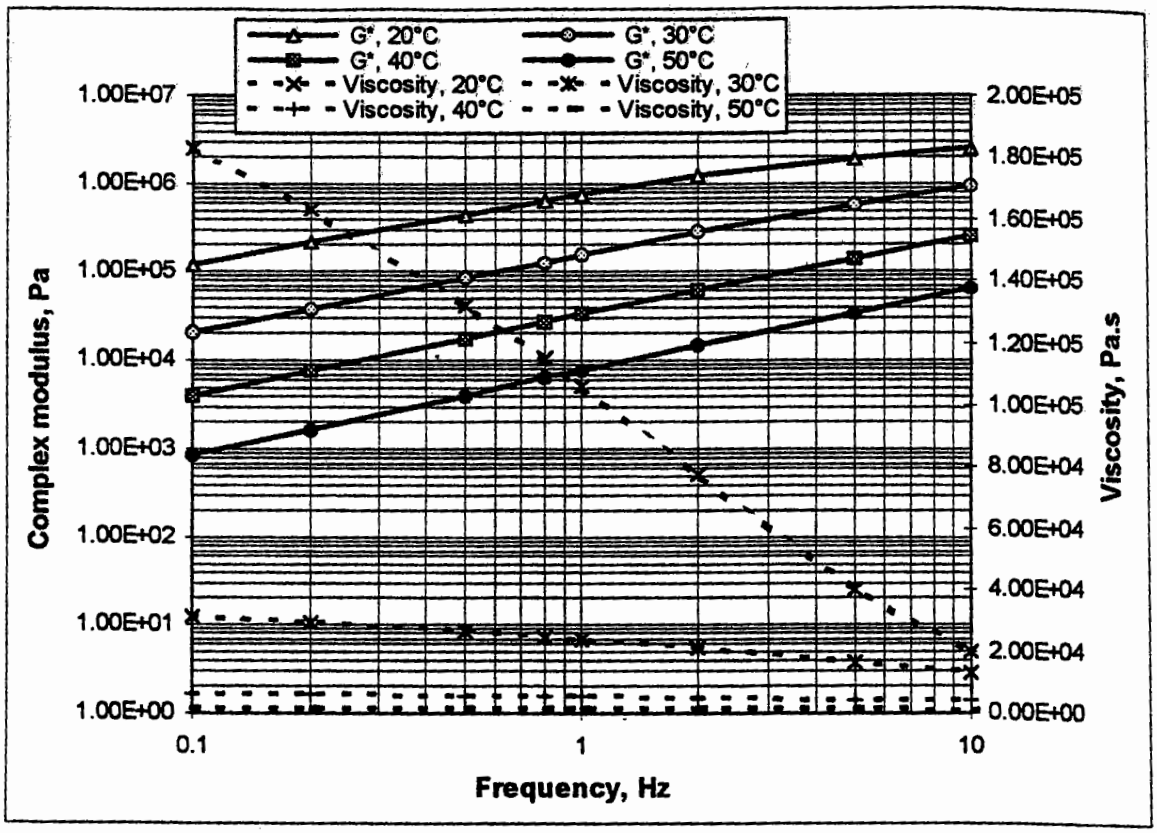


Figure 10-12 Effect of frequency and temperature on complex modulus and viscosity of base bitumen

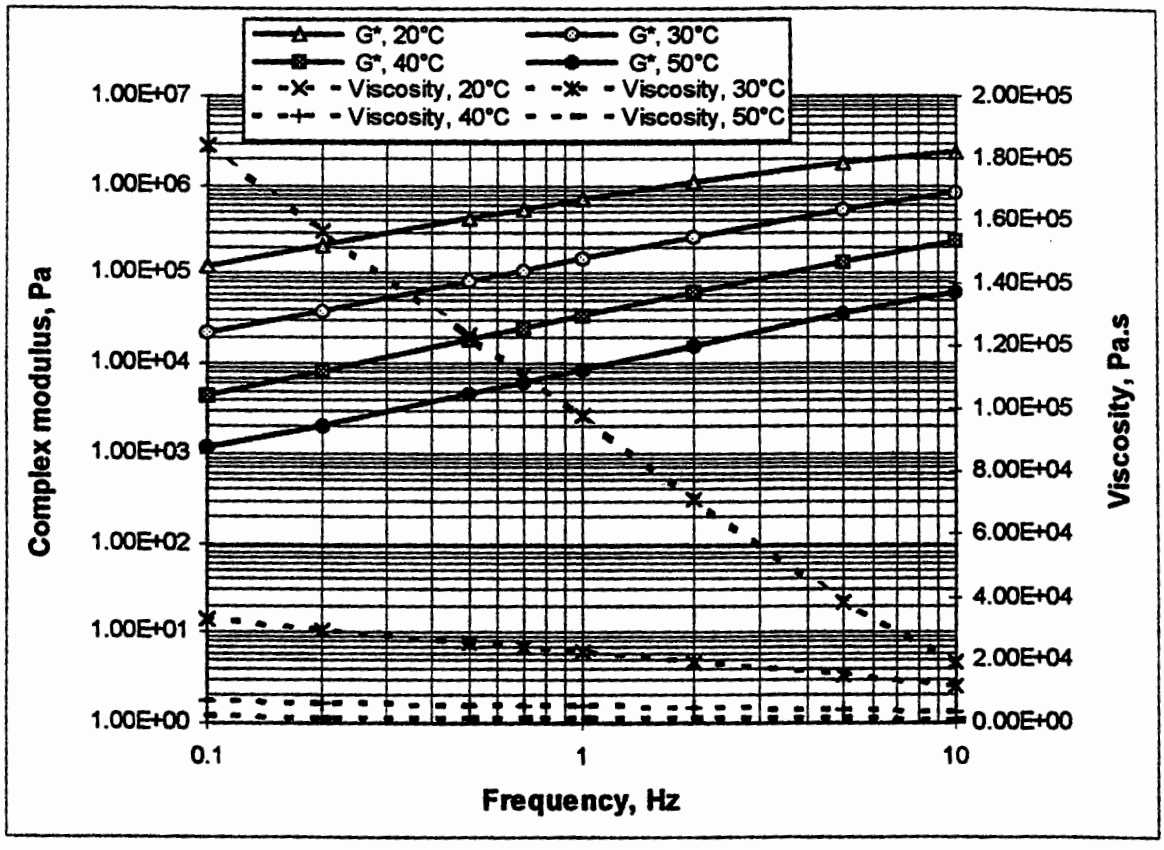


Figure 10-13 Effect of frequency and temperature on complex modulus and viscosity of emulsion residue from curing K-emulsion for 2 days at 20°C

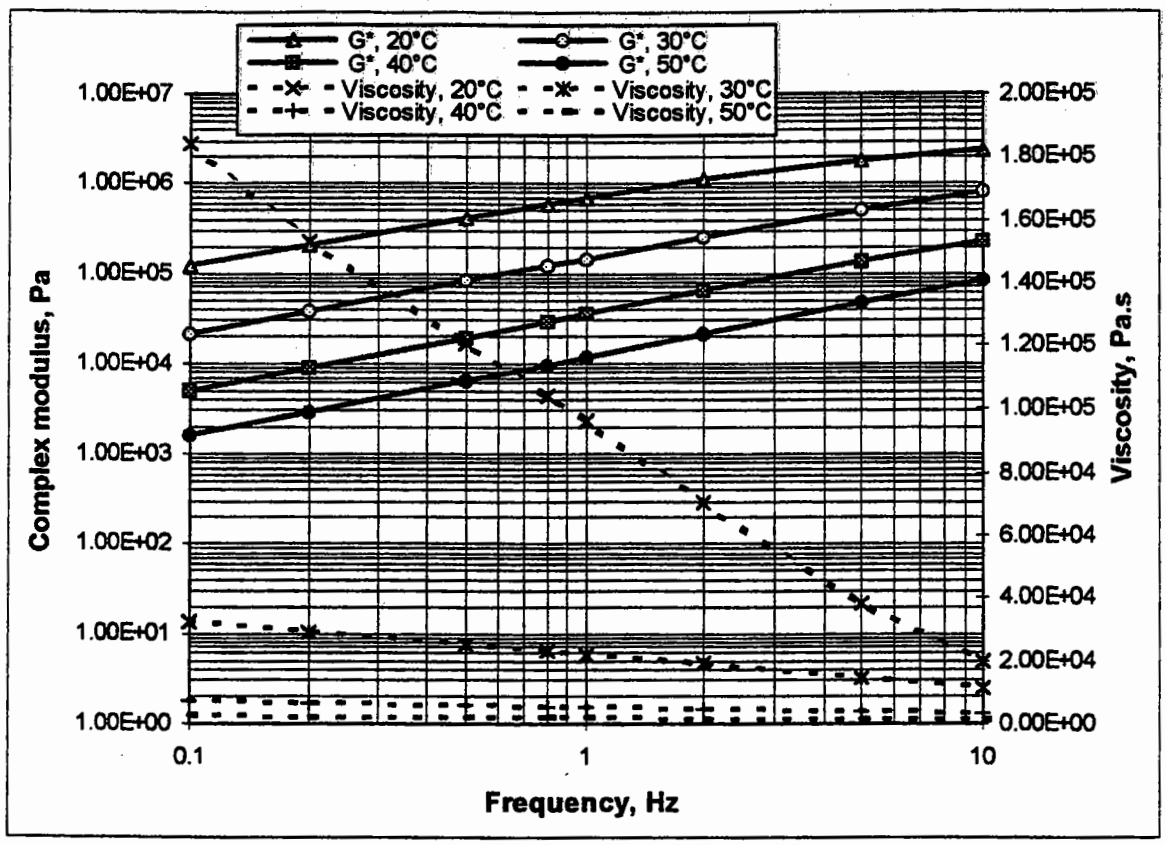


Figure 10-14 Effect of frequency and temperature on complex modulus and viscosity of emulsion residue from curing for 3 days at 40°C

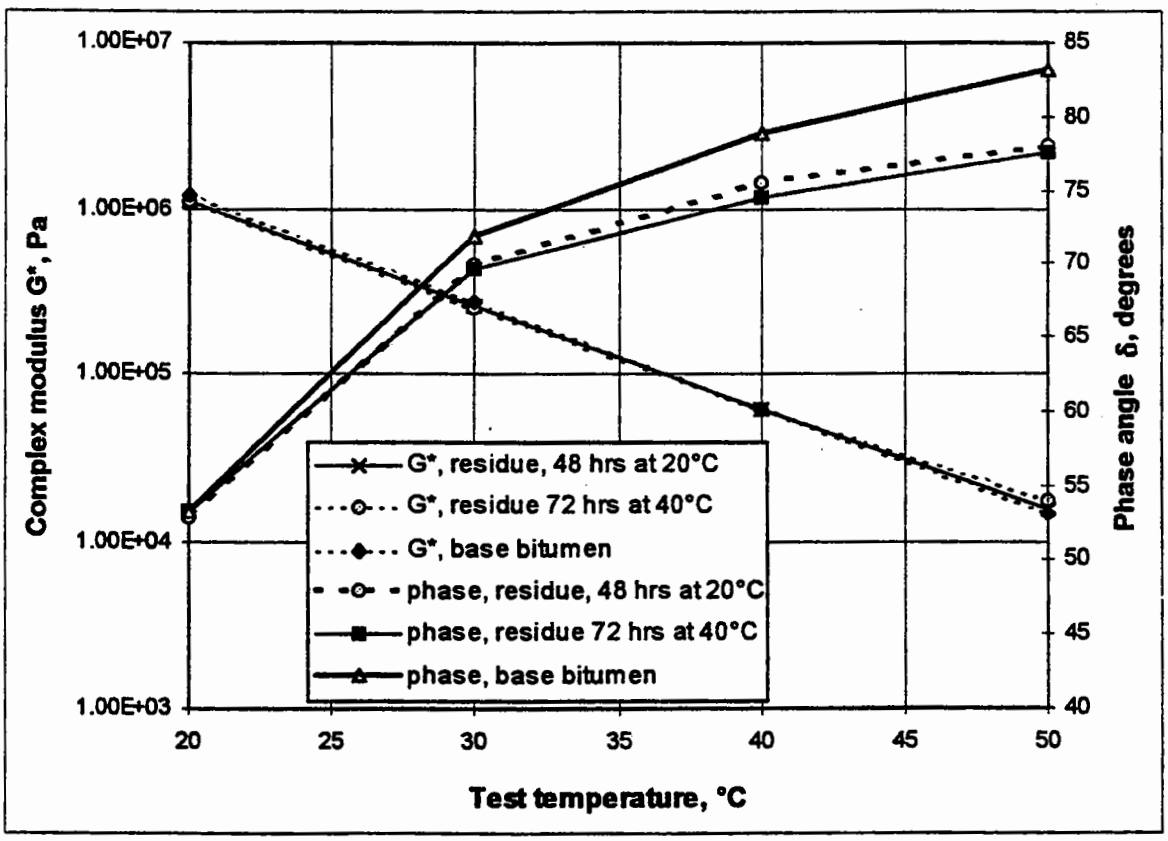


Figure 10-15 Isochrone of complex modulus and phase angle at 2 Hz of base bitumen and K-emulsion residues from curing 2 days at 20°C and 3 days at 40°C

Clearly, there was a difference between the responses of the recovered and original bitumens in terms of the phase angle, being more viscous for the base bitumen. The bitumen regained most of its original properties in terms of the absolute complex modulus but not in the phase angle at higher temperatures, and this may be related to a difference in the material structure. It is expected that emulsifier remaining in the system could result in this difference. Generally, the measurements at 20°C are in good agreement with those previously reported by Agnusdei et al (1990) and Needham (1996), discussed in Chapter 3, being that the emulsifier does not influence the rheological properties of emulsion residues. As the temperature increases, the difference in the phase angle becomes clear and the emulsion residue shows a more elastic response. Thus, the structures of the bitumens are quite different, although similarity of some rheological parameters may be observed.

10.3.4 Rheology of Bitumen Emulsion - Filler Mastic

Mixtures of emulsion and filler, cured for different curing times at 20 and 40°C, were tested in the dynamic shear rheometer. Samples were prepared by adding the required amount of filler to K-emulsion, resulting in ratios of filler to residual bitumen of 1:1 and 1:2. The mixtures were then stirred thoroughly and the required amount poured into the mould previously described to give the desired gap height + 0.2 mm at start of test. Test results are shown in Figure 10-16.

Considerable differences in the complex modulus can be distinguished at higher frequencies. The complex modulus of the filler-emulsion residue mastic at ratio 1:2 was the lowest and at ratio 1:1 was the highest. On the other hand, slightly lower differences can be observed at low frequency at which the mixtures show predominately viscous response. It can be noticed that the frequency at which the phase angle = 45° (or G' = G") of the filler-residue mastic at 1:1 is lower relative to the filler-base bitumen mastics at 1:1 and 1:2. Generally, increasing the added filler content shifts the phase angle - frequency relationship parallel to the left indicating a more elastic response.

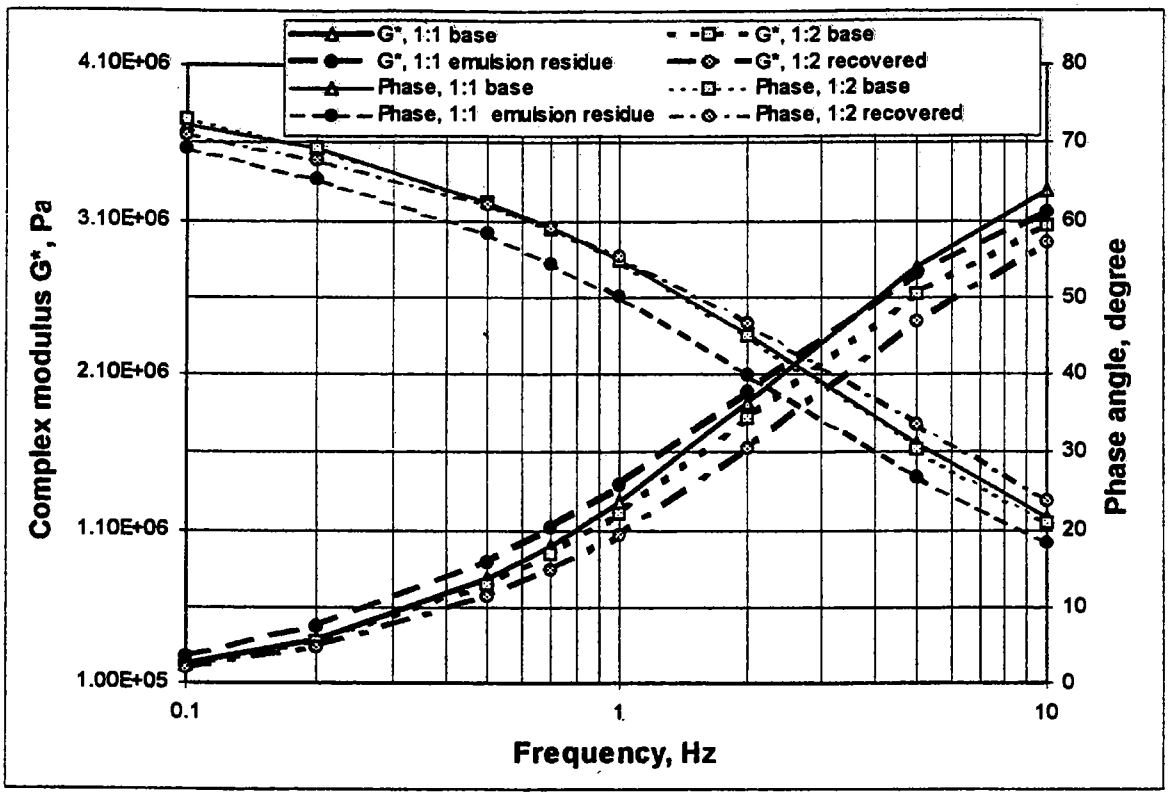


Figure 10-16 Complex modulus and phase angle versus frequency relationships of emulsion residue-filler and base bitumen filler mastics

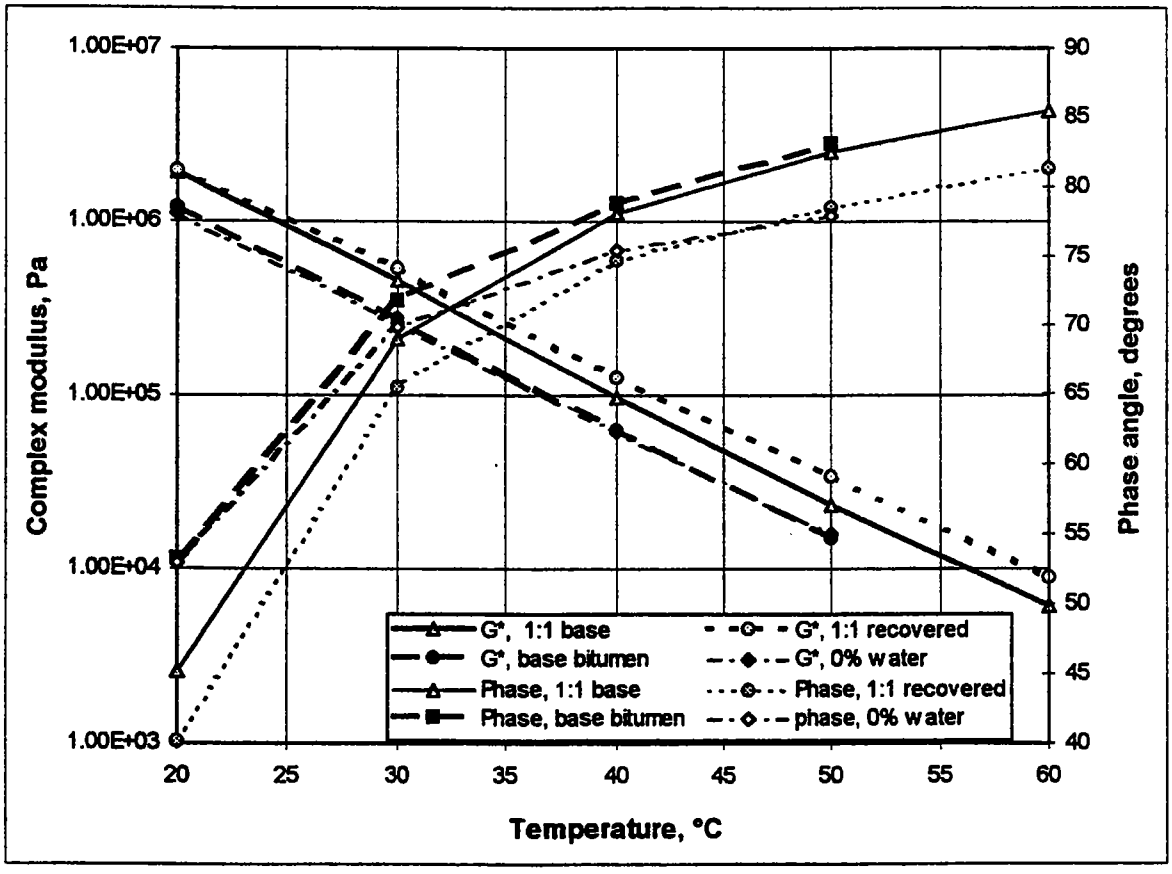


Figure 10-17 Isochrone of the complex modulus and phase angle of the mastics versus temperature of base and residual bitumens

The significance of the phase angle measurements can be seen in Figure 10-17. As presented in section 10.3.3, a similarity in the determined complex moduli at lower temperatures was observed, even though the phase angles were different. In addition, adding filler reduced the temperature susceptibility of the emulsion residue-filler mastic over the corresponding base bitumen-filler mastic. Also, the complex modulus of the mastic increased relative to the original bitumen (before adding filler). Another point is that the phase angles of the mastic and the original bitumen tend to be equal at high temperature (approximately 50°C), at which the viscous response is dominant and the influence of the filler on phase angle is negligible.

Thus, increasing filler content is beneficial to emulsion mixtures. Bear in mind that the quantity should be less than that which causes breaking of the emulsion before coating large aggregate particles.

10.3.5 Comparison between R-emulsion and K-emulsion Properties

This section compares the rheological properties of the two emulsions (see Chapter 4), as determined using the rotational viscometer, and the two emulsion residues, as determined using the dynamic shear rheometer.

Testing emulsion in the dynamic shear rheometer at different strain levels showed considerable variations in the results. Fluctuation in the measured parameters as a function of frequency was found. It was then realised that the viscosity of both emulsions is very low and the test geometry has significant influence on the measured values. In testing such low viscosity material, even with a very narrow gap, the shear stress distribution across the gap is not uniform resulting in meaningless measurements. Therefore, rotational viscometery was employed for determination of the flow behaviour of the emulsions.

The principle of the rotational viscometer is a cylinder spindle rotating coaxially inside a fixed cylinder containing the sample. As is the case with the DSR, the gap between

the inner and outer cylinder should be small to obtain a uniform stress distribution within the sample.

Bitumen Emulsion

The distribution of emulsion in a mixture depends on the emulsion properties. As previously discussed, coating of emulsion onto aggregate particles is greatly influenced by the emulsion type rather than the proportion in the mixture. It is therefore important that rheological properties of emulsion are known for the purposes of mixture design. Thus, both emulsions were tested at 20°C and 40°C using different applied torque speeds. The determined parameters were torque, shear stress, shear strain rate, and viscosity.

Figure 10-18 shows the flow behaviour of both emulsions and different viscous behaviours can be noticed. K-emulsion shows nearly Newtonian behaviour, i.e. $\sigma = \eta \times d\gamma(t)/dt$ where: η = viscosity and $d\gamma(t)/dt$ = shear strain rate (Barnes et al, 1989). R-emulsion, on the other hand, shows non-Newtonian behaviour in the form of shear thickening (dilatancy). Thus, the flow properties of the two emulsions are different. Clearly, the viscosity of the R-emulsion is affected by the shear stress level due to its non-Newtonian behaviour and both emulsion viscosities tend to be similar at higher stress level. It is clear that the temperature effect on the viscosity of R-emulsion is much more pronounced than that of K-emulsion.

In accordance with these findings, the application of the two emulsions appeared different during the mixing process. Also, better distribution of emulsion, coating of aggregate, and stiffness modulus of mixture were associated with K-emulsion. On the other hand, the DBM-mixtures with better water resistance was the one containing R-emulsion, but the better fine graded mixture was the one contained K-emulsion. It appears that higher viscosity and temperature susceptibility of an emulsion may lead to a break and coalescence of bitumen droplets onto the aggregate particles during mixing, resulting in a non-uniformity of coated aggregate. The required flow characteristics of an emulsion should therefore be a compromise according to the use of the mixture.

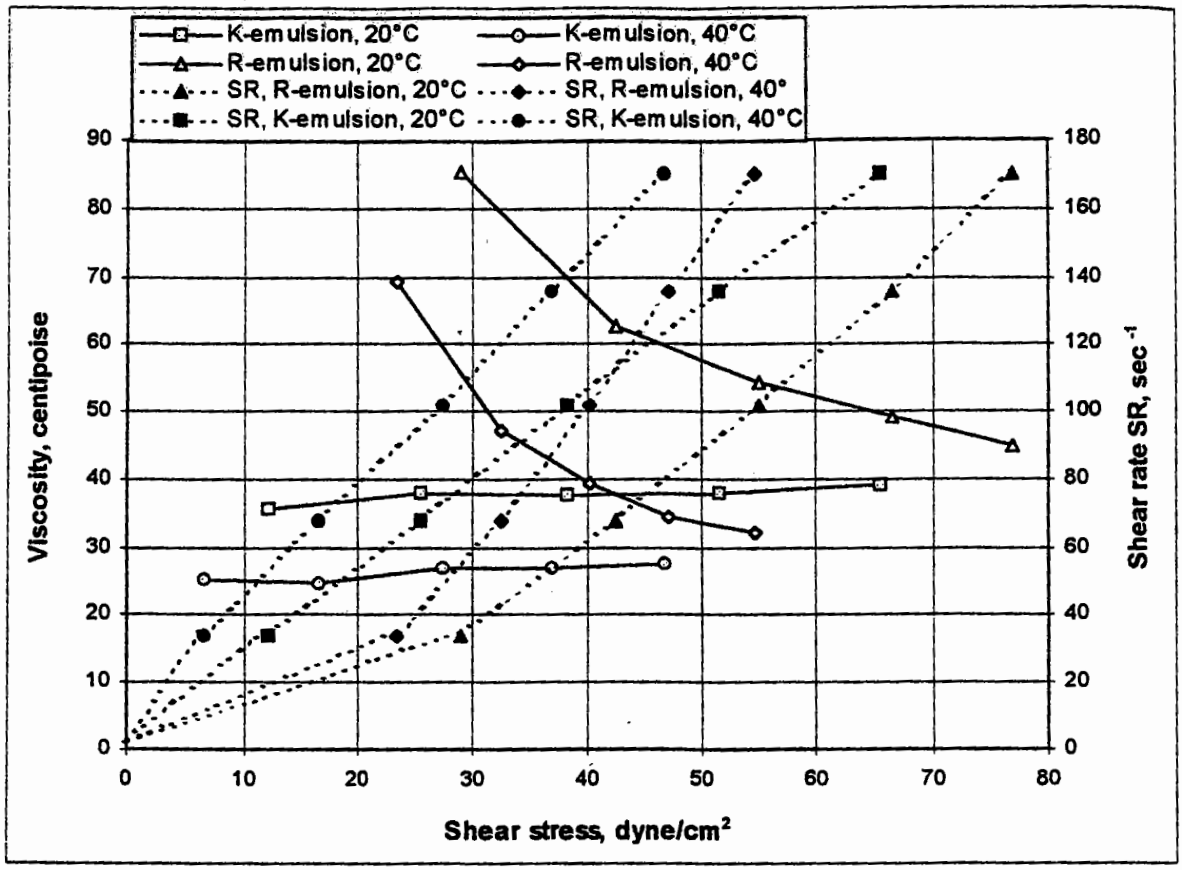


Figure 10-18 Flow behaviour of R-emulsion and K-emulsion in the rotational viscometery at 20°C and 40°C

Emulsion Residue

Over the range of frequencies at 20°C, the complex modulus of R-emulsion residue was the higher and the phase angle was the lower, see Figure 10-19. Residue of R-emulsion showed more elastic response, depicted by the frequency at which G' = G" (phase angle = 45°C), being lower than that of K-emulsion residue.

In addition, both the complex modulus and phase angle of R-emulsion residue were sensitive to the test temperature, a greater temperature susceptibility being observed compared to the K-emulsion residue. At higher temperatures, a similarity in the complex modulus of both emulsions was found. At these temperatures, differences in the phase angle were observed. Clearly, as previously discussed, the phase angle is a significant rheological parameter and is sensitive to the structure and composition of the binder. Isochrones of complex modulus and phase angle are shown in Figure 10-20.

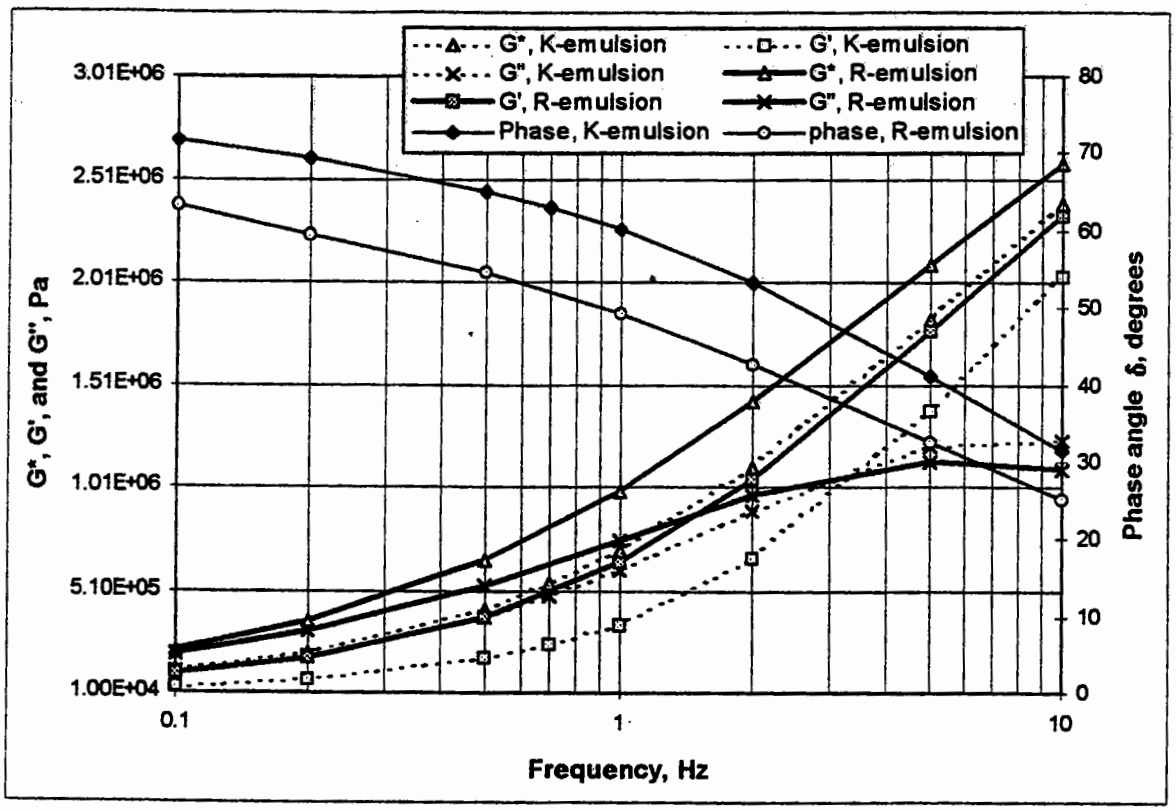


Figure 10-19 Comparison between measurements of the rheological parameters of R-emulsion and K-emulsion residues as a function of frequency

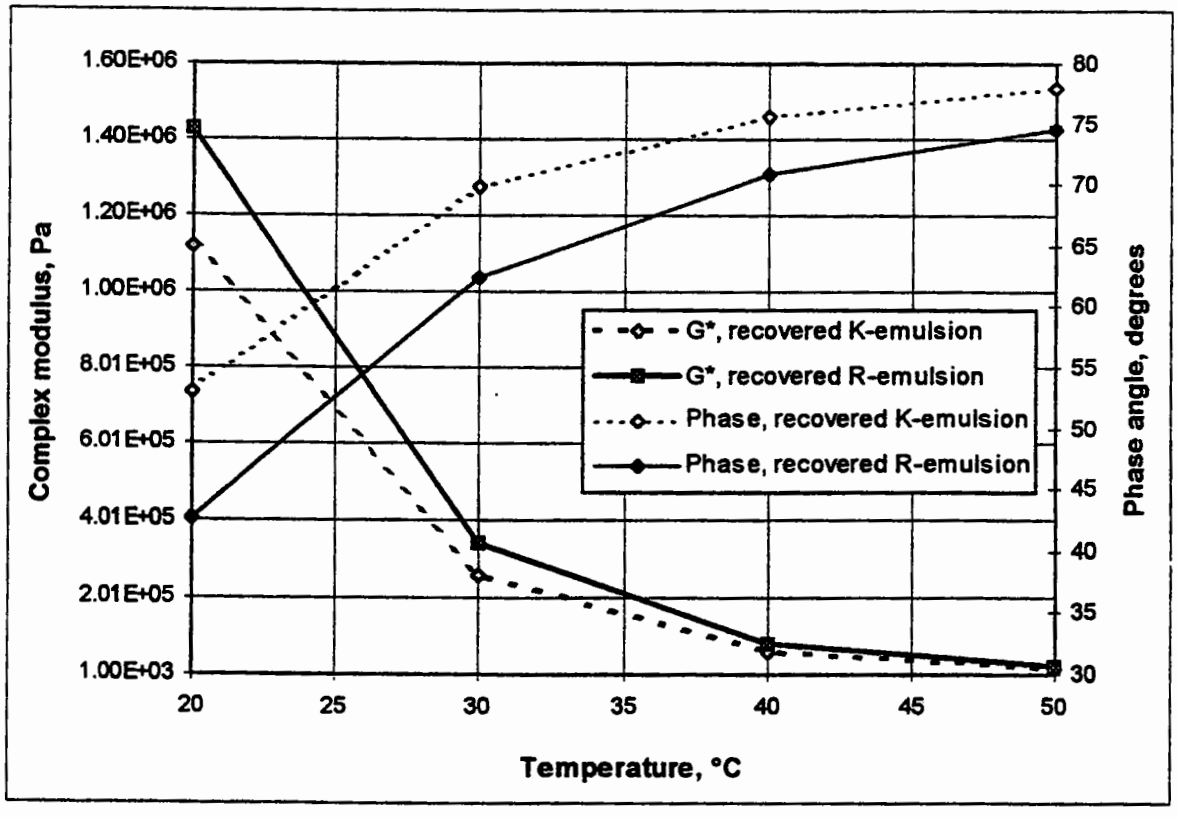


Figure 10-20 Isochrone of the complex modulus and phase angle of K-emulsion and R-emulsion residues

Referring back to the results of the emulsion mixture specimens tested in the NAT, stiffness moduli of R-emulsion mixtures were lower than those of K-emulsion mixtures. Conversely, the R-emulsion residue showed a higher complex modulus and a more elastic response. In bituminous mixtures, the contribution of the binder to the mixture behaviour is significant. The modulus of the R-emulsion mixture would thus have been higher if the distribution of emulsion and coating of the aggregate had been at least similar to that of the K-emulsion mixture. It is therefore expected that this deficiency in the mixture behaviour is related to a non-uniform distribution of the binder.

10.4 SUMMARY

For preparing and testing partially cured emulsion and emulsion residue, a modification to the base plate of the Dynamic Shear Rheometer 'DSR' was made, in order to avoid the need to bring samples to high temperatures. Partially cured samples (up to 5.14% water content of the bitumen weight, representing 0.26% water content in a mixture containing 5% RBC) had lower temperature susceptibility and storage modulus. Generally, the response in the DSR at this level of curing was dominated by the viscous behaviour (loss modulus).

Recovering bitumen from emulsion was performed by leaving samples in specially manufactured discs which could be placed directly in the DSR. This method of recovery was found suitable for comparing the results of emulsion residue and base bitumen. The recovered bitumen was found to gain most of its original properties at the temperature levels used in terms of the complex modulus but not in terms of the phase angle, which is sensitive to the structure and chemical composition of the binder. Filler and emulsion residue mastic showed better rheological response than filler and base bitumen. The results therefore indicated that the draw-back experienced in the performance of emulsion-aggregate mixtures is related to the adhesion between the binder and aggregate particles, not the binder response.

It was also found that the flow characteristics of both K-emulsion and R-emulsion were different. Newtonian behaviour was observed with the K-emulsion, while non-Newtonian behaviour was observed with the R-emulsion. This difference in the binder behaviour may lead to different distribution amongst the aggregate particles, resulting in different mixture properties.

CHAPTER

11 PROPOSAL FOR MIX AND PAVEMENT DESIGN METHODS

For mix design of any material, an evaluation of the appropriate engineering properties which significantly influence its performance is required. There are many methods in use for the design of emulsion-aggregate mixtures. None of them has wide acceptance. Most of these methods are modifications to the standard Marshall method (ASTM D1559) or Hveem method (ASTM D1560 and D1561). A strength or stability criterion is usually used to ensure good performances in terms of permanent deformation and fatigue cracking. In addition, the material must be insensitive to moisture effects.

Due to the lack of field performance of emulsion mixtures, empirical pavement design methods have not been published. The few published design methods are modifications to mechanistic methods applied to flexible pavements with hot bituminous mixtures. The objective is to limit the tensile strain at the bottom of the bituminous layer and the vertical compressive strain at top of the subgrade, accounting for changes to the material properties with curing time.

This chapter presents proposals for both mix and pavement design, based on evidence from this study. Comparisons are also presented with available information on both design elements from the literature.

11-1 SUMMARY OF MIX DESIGN METHODS

The design procedure for emulsion-aggregate mixtures, as previously discussed, involves determination of the following:

1. Preliminary estimate of the design emulsion content.
2. Water content at mixing and at compaction.
3. Optimum residual bitumen content to satisfy the design criteria.

In most mix design methods, an estimate of the design emulsion content is preferable to minimize the number of specimens to be tested. This may be based on previous experience with the emulsion-aggregate composition or estimated from the surface area of the aggregate (NCHRP No. 30, 1975). The general formula is:

$$RBC = 100 \times (SA) \times t \times \gamma_a$$

where:

RBC = estimated residual bitumen content

SA = surface area of aggregate

t = average bitumen film thickness

γ_a = unit weight of bitumen

The appropriate bitumen film thickness for emulsion-aggregate mixtures has not yet been determined. However, most of the design methods attempt to simplify this formula by establishing the estimated residual bitumen content as a function of the aggregate particle size. Some current design methods are summarised below.

11.1.1 The Asphalt Institute Method

The Asphalt Institute (1989), adopted both the Marshall and Hveem. The following are major elements of both design methods:

1. *Selection of materials*:

The aggregates which are suitable for emulsion mixtures include crushed stone, gravel, sand, silty sand, sandy gravel, slag, reclaimed aggregate, or other inert materials. Emulsion type and grade is selected for use in a particular project based in part on its ability to adequately coat the aggregate.

2. *Estimation of emulsified bitumen content*:

The Centrifuge Kerosene Equivalent test 'CKE' is used for the estimation of the amount of emulsified bitumen. If CKE equipment is not available, the following equation has been adopted in the Marshall design method for determination of approximate emulsified bitumen content based on weight of dry aggregate:

$$P = 0.7 \times (0.05A + 0.1B + 0.5C)$$

where:

A = Percent of aggregate retained on 2.36 mm (No. 8) sieve

B = Percent of aggregate passing 2.36 mm (No. 8) sieve and retained on 75 μm (No. 200) sieve.

C = Percent of aggregate passing 75 μm (No. 200) sieve.

3. *Coating test*:

This test is performed on mixtures containing the estimated emulsified bitumen content and different water contents added to the aggregate prior to adding emulsion. The appearance of the mixtures is rated by visually estimating the total aggregate surface area coated with bitumen. At least 50% coating is acceptable. In the Hveem method, the minimum fluids content (mixing water plus emulsion) required for adequate mixing is determined, while the pre-mix water content at mixing is determined in Marshall method. In using medium setting emulsions, the pre-mix water content that produces maximum coating without stripping is determined. In using slow setting emulsions, the minimum pre-mix water content required for mixing is determined, as the mixtures exhibit increased coating with increased pre-mix water.

4. *Optimum water content at compaction*:

In the Hveem design method, the estimated emulsion content is used for preparing at least three batches at the minimum fluids content for mixing. One batch is compacted immediately. The other batches are compacted after drying back to produce lower fluids contents. Compaction is performed using a light kneading followed by a double plunger static load. The optimum fluids content for compaction is determined from the dry density-fluids content at compaction relationship.

In the Marshall method, mixtures containing the determined pre-mix water and the estimated emulsion contents are produced. Different water contents of these mixtures are obtained by aeration (a fan may be used). Compaction is achieved using the Marshall compactor by applying 50 blows per face to the specimens. The optimum

fluids content results in the highest density determined from the dry density-fluids content at compaction relationship. The optimum water content at compaction is then calculated and used for all subsequent compaction regardless of the residual bitumen content.

In both methods, specimens are cured in the mould for one day at room temperature, with the moulds placed on their edge for equal ventilation at both ends. The bulk specific gravities of the specimens are then determined by displacement in water, out of the moulds.

5. *Determination of optimum residual bitumen content*:

In Hveem method, a series of specimens are prepared with at least three different emulsion contents, using the previously determined fluids contents at mixing and compaction. For base mixtures, Hveem Resistance R-value and Cohesiometer C-value are determined at 23 ± 2.8 °C on early cured specimens as well as fully cured specimens before and after water exposure. For surface mixtures, these test values from Hveem are only determined for final cured specimens, at 60 ± 2.8 °C. Early curing of specimens is one day in a mould and full curing is 3 days in a mould followed by vacuum desiccation for 4 days; or alternatively, one day in a mould at room temperature and one day out of the mould in an oven at 38°C (100°F). Water exposure is carried out by immersion for one hour under vacuum at 100 mmHg and for one hour without vacuum. The lowest emulsion content that satisfies the criteria requirements presented in Table 11-1 is the design value.

In the Marshall method, the following are determined for specimens prepared with different emulsion contents, using the previously determined optimum water contents at mixing and compaction:

- Bulk specific gravity.
- Modified Marshall stability and flow of dry specimens at 22.2 ± 1.1°C.
- Soaked stability and flow after vacuum saturation.
- Density and voids analysis.
- Moisture absorption.

The mixture design criteria shown in Table 11-2 are then used in deciding on the optimum emulsion content.

Table 11-1 Design criteria of modified Hveem method for emulsion-aggregate mixes (reproduced from the Asphalt Institute, 1989)

Test Property		Base Mixtures	Surface Mixtures
RESISTANCE R_t-VALUE at (23 ± 2.8°C)	Early Cure[a]	70 min.	N.A.
	Fully cured and water immersed[b]	78 min.	N.A.
STABILOMETER S-VALUE at 60 ± 2.8°C		N.A.	30 min.
COHESIOMETER C-VALUE at 23 ± 2.8°C	Early Cure[a]	50 min.	N.A.
	Fully cured and water immersed[b]	100 min.	N.A.
COHESIOMETER C-VALUE at 60 ± 2.8°C		N.A.	100 min.
aggregate coating		50% min.	75% min.

[a] Cured in mould for total of 24 hours at temperature of 23 ± 2.8°C (73 ± 5°C).

[b] Cured in mould for total of 72 hours at temperature of 23 ± 2.8°C (73 ± 5°C) vacuum desiccated for 4 days followed by water immersion for one hour under vacuum and one hour without vacuum.

N.A. Not Applicable

NOTE: Besides meeting the above requirements, the mix must be reasonably workable (i.e., not too stiff or sloppy).

Table 11-2 Design criteria of Marshall method for emulsion aggregate mixes

Test Property	Minimum	Maximum
Stability N (lb) at 22.2°C	2224 (500)	
Percent stability loss after vacuum saturation and immersion		50
Aggregate coating (percent)	50	

11.1.2 Southern Africa Bitumen and Tar Association (Sabita) Method

The following stages are used for design of stabilized granular emulsion mixtures (GEMS) in which residual binder contents may range from 1.5% to 5% by mass of mix:

1. *Materials*:

Stable-grade anionic emulsion (60% residual bitumen) is normally used. This type of emulsion is incompatible with acid crystalline aggregate, such as quartzites and granites. Therefore, care should be taken when this material is used because of possible stripping problems. However, Sabita state "there have been no reports of problems with the use of such aggregates together with anionic emulsions in stabilised GEMS". Usually, an additive (lime or cement) is added to aggregate, if the plasticity index 'PI' exceeds 7 %.

2. *Determination of optimum fluids content*:

Mixtures are produced by hand or mechanical mixing at different fluid contents a 50/50 blend of emulsion and water, in increments of 1% (by mass of dry material), with an oven dried aggregate. The mixtures are then compacted by applying 75 blows of a standard Marshall hammer to each face of the specimen, at room temperature or preferably at 23°C. The optimum fluid content (OFC) is determined from dry density/fluid content relationship.

3. *Determination of optimum residual binder content*:

Added moisture at mixing:

A quantity of extra moisture, X, (generally, around 2%) additional to the previously determined optimum fluids content, is required to allow for evaporation and aeration during mixing. The moisture content of the aggregate is determined before the addition of emulsion or water. For a given emulsion content, the additional water content required to obtain a mixture with total fluid content of X + OFC is calculated. This water content is added to the aggregate prior to the addition of emulsion.

Specimen preparation:

Mixtures are prepared at various emulsion contents. The determined water content at mixing for each emulsion level is added to the wet aggregate, followed by the addition of emulsion. Aeration of the mix is then conducted to allow the onset of breaking of the emulsion and to reduce the fluid content of the mixture to the previously determined optimum 'OFC'. Specimens are then fabricated using the Marshall compactor by applying 75 blows/face. Specimens are initially oven cured for four hours at 40 ± 2°C. For final curing, the specimens are left in a draft oven at 60°C for 20 hours.

Mechanical testing:

The specimens are tested in the Marshall equipment and both stability and flow are determined. The optimum emulsion content is that resulting in the highest Marshall stability. The Marshall stiffness (the ratio of the stability and flow) is used for the determination of resistance to permanent deformation. Resistance of the material to water effects is assessed by conducting a capillary soaking similar to that used by Darter (1979). In addition, both the indirect tensile strength and stiffness (resilient) modulus are determined. Design criteria used are presented in Table 11-3.

Table 11-3 Interim mix design criteria for stabilized granular emulsion mixtures (reproduced from Sabita, 1993)

PROPERTIES AFTER INITIAL CURING	TRAFFIC CLASS	
	E0 to E2 (minimum)	E3 to E4 (minimum)
Marshall stability at 23°C (kN) Marshall stability at 40°C (kN)	2,2 1,0	4,0 2,0
Marshall stiffness at 23°C (kN/mm) Marshall stiffness at 40°C (kN/mm)	1,5 1,0	3,0 2,0
Percentage voids in mix	5% to 15%	
PROPERTIES AFTER FINAL CURING	WATER EXPOSURE	
	Without	*With
Resilient modulus at 23°C (MPa)	1 000	
Indirect tensile strength at 23°C (kPa)	100	50

Note: * Only in wet region

11.1.3 Design of Grave Emulsion (the French Method)

These mixtures have high internal friction, enabling rutting resistance during curing, enhanced by the quantity of fines and filler and the emulsion type. Normally, medium setting emulsion is used and the target binder content is between 3 % and 4 %, which partially coats the aggregate particles. Nominal sizes of aggregate used are 10, 14, 20, 31.5 mm.

The following procedure is used for mix design:

- Determination of the minimum water content by investigating the distribution of the residual binder.
- Fabrication of specimens is carried out using Duriez compaction by applying a static load of 12 t for 5 minutes. A 120 mm diameter mould is normally used for mixtures containing aggregate with nominal size greater than 14 mm.

- Half of the specimens are cured in a ventilated atmosphere with controlled humidity for 14 days. The other half are cured in a ventilated atmosphere with controlled humidity for 7 days and then immersed in water for 7 days.
- Compression-immersion tests (deformation rate of 1 mm/s) are carried out from which the compression resistance or strength, defined by the maximum load the specimen sustains, and the compression-immersion ratio (the ratio of wet to dry compression strength) are determined.
- The best aggregate/emulsion combination to satisfy the criteria presented in Table 11-4 is determined. Therefore, variables used in the design method are the fines content and the residual bitumen content (at least 3 increments between 3 and 4 % RBC) for each fines content.

Table 11-4 Design criteria for grave emulsion (SFERB, 1991)

compaction	> 85 %
compression resistance (strength)	
- 180/220 pen base bitumen	> 20 bars
- 80/100 pen base bitumen	> 30 bars
immersion to compression ratio	> 0.55

11.2 PROPOSED MIX DESIGN PROCEDURE

Some important findings influencing behaviour of emulsion mixtures have been revealed from this study. These should be incorporated into the design of the material. The following is a summary of the main points related to a mix design procedure.

11.2.1 Summary of Relevant Findings from This Research

1. *Trial emulsion content*:

The estimation of a design residual bitumen content is an important element, as it reduces the number of specimens required for the mix design process. As previously seen, many formulae and methods, such as the CKE test method used by the Asphalt Institute, have been developed for the determination of an approximate design value for emulsion content. The resulting values from these methods, and therefore the bitumen film thickness, are different. As a result, the optimum fluids or water contents at compaction will be different, leading to different design values of residual bitumen contents.

For the emulsion contents (3.2 to 6.0 % RBC) and the aggregate gradations used in this study (Chapter 4), minimum mixing water contents were determined. These were carried out by visually investigating the coating of emulsion to aggregate particles and also determining the stiffness moduli of different mixtures having similar water content at compaction and similar densities, to allow the effect of mixing water to be ascertained. The following were found:

- Increasing the water content in a mixture during mixing increases the coating of slow-setting cationic emulsion to aggregate particles, as reported by Waller (1979) and the Asphalt Institute (1979 & 1989).

- The coating percentage of emulsion on the aggregate particles could not be judged immediately after mixing as stated by the Asphalt Institute. Instead, a coating test has been carried out on loose mixtures cured for 24 hours at ambient temperature. However, zero water content was found to enough for the different mixture

combinations used to achieve the minimum Asphalt Institute requirement (50 %) specified for use as a base in a pavement structure.

- Minimum water content at mixing was accurately decided using the stiffness modulus value of cured specimens (curing temperature 48°C). Generally, 1 % water content was found to be a minimum.

The effect of emulsion content, in the range used and with the aggregate gradations described in Chapter 4, on the determined optimum water content at compaction was also investigated. Because the mixtures containing higher emulsion contents were sometimes brought to a lower total water content prior to compaction, by drying back, partial setting of the emulsion was occurring, to a greater extent than for lower emulsion contents. The use of higher emulsion content in some mixtures required more aeration time than with lower emulsion content, in order to reach the water contents required to establish a compactibility curve. No big difference in the determined optimum water contents of mixtures, with the same emulsion type and aggregate gradation, was found. The total fluids contents at compaction were therefore different, being higher in mixtures containing higher emulsion contents. Keeping the total fluids content constant for the range of emulsion contents used in the design process is not considered valid.

2. *Compatibility of emulsion and aggregate*:

Emulsion type and formulation (bitumen particle size distribution, proportion and both bitumen and emulsifier type) are currently selected based on the ability of the pre-estimated design emulsion content to adequately coat the aggregate particles. According to this research, coating alone is not a sufficient criterion for use in assessing the compatibility of the materials. Some currently used emulsions were found less adhesive to the aggregate particles, although they passed the coating test. For better performance of emulsion-aggregate mixtures, a good distribution of the emulsion between the aggregate particles and better adhesion between them should be achieved. These factors are generally influenced by aggregate type and gradation,

emulsion type and formulation, water and emulsion contents and the compaction process.

3. *Post compaction curing*:

For design purposes (mix and pavement structure), accelerated curing of the material to initial and final curing levels should be performed, representing the time until covering the layer or until trafficking and the full curing condition, respectively. In reality, covering of the emulsion-mixture layer or opening the road to traffic should be delayed until a steady condition of bulk density (that is stable water content) has been reached. At this stage, much of the free water has evaporated and the material has gained some strength to withstand the effect of traffic loads. After that, the continuous movement and migration of the small amount of remaining water from the mixture leads to an increase in both the binder stiffness and the bond between the mixture components. According to the environmental condition, aggregate gradation, emulsion type and content, compaction procedure, and the level of the material in the pavement structure, an equilibrium water content will eventually be reached which should be represented by accelerating curing in the laboratory.

The work carried out in this research revealed that the curing level only slightly influenced the determined optimum water content for a given mixture combination, a maximum shift of 0.5 % being observed. On the other hand, no noticeable difference in the optimum residual bitumen content was found as a function of the curing. Accordingly, it is not necessary to reach full curing for mix design purpose. For pavement structural design, the material properties in the laboratory and those in the field should be correlated, from which a definition for the full curing condition could be determined. For initial curing, it is suggested that 2 days curing at ambient temperature of sided wrapped triaxial specimens (100 x 150 mm) is suitable, or, for Marshall size specimens, the regime recommended by the Asphalt Institute, one day in the mould at ambient temperature.

Oven curing and vacuum desiccation have been used in the literature for design purposes. In this research, it was found that 2 days oven curing at 48°C resulted in

better coalescence of bitumen on aggregate particles compared to specimens cured at 20°C for different times. For similar stiffness moduli of specimens from both curing regimes (equilibrium water content < 0.5 %), the resistance to water (stiffness ratio of wet to cured conditions) and the stress dependency of the material were better in the oven cured specimens. Oven curing of specimens for a short time, resulting in a water content higher than the equilibrium condition (e.g. 1 % as reported in UK roads) may be used, as the mechanical properties will predominately be influenced by the contained water content. Further oven curing will not result in a specimen which is representative of site conditions.

Thus, one day in the mould followed by one day out of the mould at 38°C (the Asphalt Institute method) may be used. That reported by Robinson et al (1996) and Khalid and Eta (1996 & 1997[b]), 14 days at 40°C of Marshall size specimens, or by Kent County Council (1996), 15 ± 2 hours at 60°C of loose mixtures prior to compaction, will give misleading results.

In this study, the lack of information on field curing conditions in the UK, relative to those in the laboratory, which needs to be investigated for the confident development of a suitable means of accelerating curing, has led to the use of 20 days at 20°C for triaxial specimens, resulting in less than 0.5 % water content, as representing the final curing condition.

4. *Mechanical testing of specimens*:

Marshall testing for determination of stability and flow has been extensively used in the USA and South Africa. Criteria were established, based on research carried out at the University of Illinois in the USA, for assessing the material strength or stability to withstand repeated load applications without excessive permanent deformation or fatigue cracking, and to assess sensitivity to moisture effects.

In the UK, there is no officially authorized design method, although attempts have been made by many researchers and local authorities. In these attempts, stiffness modulus, measured in the NAT in its indirect tensile mode, of fully cured Marshall size

specimens and also water exposed specimens, were the main parameters used in assessing emulsion-aggregate mixtures. However, no criteria have been published for design purposes, except of those for materials equivalent to hot mixtures, for use in reinstatement works.

This research has shown that the material behaves in a way similar to unbound materials. Curing increases its stiffness but does not reduce the stress dependency in the indirect tensile mode of loading. Triaxial testing showed some reduction in the material stress dependency, as a function of the curing time, but it remained higher than that of equivalent hot mixtures. It has also been shown that material containing a higher equilibrium water content (more than 1 %), as is expected in the field and reported from many trials in the UK, is wrongly characterised in the indirect tensile mode at a load of 150 N per 750 mm^2 of specimen cross-sectional area specified in Appendix A10 - New Roads and Street Works - Act 1991. The material has been found to be best characterised in the triaxial mode of loading and this should be incorporated into the design methods. The NAT in the triaxial mode, developed during this research and described in Chapter 5, was found to be extremely useful for determination of stiffness modulus, resistance to permanent deformation, and resistance to water.

In pavements, the material is subjected to repeated traffic loading as it cures. Two possible responses may occur:

- A densification of the mixture, leading to an increase in the stiffness modulus, in addition to that from curing.
- A breaking of the adhesion bonds, creating micro-cracks in the material during early curing, which may not ever be completely healed (depending on the applied wheel load level), leading to a smaller stiffness increase resulting from the curing process.

Therefore, in the design process, repeated load conditioning should be conducted on partially cured specimens.

11.2.2 Outline of Mix Design Method

Based on the above points, the stages of the proposed design method are as illustrated in Figure 11-1, which is explained as follows:

1. *Selection of materials*:

The emulsion needs to be compatible with the aggregate type and gradation. For cationic emulsion types, a quartzite acidic aggregate may be used. Filler content should not be more than 5 % for dense graded mixtures. The fine side of the asphaltic mixture grading (the Asphalt Institute, 1988) is preferable for better stiffness modulus and resistance to water effects at early life.

Residual bitumen content may then be assumed for preparation of trial mixtures, preferably 4 % for DBM grading and 5 % for finer grading. Alternatively, the Asphalt Institute formula for estimation of the design residual bitumen content can be used. Mixtures containing the selected aggregate grading and the residual emulsion content are then obtained for compatibility evaluation. First, at least 1% of water should be mixed with the aggregate prior to adding emulsion (the more the better in using cationic slow setting emulsion, though sloppy mixtures should be avoided). The percentage aggregate coated with emulsion is then assessed visually. Marshall size specimens are fabricated in the gyratory compaction (ram pressure 0.6 MPa, number of gyrations 70, gyration angle 1.25°, and speed 30 rpm). Water loss after compaction should not be more than 1%. The specimens are then cured for one day at 40°C in the mould, after which the soaked to unsoaked stiffness ratio is determined (should be $\geq$ 50% for compatibility). Soaking of specimens can be conducted following the Asphalt Institute method (vacuum saturation for one hour followed by immersion in water for another hour).

2. *Determination of optimum water content*:

It has been seen that properties of emulsion-aggregate mixtures are greatly influenced by the density and water content at test, and are directly related to the water content at compaction (the more the water at compaction the less the rate of curing). For maximizing the properties of emulsion-aggregate mixtures the optimum water content

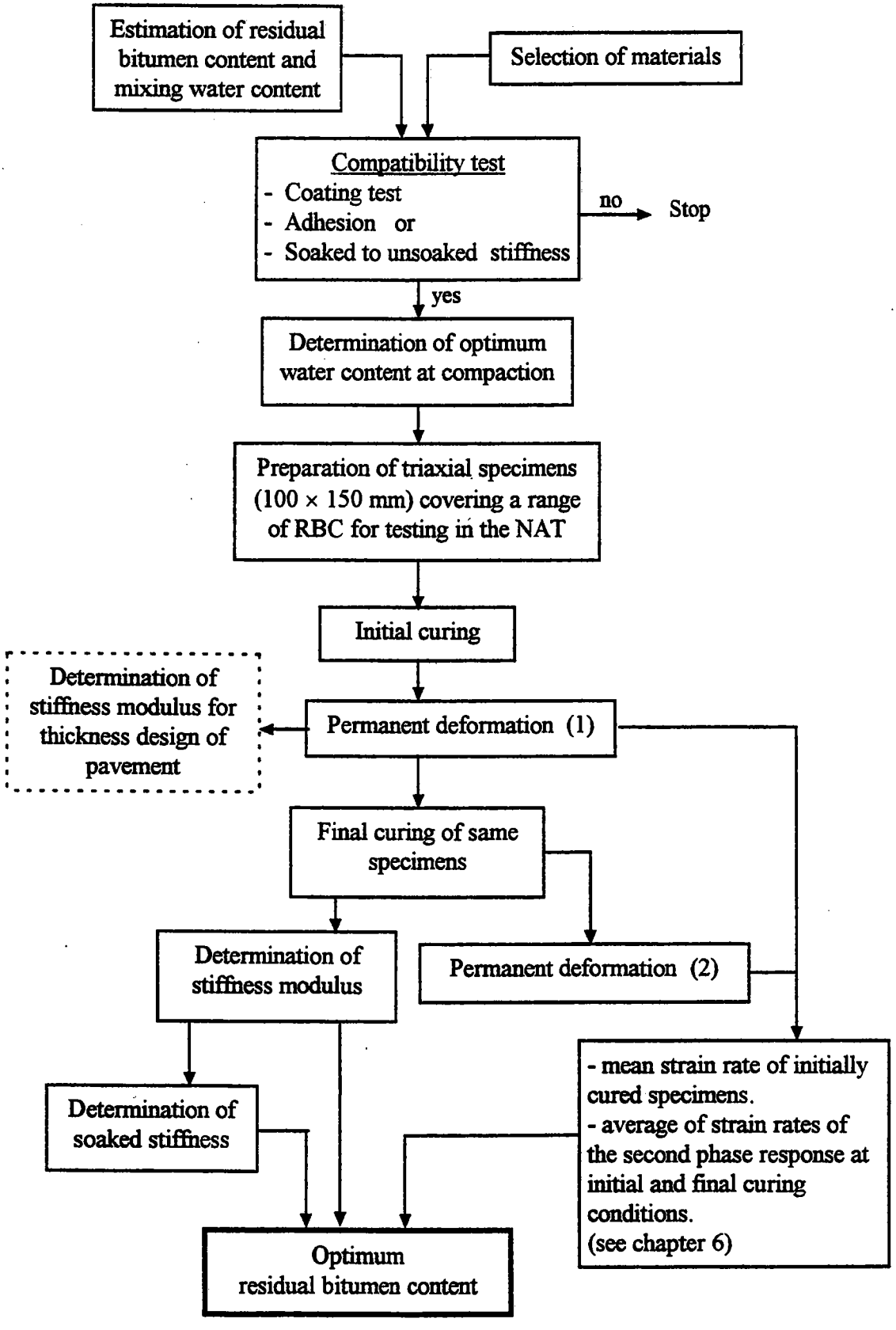


Figure 11-1 Flow chart of proposed mix design procedure

at compaction should therefore be determined using both water content-density and water content-stiffness relationships.

Mixtures containing the selected aggregate grading, the estimated trial emulsion content, and the mixing water content are compacted in the gyratory compactor. The dry density and stiffness modulus in the indirect tensile mode are then determined after one day's curing of specimens in the mould at 40°C. The water contents which maximize the stiffness modulus and the density of the material are determined.

3. *Determination of optimum residual bitumen content*:

A series of triaxial specimens are prepared over a range of residual bitumen contents using the mixing water content and the determined optimum water content at compaction. For triaxial testing in the NAT, studs should be inserted during the compaction process similar to those described in Chapter 5. The following should then be conducted:

1. The specimens are initially cured according to the likely field conditions and construction procedures used (2 days at ambient temperature in mould is suggested).
2. Testing of the specimens in the triaxial mode in the NAT is then conducted by applying 4000 pulses of 300 kPa deviator stress and 20 kPa confined pressure, during which the irrecoverable strains, as defined in Chapter 5, are captured for determination of the permanent deformation. The recoverable strains of the last 10 pulses are also captured for determination of the stiffness modulus.
3. The tested specimens are then cured, out of the mould, using a regime representing the fully cured condition in field. Curing of specimens is suggested as 2 days out of the mould at 40°C.
4. Testing of the fully cured specimens is conducted in the triaxial mode for determination of the permanent deformation and stiffness modulus as in step 2 (un-soaked condition).
5. The tested specimens, with a rubber membrane, are immersed in a water bath, each under a similar head, for 24 hours at ambient temperature, after which they are

taken out of the water bath, one after the other, for determination of the percentage saturation due to soaking. The specimen is then fully wrapped to keep the absorbed water in it, after which it is placed in the NAT for determination of the soaked stiffness.

6. The optimum RBC can then be determined from the following parameters:
   - dry density.
   - un-soaked stiffness of later cured specimens.
   - soaked stiffness of later cured specimens.
   - mean strain rate of early cured specimens from permanent deformation determination.
   - average strain rate from the second phase of the permanent deformation responses of early and later cured conditions.

11.3 PROPOSAL FOR PAVEMENT STRUCTURAL DESIGN

11.3.1 General

The thickness of pavement components can be determined from either of the following approaches:

- Empirically, by establishing a correlation between the parameters significantly affecting pavement performance and thicknesses.
- Analytically, by limiting strains in the pavement structure to the level that reduces the potential for significant distress (e.g. Claessen et al 'the Shell method, 1977', Powell et al 'TRRL method, 1984', Brown and Brunton 'Nottingham method, 1986', and Santucci 1977).

From performance studies of pavements constructed with hot bituminous mixtures, distress modes have been established as:

1. *Fatigue cracking*:

   Related to the calculated maximum tensile strain at the bottom of the bound layer, the potential for fatigue cracking can be estimated, either from laboratory fatigue

data on the material under consideration (shifted to field conditions to allow for the effect of traffic distribution and rest periods), or from a mathematical model.

2. *Excessive permanent deformation (rutting)*:

   Provided that the material of the bound layer is properly designed and the pavement layers are properly compacted to minimize the potential for permanent deformation in the pavement structure, the vertical strain at the subgrade level is limited to a level which reduces the potential for excessive subgrade deformation and depends on the pavement design life.

Models have been developed for the maximum allowable vertical strain (ε_z) at the top of the subgrade as a function of the number of load application (N). The Nottingham method (Brown and Brunton, 1986) uses the following models:

$$N = f_r \frac{7.6\times10^8}{\varepsilon_z^{3.7}} \qquad \text{for life to critical condition (10 mm rut)}$$

$$N = f_r \frac{3\times10^9}{\varepsilon_z^{3.57}} \qquad \text{for life to failure (20 mm rut)}$$

where f_r = a rut factor to account for the hot mixture type used.

These relationships were derived by back-analysis of trial pavements many of them using standard hot rolled asphalt. The rut factor then is unity. For hot dense bitumen macadam, a factor of 1.56 is used, as this material offers better resistance to permanent deformation than hot rolled asphalt.

The performance of pavements constructed with emulsion-aggregate mixtures is influenced by the change in the material properties during the curing period. This is considered in the following analytical design approaches. Design criteria applying to pavements with hot mixtures are generally used due to lack of information on the performance of emulsion-aggregate mixtures.

11.3.2 Summary of Some Current Methods

Santucci's Method

Santucci (1977) presented a procedure for thickness design of pavement structures constructed with hot bituminous mixtures (termed asphalt concrete), dense graded emulsion mixtures, or cement-modified emulsion mixtures. Two critical strains, estimated by elastic layer theory are used: the horizontal tensile strain at the bottom of the bituminous layer and the vertical compressive strain at the surface of the subgrade.

The following steps are used:

1. Cure period is estimated from 6 to 24 months according to climatic condition.
2. Resilient modulus is determined for initial and final curing. According to the monthly variation in the material's modulus, the value is determined for each month during the curing period. The following equation is based on findings from Finn et al (1968) and assumes that the rate of cure of the mix is rapid initially and then levels out, reaching 95 % of its final modulus in the specified time period:

$$M_t = M_f - (M_f - M_i)(RF)$$

where:

M_t = total modulus for the specific time after construction;

M_f = final modulus (measured at 23°C after 3 days air curing in a mould and 4 days vacuum curing at room temperature);

M_i = initial modulus measured at 23°C after one day air curing in a mould;

RF = early cure reduction factor, which can be estimated from Table 11-5.

3. The pavement thickness (full depth of treated material) is assumed and the tensile strain is evaluated as follows:
   - Determine horizontal tensile strain from design charts, according to linear elastic theory.
   - Determine number of load applications at failure 'N_f' from fatigue data. A chart is presented to determine N_f depending on the material's resilient modulus. The chart is for mixtures containing 5% voids and 11% volumetric percentage of bitumen. To obtain fatigue data for mixtures with other void and bitumen contents, the equation below may be used:

$$N_c = N_f \times 10^M$$

where:

N_c = Corrected number of repetitions to failure;

N_f = Number of repetitions to failure determined from the chart at a given horizontal strain level and resilient modulus;

M = 4.84 [Vb/ (Vv + Vb) - 0.96], Vv and Vb are the volume of voids and bitumen respectively.

- Calculate $1/N_f$ for each month and sum at end of the curing period.
- Determine damage factor (D_e) for the curing period by multiplying $\sum 1/N_f$ by average monthly traffic (Miner, 1954).
- Determine damage factor (D_f) for the remaining design life.
- Sum D_e and D_f to obtain total damage factor.
- The above steps are repeated for a different assumed thickness from which damage factor versus thickness is plotted for determination of the thickness that leads to a damage factor of 1.

4. The subgrade strain is evaluated as follows:
   - Determine lowest or critical pavement modulus (normally first month after construction) and determine traffic for the critical period.
   - Determine subgrade strain and compare with the allowable.
   - For full design life, calculate traffic and determine subgrade strain using the critical pavement modulus for this period. The result is then compared with the allowable value.
5. Thicknesses for a composite pavement structure (asphalt concrete over emulsion aggregate mixture) are determined using a thickness substitution ratio calculated from the design thickness determined as if each material under consideration is to be used separately for the full depth.

Table 11-5 Early cure reduction factors for strength development of emulsion mixtures (from Santucci, 1977)

Month	Reduction Factor (RF) Six Months' Cure	One-Year Cure	Two-Year Cure	Month	Reduction Factor (RF) Two-Year Cure
1	1.0	1.0	1.0	13	0.198
2	0.37	0.62	0.78	14	0.175
3	0.225	0.48	0.69	15	0.154
4	0.136	0.37	0.62	16	0.136
5	0.082	0.29	0.545	17	0.120
6	0.05	0.225	0.48	18	0.105
7	-	0.175	0.42	19	0.093
8	-	0.136	0.37	20	0.082
9	-	0.105	0.33	21	0.073
10	-	0.082	0.29	22	0.064
11	-	0.064	0.255	23	0.057
12	-	0.05	0.225	24	0.05

The Asphalt Institute Method

Three types of mixes are specified in the manual series no. 1 (MS-1), 1991:

1. Type 1: mixes with processed dense graded aggregates, which should be mixed in a plant and have properties similar to hot mixtures.
2. Type 2: mixes with semi-processed, crusher run, pit run, or bank run aggregates.
3. Type 3: mixes with sands or silty sand.

The stiffness moduli at initial curing (the time of placement of materials) and at full curing and the effect of curing time on the stiffness modulus suggested in Santucci's method have been used. However, charts are presented for the particular type of material based on a six month cure period. Longer periods of curing up to 30 months were reported to have no significant influence on the design thickness. In preparation of these charts the more critical of either the fatigue cracking or rutting criterion was used.

For design of pavement structures consisting of a hot mixture as a surface layer, an emulsion mixture base, and untreated base, the following steps are recommended using the charts:

1. Design a full-depth of pavement for asphalt concrete, for the appropriate traffic and subgrade condition (Ta). Assume a 2 inch surface course and the remainder is the corresponding base thickness (Ta - 2).
2. Design a pavement for the same conditions for the emulsion mixture(Te). Assume a surface course and derive the corresponding base thickness (Te - 2).
3. Divide the thickness of emulsion mixture base (Te - 2) by the thickness of asphalt concrete base (Ta - 2) to obtain a substitution ratio.
4. Design a pavement for the same conditions using asphalt concrete and desired thickness of untreated base (Tu).
5. Select a portion of the asphalt concrete thickness to be replaced by the emulsion mixture (Tu - ACmin). The minimum asphalt concrete thickness (ACmin) is based on traffic and mix type.
6. Multiply the above thickness (Tu-ACmin) by the substitution ratio from step 3 to obtain the thickness required for the emulsion mixture.

11.3.3 Proposed Design Method

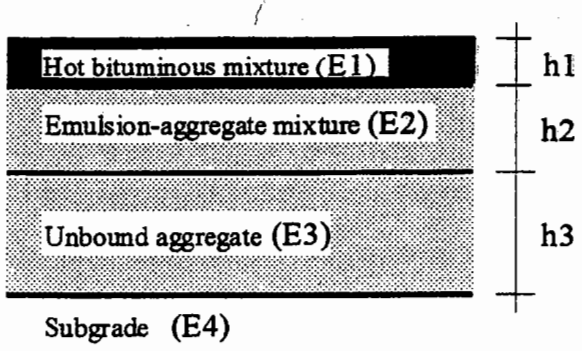
This study showed that the behaviour of emulsion-aggregate mixtures and equivalent hot bituminous mixtures are different. The response of emulsion-aggregate mixtures is highly non-linear. At early life, the material is less stiff, attributable to the water within it, retarding binder stiffness and adhesion with aggregate particles. At later stages of curing, when most of the water evaporates, binder stiffness increases, and the adhesion build-up improves, leading to a better response, but the material still has less adhesion compared to hot mixtures. The determined stiffness modulus of the material from a pilot scale wheel tracking study was found to be close to the determined value from the triaxial mode of test in the NAT, and not to that from the indirect tensile mode which was much higher.

From the results of the wheel tracking testing in the Slab Test Facility, discussed in Chapter 9, and the triaxial testing in the NAT (Chapter 5), the permanent deformation

rate of emulsion aggregate mixtures is dependent on the applied load level. Generally, the internal friction between the aggregate particles is the most significant factor contributing to rut resistance. An appropriate binder content in emulsion-aggregate mixtures may actually reduce rutting dramatically, compared to hot mixtures. Therefore, the vertical strain criterion developed for pavements constructed with hot mixtures may still be used for design of pavements with emulsion-aggregate mixtures since it relates to subgrade deformation.

In this design procedure, limiting the vertical strain at the surface of the subgrade layer and the horizontal strain at the bottom of the hot bituminous layer (surface layer) are considered the main criteria significantly influencing performance. The change of material properties during the curing period, from the time of commencing trafficking to the final curing, which depends on local conditions, is accounted for in a similar way to that suggested in the literature (originally taken from Santucci's method). Fatigue cracking of the emulsion mixture is not considered, since most of the performance studies have shown that it is not a frequent distress mechanism associated with emulsion-aggregate mixtures in the field. Besides, the pilot scale testing in this study showed that rutting in the material, depending on the applied load level, is more pronounced than fatigue cracking problems, despite the poor fatigue resistance of the material in the indirect tensile fatigue test relative to that of the hot mixtures.

Based on the above discussion, the stages of the proposed thickness design for pavement structures which have emerged from this research, are as shown in the flow chart presented in Figure 11-2.



Pavement structure

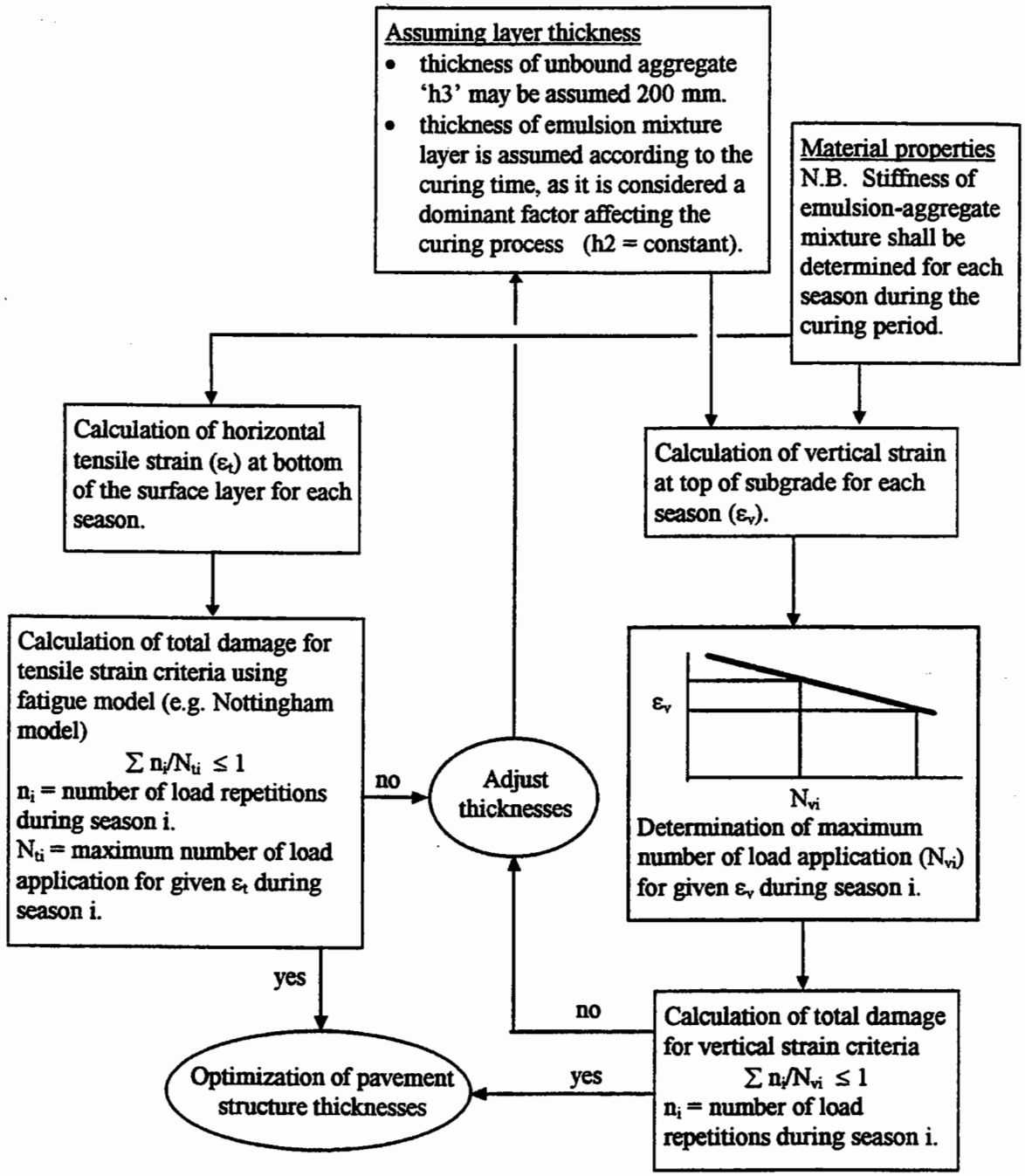


Figure 11-2 Flow chart of proposed thickness design of pavement structure

CHAPTER

12 CONCLUSIONS AND RECOMMENDATION FOR FUTURE RESEARCH

12.1 CONCLUSIONS

Based upon the results of the experimental work carried out in this study, the following conclusions were drawn:

1. For better distribution of the emulsion and hence to achieve a good coating of the aggregate, the maximum possible water content should be used in bituminous emulsion mixtures during the mixing process. On the other hand, an increased water content at compaction may lead to reduction in density and in material properties. Therefore, it is desirable to keep the water content for mixing at the lowest level which can give uniformly coated aggregate.

2. Bitumen emulsion manufactured using a harder base bitumen requires a higher amount of water for mixing, and hence coating, regardless of the amount of emulsion and the aggregate's gradation.

3. Compactibility of emulsion-aggregate mix samples using a Mechanical Marshall compactor was found to be influenced by emulsion type. For successful use, limits on emulsion viscosity must be set.

4. Determination of optimum water content using a dry density criterion is not sufficient and the stiffness modulus of the material after relevant curing should also be included. Over the range of emulsion contents used, the optimum moisture contents at compaction varied slightly, regardless of the type of emulsion or aggregate gradations. There was also a definite optimum of total water content in mixtures containing lower emulsion contents but not in mixtures with higher emulsion contents. Therefore, and due to the fact that moisture content at compaction affects the specimen's mechanical properties, it is worth keeping the total moisture content constant for mixtures with the same ingredients, using a compaction

curve based on a reasonable percentage of residual bitumen (preferably 3-4 % for DBM grading and 5 % for finer grading). Following this procedure minimizes the number of specimens required in the mix-design process, without affecting the results.

5. The use of higher water content at compaction is not beneficial to this type of mixture, depending on the aggregate gradation and emulsion type. It may result in reducing the effective RBC (as bitumen is 'lost' with water) or restructuring of the aggregate. Based on the author's experience, a water content that results in a water loss during compaction of not more than 1% is recommended.

6. Changes in water content at compaction have less effect on both dry density and stiffness modulus than changes in the residual bitumen content.

7. The compaction method and effort play a significant role in the response of emulsion-aggregate mixtures, influencing the interaction between the binder and the aggregate particles and the aggregate structure.

8. Aggregate gradation has a most significant effect on the stiffness properties of emulsion-aggregate mixtures. Fine dense grading appears to give the highest stiffness modulus. However, the response of a particular emulsion type is dependent upon the aggregate grading. Emulsion such as the K-emulsion has a relatively better effect on the stiffness moduli of fine dense graded mixtures. If coarser grading is used, the higher stiffnesses are biased towards a lower RBC.

9. Curing time does not alter the optimum residual bitumen contents of the mixtures in the way that it does with the optimum water content at compaction. Curing for a time at 20°C, leading to an early equilibrium water content (not the full curing at which the full strength of the material is attained), is enough for mix design purposes.

10.During the early stages of curing of emulsion-aggregate mixtures, both binder hardening and binder/aggregate adhesion continuously build up. Once a low mixture water content is attained, little further binder hardening takes place due to water loss

and increase in adhesion between the binder and aggregate is then the main factor, contributing to the considerable increase in stiffness experienced at later stages of curing. Therefore, during the period from laying and compacting the material until an equilibrium water content is achieved, water dominates the material's response. Consequently, stiffness and water content can be correlated. Beyond that, establishing a relationship between them is no longer representative of the real response of material as much of the stiffness gain is then dominated by other factors apart from the equilibrium water content value.

11.The time at which an emulsion bound material is covered on site is crucial, as it greatly influences the later stiffness moduli.

12.The stiffness modulus of emulsion-aggregate mixture specimens using different types of emulsions, for a range of applied stresses and curing regimes, indicated that emulsion-aggregate mixtures are highly stress dependent. An emulsion mixture generally has a variable response over the curing period and the selection of an appropriate applied stress level is therefore important in conducting the indirect tensile test for stiffness determination, to reduce the probability of material yielding. In addition, the material exhibits variation in Poisson's ratio over the curing period, measured in the triaxial test mode.

13.The stiffness-stress relationships from the indirect tensile mode are not due entirely to an inherent stress dependency of the material, but also from the damage which occurs in the microstructure of the mixture due to the applied load level. The stress levels used in this mode of testing are probably beyond the yield stresses of the emulsion-mixtures, leading to a debonding and an internal distortion in the aggregate structure due to insufficient adhesion between the binder and the aggregate particles. That is, the region of elasticity associated with emulsion-mixtures is much smaller than that for hot mixtures. However, this load-dependency response is not seen with comparable hot mixtures, indicating a lack of similarity in the behaviour of hot bituminous mixtures and emulsion-aggregate mixtures.

14.Stiffness modulus from the Nottingham Asphalt Tester (NAT) apparatus, with a pulsed vertical force equivalent to a load of 150 N per 750 mm^2 of specimen cross-sectional area, specified by the Highways and Utilities Committee (HAUC) set up in the UK in 1986 for permanent cold-lay surfacing materials - PCSMs, was found to be different than that from British Standard DD 213:1993, in which testing uses a peak load value with a rise time of 124 ms ± 4 ms, resulting in a peak transient horizontal deformation of at least 5 μm. However, in dealing with this type of mixture in the indirect tensile mode, tests should be carried out at different load levels to establish a stiffness-stress relationship for design purposes.

15.Oven curing of emulsion mixture specimens at 48°C for 2 days led to less stress dependency and improved their water resistance dramatically, although the unsoaked stiffness modulus of such specimens and of those cured at 20°C were similar. Oven curing emulsion mixture specimens at high temperatures is therefore not a representative curing method and is not suitable to be used as an accelerated curing regime.

16.A new assembly in the NAT was developed to allow testing in the triaxial mode of loading. This was found to be useful and suitable for routine testing of emulsion mixtures as it allowed:

- testing for stiffness modulus determination at different temperatures,
- accelerated curing and testing of the same specimens for establishing time-stiffness relationships,
- determination of stiffness modulus of specimens containing water after immersion for different times,
- testing for permanent deformation under constant confining pressure.

17.The stiffness modulus determined in the triaxial mode in the NAT for different applied stress levels fitted the K- θ model, usually applied to unbound aggregate. Curing of specimens certainly resulted in higher stiffness modulus values and reduced the degree of stress dependency. While test temperature greatly influenced stiffness modulus and stress dependency of specimens at later curing stages, it was not found to be so significant for specimens at an early stage of curing. The fine dense graded

mixtures appeared to have a higher stiffness than those of mid-DBM grading, in line with the trend of results from the indirect tensile mode of testing.

18. Very early loading of this type of material will generally influence the curing process and should be considered in determination of any time-stiffness relationship for design purposes. According to the stress levels expected, a correction for stiffness modulus should be determined.

19. At early stages of curing, values of Poisson's ratio were much higher than at later stages of curing. These values varied between 0.35 and 1.00 depending on the test stress level and the curing time. The value of Poisson's ratio was found not to be a function of compaction method or conditioning stress level.

20. The results from the indirect tensile mode were generally found to be sensitive to the mixture variables, and can therefore be used for material ranking tasks and hence for mixture design purposes. On the other hand, stiffness modulus from the triaxial mode was found to be close to back-calculated values from a pilot scale wheel tracking test, whereas that from the indirect tensile mode was not. Since the material also behaves non-linearly, the triaxial test result is greatly preferred for pavement structure design purposes. Emulsion aggregate mixtures may be characterised better by the triaxial mode of testing than the indirect tensile mode because the stress conditions are more appropriate.

21. Water in an emulsion-aggregate mixture dominates its deformation behaviour. At early stages of curing, both the viscous resistance contributed by the binder and the frictional resistance contributed by the mineral aggregate matrix are low, leading to movement within the aggregate particles. As the material undergoes curing, and water evaporates, a reduction in the strain rate increase occurs during the primary phase of permanent deformation response. During the second phase, for all curing levels, the strain rate may be similar, being influenced mainly by the aggregate structure. Increasing RBC in a mixture may increase the strain rate depending on the emulsion type and how far it distributes

among the aggregate particles. This response of the material is dependent upon specimen density, bitumen content and test temperature.

22.The overall permanent deformation of a mixture in the field is a result of the accumulation of deformation which occurs during its life. This will therefore be dominated by its response at early curing times, influencing the ranking of the different mixture combinations for design purposes. Partially cured specimens should then be representative of the condition of the paving mixture at the time of commencing trafficking.

23. Specimens of emulsion-aggregate mixtures with smooth and even surfaces for testing in the repeated load axial test are difficult to achieve. Using the triaxial mode of loading in the NAT, with mounted LVDTs, is preferred for assessing the material's resistance to permanent deformation, to reduce the effect of the end constraints which inevitably develop.

24.Lower RBC in a mixture, at both early and later stages of curing, gives rise to a performance dominated by the frictional resistance of the aggregate matrix. In this case, the viscous component of the mixture is not sufficient to affect the strain rate, leading to a better internal friction between the aggregate particles than that of mixtures containing higher RBC. In the wheel tracking test, the deformation performance of the material relative to hot mixtures is dependent on the residual bitumen content. Using a lower RBC, emulsion mixtures deform much more than hot mixtures during the initial phase of testing. But, because of its lower strain rate at later life relative to a hot mixture, the overall deformation will be less. On the other hand, emulsion mixtures containing higher RBC will deform much more than hot mixtures over the whole life of the material. Using lower RBC in emulsion aggregate mixtures is therefore beneficial, as it may mitigate the problem of permanent deformation.

25.The more the confinement of tested specimens the better the performance. This effect is much greater in emulsion mixtures than in hot mixtures because of their higher internal frictional resistance and a smaller lubrication effect from the binder.

26.Reducing the voids content in a mixture down to 8 % had no influence on the binder-aggregate interaction, leading to an unchanged adhesion condition. As a result, the same basic fatigue applied for voids content higher than 8 %. Emulsion-aggregate mixtures generally showed poor fatigue resistance. At lower strain levels, likely in the field, no significant influence of RBC on fatigue performance of the material could be distinguished. A better fatigue response would require reducing the voids to the level where water is squeezed from the mixture, giving a better bond between the aggregate and the binder. However, no such reduction in the voids of the mixture has been attempted, as it would not be realistic. Current experience shows that field compaction of emulsion-aggregate mixtures, even under controlled conditions, leads to much higher voids than is experienced with hot bituminous mixtures.

27.An emulsion-aggregate mixture with a good coating of the aggregate particles and a high stiffness modulus does not necessarily indicate a water resistant material. Even though specimens containing K-emulsion and DBM grading gained much of their final stiffness modulus at an early stage of curing, they had the highest stiffness throughout the curing process, and the coating to the aggregate particles was the best of all the emulsion mixtures used, they had very low retained stiffness modulus after being soaked.

28.DBM emulsion mixtures showed poor water resistance and provisions must be taken to prevent water intrusion when such mixtures are used as a road's structural layer. On the other hand, C2 'fine-dense' graded mixtures showed much better resistance to water. However, the benefit of using a fine grading in a mixture is greatly dependent on the emulsion formulation used and its effectiveness in coating the fine particles. The best use of a particular emulsion type is thus dependent on the aggregate gradation used and this should be considered in the mix design process.

29.A series of tests in a pilot scale wheel tracking test, approximately 1/3 scale, showed that the level of wheel load is a significant factor affecting performance of this material. Excessive load might lead to deformation in the surface of the emulsion mixture layer which is considered to be due to a loss of cohesion, leading to less tensile stress resistance and the occurrence of cracks at the layer surface. Two cases

associated with emulsion mixtures could be distinguished. When applying a low wheel load, there was little rutting and reasonable fatigue resistance but the failure was prone to be in fatigue rather than in rutting. When applying high wheel load, excessive rutting occurred and the failure was in rutting rather than in fatigue. The emulsion mixtures showed a similar behaviour to granular materials rather than hot asphalt mixtures, even after significant curing.

30.A modification to the base plate of the dynamic shear rheometer was made in this study, enabling preparation and testing of partially cured emulsion and emulsion residue at 20°C.

31.As the material cured and water was lost, the material behaviour was more elastic, indicated by the increased storage modulus (elastic response) relative to the loss modulus (viscous response). Generally, at early stages of curing the material is less temperature susceptible. As the material cures with time it tends to become more temperature susceptible.

32.The phase angles of the emulsion residues and the base bitumen were equal at a test temperature of 20°C, but not at higher temperatures. The difference in the phase angle was found to increase with the temperature. In general, the phase angle of the base bitumen was higher over the test temperatures used, indicating more viscous behaviour for the base bitumen. In terms of the complex modulus, no appreciable difference was noticed. The bitumen regained most of its original properties in terms of the absolute complex modulus but not the phase angle at higher temperatures. Since the phase angle is a significant rheological parameter and is sensitive to the structure and composition of the binder, one possibility is that emulsifier remaining in the system, leading to differences in the two bitumen structures, could be the reason.

33.Increasing the filler content is beneficial to emulsion mixtures. However, the quantity of filler in emulsion mixtures should be less than that which causes breaking of the emulsion before coating of larger aggregate particles is achieved.

34.Methods for mix design of emulsion-aggregate mixtures and for design of pavement structure incorporating emulsion-aggregate mixtures have been proposed.

12.2 RECOMMENDATION FOR FUTURE RESEARCH

In view of the findings of this research, the following recommendations are made:

1. Further investigations are needed into specimen preparation of emulsion-aggregate mixtures. The way the water drains from the mixtures and the water content remaining after compaction certainly affect the mechanical properties of the material in the short and long term. The compaction method and procedure which produces specimens with water contents, densities, and mechanical properties comparable to those expected in pavements should be investigated; otherwise, actual performance will not be replicated.

2. The aggregate grading in emulsion-aggregate mixtures is a significant parameter affecting the short and long term properties of the material. This research has shown the importance of the aggregate grading for each particular bitumen emulsion used, better performance generally being found with a fine-dense grading rather than the DBM mixtures currently used. Optimization of the mixture combination needs to be determined.

3. In this research, the repeated triaxial mode of loading was found to be a feasible mean for determination of stiffness modulus and for assessing the resistance to permanent deformation, or resistance to water effects. For routine tests, the NAT can be configured for this test mode as described in this thesis. The results from this test mode correlated relatively well to those from the pilot scale wheel tracking test. However, repeatability and reproducibility of the results from this test mode in the NAT needs to be determined. Laboratory tests related to material performance insitu also need to be determined. Full scale tests that simulate actual field conditions are required to study actual performance; for this the Falling Weight Deflectometer (FWD) will be a most useful assessment tool. The insitu test results and the various laboratory

test results, on both samples taken from the field and laboratory prepared samples, will lead to recommendations for a relatively simple suite of laboratory tests for use in characterising the material, both in the short and long term.

4. It was found during this study that the overall permanent deformation performance of emulsion-aggregate mixtures is influenced by its response during the early stages of curing. Accumulation of permanent deformation during the curing period, in principle as depicted in Figure 12-1, should be considered to take account of this early behaviour of material.

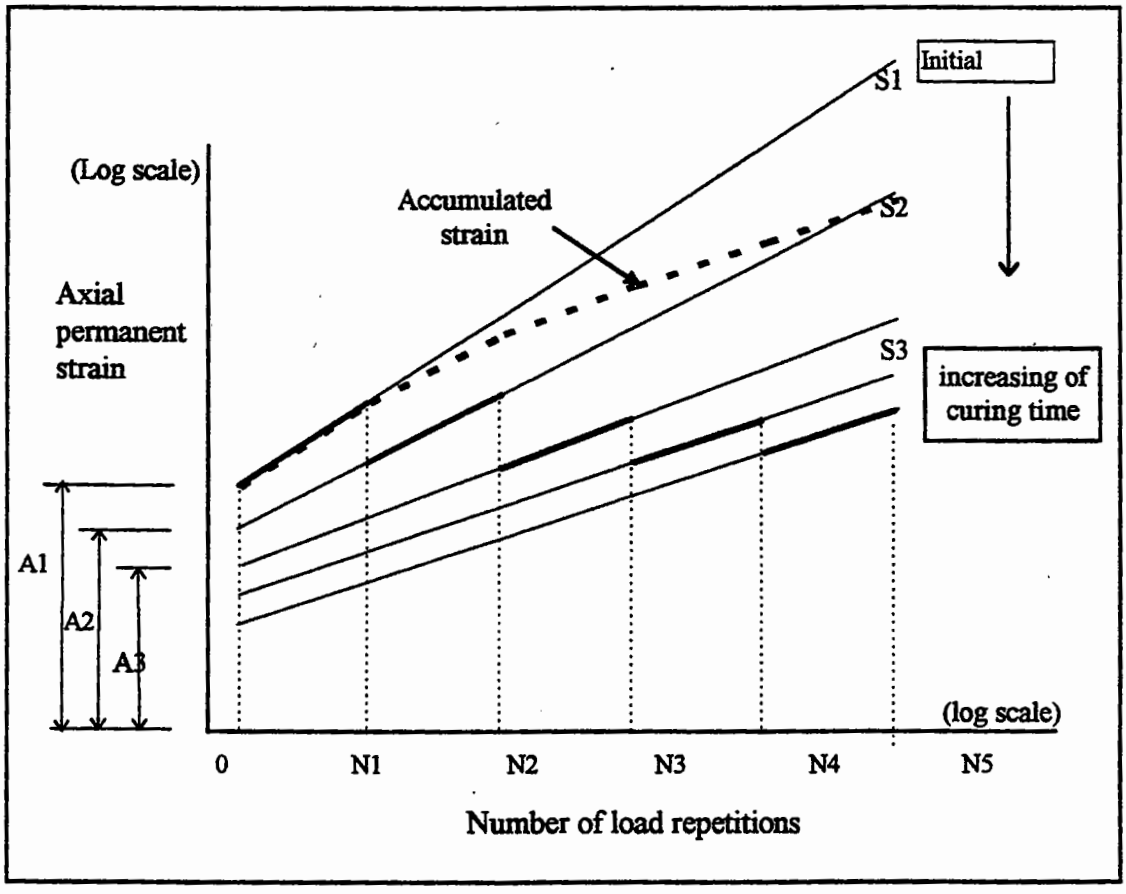


Figure 12-1 Accumulation principle of permanent deformation for cold mixtures during curing period

Validation of this principle of permanent deformation accumulation needs to be studied. This can be done through pilot scale testing of slabs dimensioned 100 cm × 100 cm at various stages of curing.

5. The thickness of an emulsion-aggregate mix layer certainly affects the curing rate of the material. The lower the layer thickness the faster the curing process. Constructing small test areas of the material (simulating actual conditions) and monitoring both the water content and the properties of the material are therefore important for pavement structural design. Therefore, the development of an accelerated curing for the material in the laboratory to simulate the field curing process is also important.

6. Further investigations are also needed to check the general applicability of the mix and pavement structural design methods proposed in this study.

REFERENCES

AASHTO TP5 (1994) "Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)".

Agnusdei, J.O., Bolzan, P.E., and Losco, O. (1990) "Rheological Behaviour of Asphalt Emulsion and Asphalt Emulsion Residues," Indian Highways 18 (9) - 31 - 39.

Almeida, J. (1993) "Analytical Techniques for the Structural Evaluation of Pavements," Ph. D Thesis, University of Nottingham.

ASTM Standard D 224 (1986) "Standard Methods of Testing Emulsified Asphalts," American Society for Testing and Materials, Philadelphia.

ASTM Standard D 4123-82 (1987) "Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures," American Society for Testing and Materials, Philadelphia.

ASTM Standard D 2041 (1990) "Theoretical Specific Gravity of Bituminous Paving Mixtures," American Society for Testing and Materials, Philadelphia.

Barnes, H.A., Hutton, J.F., and Walters, K. (1989) "An Introduction to Theology," Elsevier Science Publishers.

Bohlin Instruments "Bohlin Dynamic Shear Rheometer Installation, Operation & Software Manual".

Boussad, N. and Martin, N. (1996) "Emulsifier in Water Phase and Particle Size Distribution: Two Key-Parameters for the Management of Bituminous Emulsion," Eurasphalt & Eurobitume Congress, Paper no. E&E 6.159, Strasbourg.

Bowering, R.H. and Martin, C.L. (1976) "Foamed Bitumen Production and Application of Mixtures Evaluation and Performance of Pavements," Proceedings, Association of Asphalt Paving Technologists, Volume 45.

Brennen, M., Tia, M., Altschaeffl, A., and Wood, L.E. (1983) "Laboratory Investigation of the Use of Foamed Asphalt for Recycled Bituminous Pavements," Transportation Research Record No. 911.

British Standards Institution, BS 598: Part 3 (1985) "Sampling and Examination of Bituminous Mixtures for Roads and other Paved Areas".

British Standards Institution, BS 4987: Part 1 (1988) "Coated Macadam for Roads and Paved Areas- Specification for Constituents Materials and for Mixtures".

British Standards, Draft for Development DD 213: 1993 "Method for Determination of the Indirect Tensile Stiffness Modulus of Bituminous Mixtures".

British Standards, Draft for Development DD 185: 1994 "Methods for Assessment of Resistance to Permanent Deformation of Bitumen Aggregate Mixtures Subject to Unconfined Uniaxial Loading".

British Standards Institutes (June 1996), first draft DD ABF, "Method for the Determination of Fatigue Characteristics of Bituminous Mixtures using Indirect Tensile Fatigue".

Brown, S.F. (1979) "A Flexible Approach to Asphalt Mix Design," Journal of the Institution of Asphalt Technology, No. 27, pp.29-35.

Brown, S.F. and Brodrick, B.V. (1981) "Instrumentation for Monitoring the Response of Pavements to Wheel Loading," Sensors in Highway and Civil Engineering, Proceedings of the Conference Organized by the Institution of Civil Engineering, London.

Brown, S.F. and Brunton, J.M. (1986) "An Introduction to the Analytical Design of Bituminous Pavements," Third edition, University of Nottingham.

Brown, S.F. (1988) "Effect of Mix Properties on Structural Design: A Review," Proceedings, Association of Asphalt Paving Technologists AAPT, volume 57.

Brown, S.F. and Cooper, K.E. (1993) "Simplified Methods for Determination of Fundamental Properties of Asphalt Mixes," Proceedings of the Conference on Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents, The Hague, No. 1A, pp 124-136.

Brown, S.F. (1995) "Practical Test Procedures for Mechanical Properties of Bituminous Materials," Proceedings of the Institution of Civil Engineering, Transport.

Brown, S.F. , Gibb, J.M., Read, J.M., Scholz, T.V., and Cooper, K.E. (1995)[a] "Design and Testing of Bituminous Mixtures," University of Nottingham, Link Bitutest Project, Volumes 2: Research Report.

Brown, S.F. , Gibb, J.M., Read, J.M., Scholz, T.V., and Cooper, K.E. (1995)[b] "Design and Testing of Bituminous Mixtures," University of Nottingham, Link Bitutest Project, Volume 3: Experimental Procedures.

Burger, J.M. (1935) "First Report on Viscosity and Plasticity," Academy of Sciences, Amsterdam.

Cabrera, J.G. and Nikolaides, A.F. (1988) "Creep Performance of Cold Dense Bituminous Mixtures," Journal of the Institution of Highways and Transportation, No. 10, Volume 35.

Christensen, D.W. and Anderson, D.A. (1992) "Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt Cements," Journal of the Association of Asphalt Paving Technologists, Volume 61, pp 67 - 116.

Claaessen, A.I.M., Edwards, J.M., Sommer, P., and Uge, P. (1977) "Asphalt Pavement Design - The Shell Method," Proceedings, Fourth International Conference on the Structural Design of Asphalt Pavements, Vol. I, University of Michigan, Ann Arbor, pp. 39-74.

Cooper, K.E. and Brown, S.F. (1989) "Development of Simple Apparatus for the Measurement of the Mechanical Properties of Asphalt Mixes," Proceedings 4th Eurobitume Symposium, Volume 1, pp 494 - 498, Madrid.

Cooper, K.E. and Brown, S.F. (1993) "Assessment of the Mechanical Properties of Asphaltic Mixes on a Routine Basis using Simple Equipment," Proceedings Eurobitume Congress, Volume 1B, pp 872 - 876, Stockholm.

Coyne, L.D. and Ripple, R.M. (1975) "Emulsified Asphalt Mix Design and Construction," Proceedings, Association of Asphalt Paving Technologists, volume 44.

Darter, M.I., Truebe, M.A., and Abdulla, E.S. (1976) "Factors Affecting the Response of Emulsified Asphalt Mixtures," Proceedings AAPT, Volume 45.

Darter, M.I., Ahlfield, S.R., Wilkey, P.L, and Wasill, R.G. (1978) "Development of Emulsified Asphalt-Aggregate Cold-Mix Design Procedure," Research Report IHR-505-5, University of Illinois.

Darter, M.I., Wasill, R.G., and Ahlfield, S.R. (1980) "Use of Marshall Equipment in Development of Asphalt Emulsion Mixture Design Methods and Criteria," Transportation Research Record 754.

Epps, J.A. and Monismith, C.L (1971) "Fatigue of Asphalt Concrete Mixtures - Summary of Existing Information," Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM STP 508, American Society of Testing and Materials, pp. 19-45.

Epps, J.A. (1990) "Cold-Recycled Bituminous Concrete Using Bituminous Materials," National Cooperative Highway Research Program (NCHRP) No. 160.

Finn, F.N., Hicks, R.G., Kari. W.J., and Coyne, L.D. (1968) "Design of Emulsified Asphalt Treated Bases," Highway Research Record 239.

Fordyce, D., Markham, D. and Preston, N. (1993)"The Compaction Properties of Emulsion Macadam," First World Congress on Emulsion, Paper 4-12-012, Paris.

Gadallah, A.A., Wood, L.E., and Yoder, E.J. (1977) "A Suggested Method for the Preparation and Testing of Asphalt Emulsion Treated Mixtures Using Marshall Equipment," Proceedings Association of Asphalt Paving Technologists AAPT, Volume 46.

Gadallah, A.A., Wood, L.E., and Yoder, E.J. (1979) "Effect of Portland Cement on Certain Characteristics of Asphalt -Emulsion Treated Mixtures," Transportation Research Record No. 712.

Gibb, J.M., (1996) "Evaluation of Resistance to Permanent Deformation in the Design of Bituminous Paving Mixtures," Ph.D Thesis, University of Nottingham.

Head, R.W. (1974) "An Informal Report of Cold Mix Research using Emulsified Asphalt as a Binder," Proceedings, Association of Asphalt Paving Technologists, Volume 43.

Heukelom, W. (1969) "A Bitumen Test Data Chart for Showing the Effect of Temperature on the Mechanical Behaviour of Asphaltic Bitumen," Journal of the Institute of Petroleum Technologists, Vol. 55, pp. 404-417

Heukelom, W. (1973) "An Improved Method of Characterising Asphaltic Bitumens with the Aid of Their Mechanical Properties", Proceedings of the Association of Asphalt Paving Technologists, Vol. 42, pp. 62-98.

Hicks, R.G. and Monismith, C.L. (1971) "Factors Influencing the Resilient Response of Granular Materials," Highway Research Record, No. 345, pp. 15-31.

Hicks, R.G., Willianson, R., and Santucci, L.E. (1979) "Effect of Laboratory Curing and Compaction Methods on the Stress-Strain Behavior of Open-Graded Emulsion Mixes," Transportation Research Record 712.

Highway Authorities and Utilities Committee 'HAUC', (1992) "New Roads and Streetworks Act 1991 - Specification for the Reinstatement of Opening in Highways," HMSO Publishers.

Hopman, P.C., Kunst P.A.J.C. and Pronk, A.C. (1989) "A Renewed Interpretation Method for Fatigue Measurement, Verification of Miner's Rule," 4th Eurobitume Symposium, Volume 1, Madrid, pp. 557-561.

Hudson, W.R. and Kennedy, T.W. (1968) "An Indirect Tensile Test for Stabilized Materials," Research Report 9801, Center for Highway Research, The University of Texas at Austin.

Huhtala, M., Alkio, R., Pihljamaki, J., Pienmaki, M. and Halonan, P. (1990) "Behavior of Bituminous Materials Under Moving Wheel Loads," Journal of the Association of Asphalt Paving Technologists, Volume 59, pp 422 - 442.

Huschek, S. (1985) "The Deformation Behaviour of Asphaltic Concrete under Triaxial Compression," Journal of the Association of Asphalt Paving Technologists, Volume 54, pp 407 - 431.

Ibrahim, H.E, (December 1995) "Laboratory Assessment of Cold Bituminous Mixtures," report no. PGR95028, University of Nottingham.

Ibrahim, H.E. and Thom, N.H. (1997) "The Effect of Emulsion-Aggregate Mixture Stiffness on both Mixture and Pavement Design," Proceedings of the Second European Symposium on Performance and Durability of Bituminous Materials, Leeds, pp. 351-367.

Ibrahim, H.E. and Thom, N.H. (1998) "Performance of Emulsion Aggregate Mixtures during early life," paper accepted for publication, Fifth International Conference on the Bearing Capacity of Roads and Airfields, Trondheim, Norway, 6-8 July 1998.

Ishai, I., Herrin, M., and Leverenz, D. (1975) "Analysis of Failure Modes and Related Required Properties in Asphalt-Treated Cold Mix Bases," Proceedings AAPT, Vol. 44.

Jimenez R.A (1971) " Setting and Durability of Asphalt Emulsions," Proceedings, Association of Asphalt Paving Technologists, Volume 40, pp. 463-486.

Kazmierowski, T.J., Bradbury, A., Cheng, S., and Raymond, C. (1992) "Performance of Cold In-Place Recycling in Ontario: In Flexible Pavement Construction, Performance, and Recycling, Transportation Research Record 1337.

Kent County Council : Highways & Transportation (1996) "Laboratory Test Report on Permanent Cold Lay Basecourse (HAUC)," Report No. B58754

Khalid, H. and Eta, K.E. (1996) "Laboratory and Field Performance of dense Emulsified Bitumen Macadams used for Highway Reinstatement," Eurasphalt & Eurobitume Congress, Strasbourg, Paper E&E 1.093.

Khalid, H. and Eta, K.E. (1997)[a] "Design and Fatigue Behaviour of Emulsified Bitumen Macadams for Highway Reinstatement," Proceedings, 8th International Conference on Asphalt Pavements, Seattle, Washington DC.

Khalid, H. and Eta, K.E. (1997)[b] "Structural Support Values for Emulsified Bitumen Macadams in Highway Reinstatement," Proceedings of the Second European Symposium on Performance and Durability of Bituminous Materials, Leeds, pp. 307-336

Khosla, N.P. (1983) "Effect of Emulsified Binders on Characteristics of Bituminous Mixtures," Transportation Research Record 911.

Killeen, J., Flynn, E., and Brennan, M.J. (1993) " Cold Mix Macadams Experience in Ireland," 5th Eurobitume Congress in Stockholm.

Kim, Y.R., Little, D.N., and Benson, F.C. (1990) "Chemical and Mechanical Evaluation on Healing Mechanism of Asphalt Concrete," Proceedings of Association Asphalt Paving Technologists, Volume 59, pp. 240-275.

Kim, Y.R., Khosla, N.P, and Kim, N. (1991) "Effect of Temperature and Mixture Variable on Fatigue Life Predicted by Diametral Fatigue Testing," Transportation Research Record 1317.

Kubitshek, H.E. (1960) "Electronic Measurement of Particle Size," Research Applied in Industry, Volume 13, London.

Lafon, J., Goyon, V., Samanos, J., and Chaignon, F. (1993) "In-situ Performance of Cold Mixes - The French Experience," First World Congress on Emulsion, Paris, Volume 3.

Lee, D.Y. (1981) "Treating Marginal Aggregates and Soils with Foamed Asphalt," Proceedings Association of Asphalt Paving Technologists AAPT, Volume 50.

Leech, D (1994) "Cold-Mix Bituminous Materials for use in the Structural Layers of Roads," Transport Research Laboratory, Crowthorne, Project Report 75.

Mamlouk, M.S. and Wood, L.E. (1979) "Evaluation of the Use of Indirect Tensile Test Results for Characterization of Asphalt Emulsion-Treated Bases," Transportation Research Record 733.

Mamlouk, M.S., Wood L.E., and Gadallah, A.A. (1980) "Laboratory Evaluation of Asphalt Emulsion Mixtures by Use of the Marshall and Indirect Tensile Tests," Transportation Research Record 754.

Marais, C.P. and Tait, M.I. (1989) "Pavements with Bitumen Emulsion Treated Bases: Proposed Material Specifications, Mix Design Criteria and Structural Design Procedures for Southern African Conditions," Proceedings 5th Conference on Asphalt Pavements for Southern Africa.

Marchal, J.L., Boussad, N., and Julien, P. (1993) "A New Approach to Cold Mixes Design and Performance," 5th Eurobitume congress, Stockholm, Sweden.

McLeod, N.W. (1976) "Asphalt Cement: Pen-Vis Number and its Application to moduli of Stiffness," ASTM Journal of Testing and Evaluation, Vol. 4, No. 4.

Miner, M.A. (1954) "Cumulative Fatigue Damage," International Conference on the Fatigue Damage of Metals, London.

National Cooperative Highway Research Program, NCHRP, (1975) "Bituminous Emulsions for Highway Pavements," Synthesis of Highway Practice 30.

Needham, D. (1996) "Developments in Bitumen Emulsion Mixtures for Roads," Ph.D Thesis, University of Nottingham.

Nikolaides, A.F. (1993) "Proposed Design Method for Cold Dense Graded Bituminous Mixtures," 5th Eurobitume Congress in Stockholm.

Nikolaides, A.F. (1994) "A New Design Method for Dense Cold Mixtures," Proceedings of Symposium, Performance and Durability of Bituminous Materials, University of Leeds, pp. 259-269.

Nunn, M.E. and Bowskill, G. (1992) "Towards a Performance Specification for Bituminous Roadbases," Proceedings of the 7th International Conference on Asphalt Pavements, Volume 3: Design and Performance, pp 266-279.

Nunn, M.E. (1996) "The Characterisation of Bituminous Macadams by Indirect Tensile Stiffness Modulus," Transport Research Laboratory, Crowthorne, Report 160.

Paute J. L, Dawson A. R, and Galjaard P. J. (1993) "Recommendation for Repeated Load Triaxial Test Equipment and Procedure for Unbound Granular Materials," Proceedings of the European Symposium [illegible]

22 September 1993, Published Flexible Pavements, Gomes Correia (ed.) 1996 Balkema, Rotterdam.

Pell, P.S. (1974) "Characteristics of Bound Paving Materials," Lecture J, In: Lecture Notes for the Third Residential Course, University of Nottingham.

Pell, P.S. and Cooper, K.E. (1975) "The Effect of Testing and Mix Variables on the Fatigue Performance of Bituminous Materials," Proceedings Association of Asphalt Paving Technologists, Volume 44.

Petersen, J.C. et al (1994) "Binder Characterization and Evaluation - Volume 4 : Test Methods," Strategic Highway Research Program, Project No. SHRP-A-370.

Pfeiffer, J and Van Doormal, P.M. (1936) "The Rheological Properties of Asphaltic bitumens," Journal of the Institute of Petroleum, Vol. 22, pp. 414-440.

Powell, W.D., Potter, I.F., Mayhew, H.C. and Nunn, M.E. (1984) "The Structural Design of Bituminous Roads," Laboratory Report 1132, Transport and Road Research Laboratory, Crowthorne.

Preston, J.N. (1991) "The Design of Bituminous Concrete Mixtures," Ph.D Thesis, the University of Nottingham.

Puzinauskas, V.P. and Jester, R.N. (1983) "Design of Emulsified Asphalt Paving Mixtures," NCHRP, Report No. 259.

Rao Tangella, S.C.S, Craus, J., Deacon, J.A., and Monismith, C.L., (1990) "Summary Report on Fatigue Response of Asphalt Mixtures," Strategic Highway Research Program, SHRP Project A-003-A.

Read, J.M. (1995) "Asphalt versus Macadams," The Institute of Asphalt Technology, Training Seminar: Blacktop Now and in the Future.

Read, J.M. (1996) "Fatigue Cracking of Bituminous Paving Mixtures," Ph.D dissertation, University of Nottingham.

Rice, J.M. (1952) "The Measurement of Voids in Bituminous Mixtures," Proceedings Association of Asphalt Paving Technologists, Volume 21.

Roberts, F.L., Engelbrecht, J.C., and Kennedy, T.W. (1984) "Evaluation of Recycled Mixtures Using Foamed Asphalt," Transportation Research Record No. 968.

Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y., and Kennedy, T.W. (1991) "Hot Mix Asphalt Materials, Mixture Design, and Construction," Napa Education Foundation, Maryland, First Edition.

Robinson H., Fordyce D., and Khweir, R. (1996) "Road Maintenance using Cold Mix Materials with Hot Mix Properties," Eurasphalt & Eurobitume Congress, Strasbourg, Paper E&E 1.021.

Row, G.M. (1996) "Application of the Dissipated Energy Concept to Fatigue Cracking in Asphalt Pavement," Ph.D Thesis, University of Nottingham.

Row, G.M. and Brown, S.F (1997) "Fatigue Life Prediction Using Visco-Elastic Analysis," Proceedings, 8th International Conference on Asphalt Pavements, Seattle, Washington DC., pp. 1109-1122.

Ruckel, P.J., Acott, S.M., and Bowering R.H. (1983) "Foamed-Asphalt Paving Mixtures: Preparing of Design Mixes and Treatment of Test Specimens," Transportation Research Record No. 911.

Sabita (1993) "The Design and Use of Granular Emulsion Mixes," Manual 14, South Africa.

Santucci, L.E (1977) "Thickness Design Procedure for Asphalt and Emulsified Asphalt Mixes," Proceeding 4th International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, USA.

Santucci, L.E. and Hayashida, M.T. (1983) "Design and Testing of Cold Recycled Asphalt Mixes," Proceedings, Association of Asphalt Paving Technologists, Volume 53.

Shell Pavement Design Manual (1978) "Asphalt Pavements and Overlays for Road Traffic," Shell International Petroleum Company Ltd. London, with Addendum 1985.

Shell Bitumen (1990) "The Shell Bitumen Handbook," chapter 4, pp 45 -59.

Shell Bitumen (1995) "The Shell Bitumen Industrial Handbook," chapter 6, pp 119-142.

Smith, T.M. (1996) "A Comparison of Different methods of Analysing Dynamic Creep Test Results," Transport Research Laboratory, Crowthorne, Report 159.

Snaith, M.S. (1973) "Deformation Characteristics of Dense Bitumen Macadam

Snaith M., Kerali H., and Koole R., (1993) "A Logical Design Method for Grave Emulsion Road Pavements," 1st world congress, Paris, Paper 4-12-026.

Sosnovske, D., Leahy, R.B.and Hicks, R.G., (1994) "Evaluation of Rutting Potential of Oregon Surface Mixtures," Proceedings of Association Asphalt Paving Technologists, Volume 63.

Sousa, J.B, Craus, J. and Monismith, C.L. (1991) "Summary Report on Permanent Deformation in Asphalt Concrete," Report SHRP-A/IR-91-104, Institute of Transportation Studies, University of California Berkeley.

Sweere, G.T.H. (1990) "Unbound Granular Bases for Roads," Ph.D Thesis, Delft University of Technology, The Netherlands.

Syndicat Des Fabricants D'Emulsions Routieres De Bitume, SFERB (1991) "Bitumen Emulsions : General Information Applications," Paris.

Terrel, R.L and Wang, C.K. (1971) "Early Curing Behaviour of Cement Modified Asphalt Emulsion Mixtures," Proceedings Association of Asphalt Paving Technologists, Vol. 40, pp. 108-125.

The Asphalt Institute (1979) "A basic Asphalt Emulsion Manual," Manual Series No. 19, First Edition.

The Asphalt Institute (1983) "Asphalt Cold-Mix Recycling," Manual Series No. 21 (MS-21).

The Asphalt Institute (1988) "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types," Manual Series No. 2 (MS-2).

The Asphalt Institute (1989) "Asphalt Cold Mix Manual," Manual Series No. 14, Third Edition, Lexington, USA.

The Asphalt Institute (1991) "Thickness Design : Asphalt Pavements for Highways & Streets," Manual Series No. 1 (MS-1).

Tia, M. and Wood, L.E. (1985)[a] "The Use of Water Immersion Tests in the Evaluation of the Effects of Water on Cold-Recycled Asphalt Mixtures," Evaluation and Prevention of Water Damage to Asphalt Materials, ASTM STP 899, pp. 89-103.

Tia, M. and Wood, L.E. (1985)[b] "The Use of a Gyratory Testing Machine in the Evaluation of Cold-Recycled Asphalt Paving Mixtures," Pavement Maintenance and Rehabilitation, ASTM STP 881, pp. 74-90.

Transportation Research Board (1975) "Test Procedures for Characterising Dynamic Stress-Strain Properties of Pavement Materials," Special Report 162.

Wallace, K., and Monismith, C.L. (1980) "Diametral Modulus Testing on Nonlinear Pavement Materials," Proceedings of Association Asphalt Paving Technologists, Volume 50.

Waller, H.F. (1980) " Emulsion Mix Design Methods- An Overview," Transportation Research Record 754.

White, T.D. (1985) "Marshall Procedures for Design and Quality Control of Asphalt Mixtures," Journal of the Association of Asphalt Paving Technologists, Volume 54, pp 265 - 284.

Wijk, A.J. (1983) "Structural Comparison of Two Cold Recycled Pavement Layers," Transportation Research Record 954.