The Use of Secondary Aggregates in Bituminous Mixtures

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Abstract

This project assesses the mechanical properties of a range of both base and surfacing materials incorporating different combinations, size fractions and percentages of two primary aggregates (limestone and gritstone) and three secondary aggregates (basic oxygen steel slag, blast furnace slag and glass cullet). The mechanical properties of the asphalt mixtures have been measured using the suite of tests (stiffness modulus, resistance to permanent deformation and resistance to fatigue cracking) possible with the Nottingham Asphalt Tester (NAT). Ageing and moisture susceptibility of the mixtures also has been assessed using recognised testing (conditioning) procedures and protocols. The mixtures have been designed using volumetric grading in order to take into account the difference of the particle density of aggregates.

The results indicate that the use of glass cullet fine aggregate in a 28 mm continuously graded base material only marginally reduces the stiffness modulus of the secondary aggregate modified mixture. The moisture susceptibility of the material was also shown to be less than what would be expected for a smooth surface textured aggregate such as glass, with and without the use of an anti-stripping agent. The replacement of primary aggregate with glass cullet also significantly reduced the aging susceptibility of the mixture, while the permanent deformation resistance, although inferior to that of a primary aggregate mixture, was still acceptable with the fatigue performance being comparable to the control mixture.

The use of basic oxygen steel slag and blast furnace slag secondary aggregates significantly increases the mixture density and stiffness modulus compared to primary aggregate mixtures. The moisture susceptibility of these secondary aggregate mixtures was also found to be similar to that of the control mixtures, although the DBM slag mixtures did show an increased susceptibility to moisture conditioning when the binder content of the mixture was not enough to cover the aggregate. The age hardening of the slag mixtures was found to be much greater than that of control mixtures. Overall the permanent deformation resistance and fatigue performance of the slag mixtures tended to be similar to that of the limestone and gritstone base and surfacing control mixtures. However, results indicate that the slag mixtures become more brittle material than the other mixtures.

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Chapter 1 Introduction

1.1 Background of the use of secondary aggregates

1.1.1 Definition of secondary aggregate

The term "Secondary aggregate" is defined as an aggregate, which is not obtained from a quarry (aggregates obtained from quarry are called primary aggregates), but is a by-product or recycled material generated from production activities. Examples are slag from the steel making process, crushed glass, crushed concrete, recycled asphalt and so on.

The idea of utilising these by-products or recycled materials as an aggregate is not a new concept. Probably it can be conjectured that the utilisation of waste materials began when human beings started production activity. In modern times, the example of the use of secondary aggregates in road construction was found in a publication in 1894 [9]. Slag was used as an aggregate in a tarred footpath in Nottinghamshire. After the industrial revolution, there would be much waste materials generated from iron making process. Regarding the use of secondary aggregates as road aggregates, it was found that the first slag tarmacadam has been laid in Derbyshire in 1901 [11].

Of course, recent activities have been generating not only these slag materials from steel/iron making process, but wide range of waste materials, such as PBA (Pulverised Bottom Ash) from power station to crushed glass from our ordinary life. How these materials should be utilised or recycled seems to be one of the most important matters of the government.

1.1.2 Problem definition

According to the report published by British Geological Survey [1], approximately 210 million tonnes of aggregates was used for construction in the U.K. in 1999. Most aggregates are derived from land-won sources and are called primary aggregate, such as sand, gravel and crushed rock. Although the figure is not precise, some 5% of total aggregates is accounted for by secondary aggregates, such as China clay waste, metallurgical slag and power station ash, or recycled aggregates, such as road planings and construction and demolition materials.

The government has published guidance aimed not only to guide the proper usage of natural aggregates but also to reduce the proportion of primary aggregates. A target has been set to increase the use of secondary and recycle aggregates from 30million tonnes in 1989 to 55million tonnes in 2006 [2]. In this report, it can be found that there seems to be large quantities of mineral resources, which will be sufficient for the demand for construction, however, it has been recognised that it is becoming more difficult to exploit new sites because of growing concern for the protection of environment.

On the other hand, it seems that the government needs to decide urgently how the waste materials derived from industrial activity or our daily life shall be treated. Furthermore, to make development sustainable, it becomes important to consider recycling. To meet this social responsibility, developing the use of secondary and recycled materials as aggregate has begun to be addressed. To encourage the use of secondary and recycled materials and reduce the demand for virgin aggregates, the government announced that an Aggregates Levy of £1.6/tonne would be introduced in April 2002 [4]. The Aggregates Levy is applied to sand, gravel and crushed rock. Secondary and recycled aggregates arising from road construction, the spoil or waste, and industrial by-products will be exempt from the Levy.

Approximately one-third of total aggregate consumption is used for road construction, repair and maintenance, therefore the responsibility for using secondary and recycled materials in the road construction area is significant. Secondary materials, such as colliery spoil, China clay waste, power station waste, blast furnace slag, slate waste, and construction and demolition wastes have been used as road construction aggregate [3,6]. One of the secondary aggregates highly exploited is blast furnace slag (BFS). It is reported that this material is utilised completely as a construction aggregate [1]. As research on the utilisation of BFS as an aggregate began in the 1940's in the U.K. [7], it is recognised that BFS is a durable and stable material and can be used in asphalt mixtures and concrete mixtures.

1.2 Objective and Outline of the Research

1.2.1 Objective

The aim of this project is, primarily, to investigate the properties of bituminous mixtures that contain secondary aggregates. One of the secondary aggregates employed in this project is steel slag. It seems that steel slag can be expected to enhance the mechanical properties of the mixture because of its durable nature. The other secondary aggregate employed in this project is crushed glass. Many cases of using crushed glass in bituminous mixtures were found in U.S.A in the 1970's. However, to increase the recycling ratio of glass, the use of crushed glass in bituminous mixtures has been addressed recently in the U.K. [5] as well as other countries, such as Japan [10]. In addition to these materials, because of its lower specific gravity, BFS aggregate was used in combination with steel slag aggregate.

1.2.2 Outline

Two types of bituminous mixture were selected: Stone Mastic Asphalt (SMA) and Dense Bitumen Macadam (DBM). SMA is a wearing course material, which was developed in Germany and has been used in many countries because of its superior performance, such as good resistance to rutting and cracking. It is also known that traffic noise is reduced approximately 2dB in relation to the more traditional Hot Rolled Asphalt because of its open surface texture [8]. DBM is a basecourse / roadbase material, which is employed primary in the U.K. In this project, DBM is regarded as roadbase material, mainly because ravelling of glass aggregate is one of the problems, as explained later in Section 2.2, when crushed glass mixture is trafficked directly, making roadbase a more suitable mixture than basecourse, which is sometimes trafficked.

Conventional evaluation methods, such as the Nottingham Asphalt Tester (NAT) and the Immersed Wheel Tracking test were employed to assess the mixture performance. The NAT was developed in the University of Nottingham and is used in the U.K. to obtain the fundamental properties of bituminous mixtures. The Indirect Tensile Stiffness Modulus (ITSM), Indirect Tensile Fatigue Test (ITFT), and Vacuum Repeated Load Axial Test (VRLAT) can be undertaken using NAT machine [12]. It will be important to assess the long-term performance of the mixture containing secondary aggregate, especially if there are not many precedents for using these materials. Therefore, a conditioned test, after ageing and/or water sensitivity, was also conducted using the NAT.

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Chapter 2 Literature review

2.1 Steel slag

2.1.1 Definition

Steel slag is defined as a non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused and mineralogically combined oxides of iron, aluminium, manganese, calcium and magnesium, that is developed simultaneously with steel in basic oxygen, electric arc, or open hearth furnaces [1]. In the steel industry, Blast furnace slag (BFS) and steel slag are mainly produced as by-products of the steel making process. The basic oxygen furnace (BOF) process and electric arc furnace (EAF) process are the steel making processes employed in the UK presently, with almost 75% of steel produced by the BOF process [2].

2.1.2 Process

In the BOF process, steel is produced from iron ore through two stages. In the first stage, iron ore is charged in the blast furnace and smelted with coke as fuel and limestone as flux. During the smelting process, while the reduction of the iron oxide occurs, slag is formed as a combination of the impurities in the ore and lime. At regular intervals, molten slag is removed and molten pig iron is tapped in the ladle. Molten pig iron is sent to the BOF to produce steel, while slag is processed to form blast furnace slag aggregate.

Selective cooling of the liquid slag results in four distinct types of blast furnace slag [3,11]:

1- Air cooled; material resulting from solidification of molten blast furnace slag under atmospheric conditions. This material can be extensively used in conventional aggregate applications.
2- Expanded or foamed; lightweight cellular material obtained by controlled processing of molten blast furnace slag with water or water and other agents, such as steam or compressed air or both. This material is mainly used as a lightweight aggregate.

3- Granulated; glassy, granular material formed when molten blast furnace slag is rapidly chilled, as by immersion in water. This material is mainly used in slag cement manufacture.
4- Pelletised (solidified by water and air quenching in conjunction with a spinning drum), which is used both as a lightweight aggregate and in slag cement manufacture.

The molten pig iron is sent to the Basic Oxygen Furnace (BOF) where it is combined with steel scrap, various metallic elements, additional lime or dolomitic lime fluxes. High-pressure oxygen is injected to remove and to combine with the impurities and fluxes such as lime and dolomitic lime. Steel slag is formed by the combination of these impurities, lime and dolomitic lime.

The main differences between BOF and EAF is that the EAF steel making process is more energy efficiency and cold steel, such as scrap steel, is mainly used in the EAF process instead of molten pig iron as in the BOF process [4].

2.1.3 Properties of slag aggregate

Steel slag and blast furnace slag processed as aggregates have suitable properties for road construction materials. Typical values of the physical properties are listed in Table 2.1. It is obvious that steel slag aggregates have good physical properties, such as Aggregate Crushing Value (ACV, resistance to crushing under a gradually applied compressive load), Aggregate Impact Value (AIV, resistance of an aggregate to impact) and Aggregate Abrasion Value (AAV, resistance to surface wear by dry abrasion), and Polished Stone Value (PSV, used to evaluate the potential for skid resistance) [5]. However, steel slag has a relatively high specific gravity, compared to blast furnace slag or natural aggregate.

Typical basic oxygen process steel slag and blast furnace slag composition is listed in Table 2.2.

Table 2.1. Physical properties of slag aggregates [6]

Properties	Steel slag	Blast furnace slag	Typical limit [5]
Specific gravity	3.1 - 3.5	2.38 - 2.76	
ACV	12 - 25	25 - 39	<25
AIV	18 - 24	21 - 42	<30
AAV	3 - 4	5 - 31	<16
Water absorption	0.2 - 2	1.5 - 5	
PSV	53 - 72	50 - 63	>58(surfacing)

Table 2.2. Chemical Properties [7]

Constituent	Composition (%) Steel slag	Composition (%) Blastfurnace slag
CaO	42 - 44	41
SiO_2	10 - 12	35
Fe_2O_3	27 - 31	
MnO	3 - 4	
MgO	5 - 6	7
Al_2O_3	1 - 2	14
P_2O_5	1 - 2	
TiO_2	0.5	
S		0.8

Steel slag has expansive nature because of the presence of free calcium oxide and magnesium oxide. This is explained in more detail in 2.1.5.

2.1.4 Application of slag aggregates

Blast Furnace Slag

Air-cooled BFS is used in a similar way to conventional aggregate. Applications are; granular base, ballast, trench fill, backfill, asphalt concrete and Portland cement concrete. Because of its low bulk density, the self-weight of structure and transportation costs on a volumetric basis can be reduced. High stability and friction angle are also attractive characteristics of the air-cooled BFS. However, due to the vesicular surface and high water absorption ratio, larger amounts of bituminous binder (approximately 8% for a dense graded mixture) may be required when used in bituminous mixtures [11]. In the U.K., a full-scale experiment of the use of blast furnace slag as an aggregate in bituminous materials was conducted after the Second

World War. It was observed that the use of blast furnace slag aggregate in bituminous mixtures had some advantages, such as high skid resistance and good rutting resistance [6].

Expanded and Pelletized BFS are used not only as aggregates but also as slag cement. When these slag aggregates are used in concrete, self-weight of structure can be reduced significantly. Moreover, as the granulated and pelletized BFS have cementitious properties, these materials are used as slag cement.

Steel slag

Steel slag aggregate has been used in bituminous mixtures. General features of steel slag mixtures are; high Marshall stability with good flow properties, excellent resistance to stripping, good skid resistance, and high bulk density, which is a disadvantage of the mixture [11]. The expansive nature of steel slag aggregates may cause premature deterioration, such as cracking, therefore, steel slag is used under restricted conditions in many countries, such as the U.S.A., Belgium, Germany and Japan [15]. In these countries both aggregate and mixture expansion tests are required. In the U.K., according to the British Standard, steel slag should be weathered until it is no longer susceptible to expansion [17]. Because of its expansive nature, steel slag aggregate is not used in cement concrete.

2.1.5 Expansive nature of steel slag

In fact, map cracking (cracks formed of a similar shape to a hexagonal pattern, see Figure 2.1) has been observed in 100% steel slag aggregate mixtures in several countries [8] and it is thought that the expansion of steel slag aggregate caused the cracking. According to the Steel Slag User Guidelines [8], expansion of steel slag will result in cracking of the slag particles. Cracks or pop-outs can appear when such a reaction occurs in the pavement. Emery [11] noted that the hydration of unslaked lime (free CaO) and magnesium oxide (MgO) in contact with moisture is largely responsible for the expansive nature of most steel slag and free CaO reacts rapidly and may cause large volume change in the short term, while MgO reacts slowly and can expand in the long term. However, the detailed mechanism of expansion seems still unclear. In Canada, the Ministry of Transportation prohibited the use of steel slag in 1991 because the cause of the map cracking was still unclear.

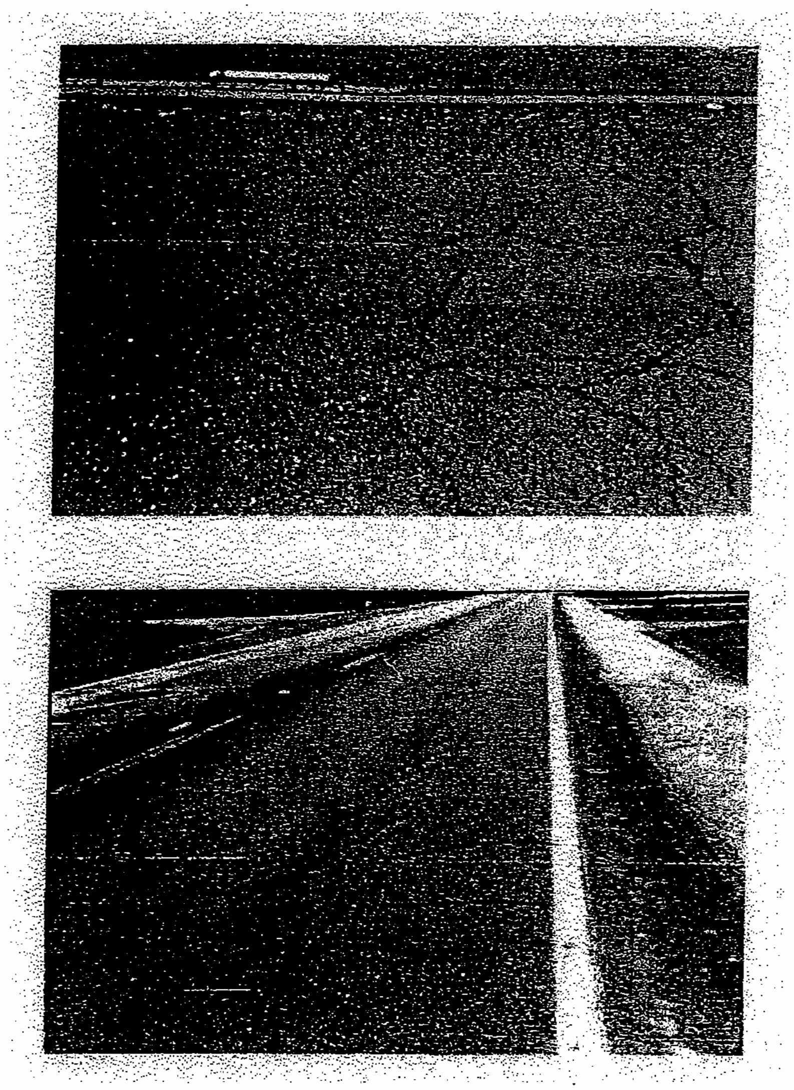

Figure 2-1 Example of Map Cracking Observed on a Steel Slag Mixture [10]

The detailed analysis of steel slag aggregate

Coomarasamy and Walzak [14] investigated material composition, morphology and surface chemistry of different sources of steel slag aggregate (three BOF, one EAF and two experimental BOF steel slags; weathered in laboratory) using three techniques (scanning electron microscopy coupled with energy dispersive x-ray analysis (SEM/EDX), electron probe x-ray microanalysis (EPMA), and x-ray diffraction (XRD)). The result of surface characterisation obtained by EDX showed that the different steel slag surfaces were consistent. Namely, calcium was enriched in all slag surfaces with varieties of oxide of silicon, iron, aluminium, magnesium and manganese. However, the result of EPMA [14] indicated that the cross section of steel slag was not uniform (except for the EAF steel slag sample). It was also shown that there was a difference between the interior region and the interface region for the BOF slag. Primary phases of these samples were different in their detailed composition, distribution and microstructure. Also, the results indicated that the mixed oxide region in the EAF slag had higher MgO component compared to the BOF slag.

Chemical compositions of these slag samples were examined and the results showed that all the BOF slags had consistent composition, whilst EAF had a lower iron oxide content and free lime content than the BOF slag samples.

Reaction with moisture

The reaction observed firstly on the steel slag surface during weathering was the formation of thick crystal-like deposit, which is calcium-rich and easily removed. The calcium rich crystals were also observed in cracks formed in Marshall briquette samples during the process of weathering.

2.1.6 Expansion test of slag aggregate

Test method

Expansion tests were developed with the aim of determining the potential for expansion of steel slag aggregate using a similar procedure to that of the California Bearing Ratio (CBR) laboratory test [11,12]. The sample is compacted in a 152mm diameter CBR mould in three layers with 56 blows per layer. To allow free access of water to the top and bottom, a perforated base plate and top plate are used. The compacted sample and mould are submerged in hot water to accelerate the expansion of steel slag and the vertical displacement is measured daily by a dial gauge. Emery [11] selected a test temperature of 82°C because the expansion levels observed at 82°C were approximately three times those observed at 60°C.

The Pennsylvania Department of Transportation developed the expansion test as PTM130 [12]. They selected a test temperature of 71°C. The expansion test is conducted not only on submerged samples but also on unsubmerged samples for the following 7days, because some materials expand at a more rapid rate in one condition, some in the other. Based on this research, ASTM developed the standard test method "Potential Expansion of Aggregates from Hydration Reactions" (D4792-88) [18]. In the standard test, the temperature is designated at 70 ± 3°C and the height of specimen is measured for a period of 7 days in a submerged state.

Test results

Emery [11] reported results from accelerated expansion tests conducted at 82°C and 60°C using fresh (unweathered) steel slag and two types of aged steel slag. As can be seen in Figure 2.2, the unweathered steel slag expanded 9% by volume at 82°C and 3% at 60°C, while the weathered steel slag expanded 5% at 82°C and 1% at 60°C. The results showed that ageing or weathering could limit the expansion of steel slag. Figure 2.3 shows the results of long term expansion tests conducted for 475 days at 20°C using unweathered and weathered, and coarser and finer fraction samples. Results indicated that the unweathered coarser and finer samples expanded approximately 2.8% and 3.5% respectively, while weathered coarser and finer samples expanded 1.5% and 2% respectively. It was, therefore, observed that coarser samples tend to expand less.

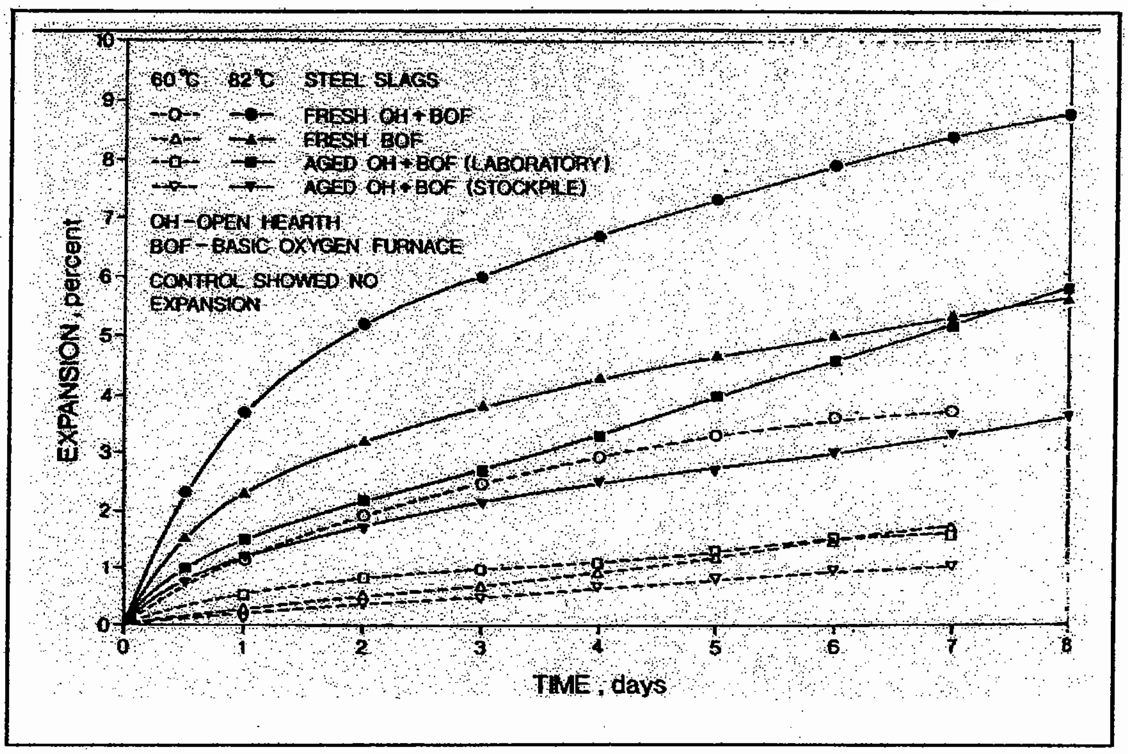

Figure 2-2 Expansion tests results (60°C & 82°C, 8days) [11]

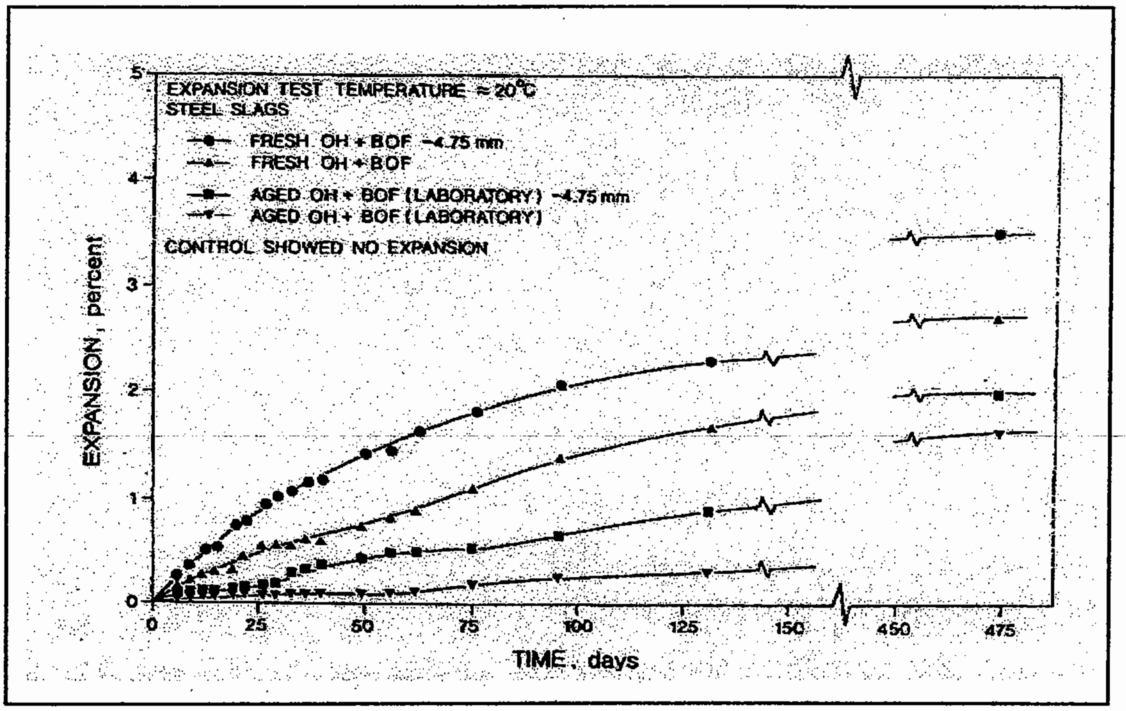

Figure 2-3 Expansion tests results (20°C, 475days) [11]

Kandhal and Hoffman [12] conducted an investigation into the expansive characteristics of steel slag aggregates using 10 different sources including 3 unweathered steel slags. The accelerated expansion test was conducted at a temperature of 71°C. Results showed that the unweathered steel slag aggregate expanded approximately 1% to 2.8% by volume, whereas, weathered steel slag did not expand by more than 0.5%.

Coomarasamy and Walzak [14] conducted the expansion test complying with ASTM D-4792 using two BOF slags, EAF slag and experimental BOF slag. Results showed that EAF and experimental BOF slag expanded less than the other slags, although the expansion volume of all samples exceeded 1% in a week, which is the criterion for highway construction material. The authors also found that expansion volume was not dependent on the quantity of the free lime observed in the samples.

2.1.7 Mixture evaluation

Marshall stability

It has been reported that mixtures containing steel slag aggregates exhibit high Marshall stability. Mixtures containing both coarse and fine steel slag aggregates have exhibited 10 to 18kN Marshall stability [9,11]. A mixture containing steel slag fine aggregate and limestone coarse aggregate also showed higher Marshall stability (9 to 10kN) than a control mixture (limestone aggregate mixture; 7kN) [12].

Conditioned Marshall stability

According to Emery [11], the specimen is conditioned by immersion in hot water (71°C) for 48 hours and then tested for Marshall stability. Retained stability is designated as the ratio of unconditioned and conditioned stability. 75% of retained stability is the minimum value for a desirable mixture. The retained Marshall stability obtained from mixtures containing steel slag coarse and fine aggregates have been reported as being between 73.5 and 82.5%, although the lower value was obtained from the mixture containing open hearth steel slag aggregate [11]. Retained Marshall stability was carried out by Kandhal and Hoffman [12] on four mixtures containing different steel slag fine aggregate and limestone coarse aggregate. The retained stability of the control mixture (limestone aggregate) was 88%, whilst between 75%

and 86% were obtained from steel slag mixtures. Although these values satisfied the minimum limit for an allowable mixture, the mixture containing steel slag aggregate could have a slightly lower retained stability value than the conventional mixture.

Lottman Freeze and Thaw Conditioning

Lottman freeze and thaw conditioning tests were conducted by Kandhal and Hoffman [12] on the mixtures containing different steel slag fine aggregates. The conditioning process of the test is as follows. The specimen is saturated in water for 30 minutes under vacuum conditions. Then the specimen is placed in a plastic bag containing distilled water and the bag is sealed and placed in a freezer at -18°C for 15 hours. Finally, the specimen is placed in a water bath at 60°C for 24 hours. The tensile strength ratio (TSR) is calculated using the tensile strengths of conditioned and unconditioned specimens. The results showed that the retained TSR of all steel slag mixtures was higher than that of the control mixture (limestone mixture).

Indirect Tensile Stiffness Modulus (ITSM)

Rockliff et al [13] reported the ITSM of the SMA mixture containing Steel slag coarse aggregate and BFS fine aggregate. The results showed that the SMA mixture containing slag aggregates exhibited higher stiffness (3500MPa) than the SMA mixture containing gritstone aggregates (2900MPa). Moisture conditioned stiffness modulus of these mixtures were also determined after 3 conditioning cycles and the results showed that the retained stiffness of SMA slag aggregates mixture was higher (110%) than that of SMA gritstone mixture (100%).

Skid resistance

Ryell, et al [9] reported improvements to the Toronto by-pass surfacing project, which was constructed in 1974. In this project, dense graded wearing course mixtures were constructed using slag aggregates (steel slag and blast furnace slag) and conventional aggregate (traprock (basaltic quarried material), limestone and natural sand). The skid resistance of these mixtures was evaluated using 4 different types of measurement method (ASTM-Brake force trailer, Mu-meter trailer, SCRIM and Photo-interpretation). The initial skid characteristics of all mixtures were satisfactory. The result of measuring the skid number after 4 years in-service indicated that both the steel slag aggregate mixture and the blast furnace slag aggregate mixture maintained good skid characteristics, while the mixtures which contained natural sand or limestone fine aggregate with slag coarse aggregate indicated lower values.

Noureldin and McDaniel [10] conducted field investigations on an existing road containing steel slag aggregate constructed between 1979 and 1981. Skid numbers were measured in accordance with ASTM-E274 after 6 to 9 years in-service. It was reported that the mixture containing steel slag aggregate maintained good skid characteristics. However, it was also reported that map cracking appeared on the surface and these cracks were only associated with the surface course. The authors considered that the age hardening, weathering, or accelerated hardening of asphalt binder caused by the presence of ferric and ferrous oxide in steel slag might have caused the map cracking.

Field samples

Core samples, which were taken from good and poor performing sites, respectively, were examined [14]. The interface and cross section of the 'good performance' cores appeared to show good adhesion and no debris in the internal voids. In contrast, the 'poor performance' cores showed that white debris had accumulated between the steel slag and the bitumen coating. However, even in samples from the 'good performance' sites, which had been in-service for many years, calcium rich deposits had formed on the surface of steel slag after weathering. This means that if moisture is allowed to enter the steel slag and asphalt binder interface, calcium rich crystals will be formed and this can be a reason for premature deterioration, such as map cracking. It is not clear whether weathered steel slag aggregate was used in the 'good performance' sites.

2.1.8 Other mixtures

The Ministry of Transport in Canada has investigated the expansive behaviour of reclaimed asphalt pavement (RAP) containing steel slag aggregate. Senior et al [16] reported that expansion test results indicated that steel slag derived from RAP still had expansive characteristics even though the steel slag had spent about 10 years in an asphalt pavement.

2.2 Crushed Glass

2.2.1 Background

Approximately 2 million tonnes of container glass, such as bottles and jars, are consumed annually in the U.K. (70% of the glass is coloured glass). Although the average recycling rate in Europe is over 50%, only 22% of container glass was recycled in the U.K. in 1998 [19]. Glass can be recycled without loss of properties. Recycled crushed glass is called 'cullet', and a proportion of cullet can be mixed with other materials such as sand, soda ash and limestone, in the process of production of new glass. In 1998, 657,000 tonnes of cullet were recycled (over half was green glass). Nowadays, the amount of collected green glass is larger than the capacity of recycling by glass container manufacturers. Furthermore, quality and colour imbalance of cullet would be the objection to increasing recycling rates. Therefore, developing alternative use of cullet is important to increase the recycling rates. In particular, the use of excess cullet as an aggregate in bituminous mixtures, known as 'Glasphalt', is recommended in the government report [19].

The idea of using crushed glass as an aggregate in bituminous mixtures was developed in the U.S.A. in 1960's [20]. Since then, many studies have been conducted in the U.S.A. For example, Glasphalt was placed in 19 test sections, in parking lots or streets, in the U.S.A. and Canada in 1969 to 1971 [21]. However, a survey conducted in 1994 indicated that only 6 state highway agencies use glass aggregate in bituminous mixtures [22]. The reasons why the use of glass aggregate does not increase are thought to be cost, availability and performance of bituminous mixtures containing glass aggregate [23]. The costs of obtaining the ground cullet comprise collection cost for cullet and grinding and pulverisation costs. These costs vary depending on geographical region and quantity of the cullet. It is estimated that the costs of producing ground cullet in the U.K. are likely to be in the range of £25 to £90 per tonne [19]. The availability of the glass aggregate is dependent on whether a recycling system has been established. Big cities, such as New York and Los Angels in the U.S.A., have their own systems where glass can be obtained free and processed. Therefore, glass aggregate can be available steadily and it would not be expensive. Apart from these problems, the mechanical properties of glass aggregate and the mixture containing glass aggregate have to be addressed by engineers. The properties of glass aggregate and the bituminous mixtures containing glass aggregate will be stated below.

2.2.2 Properties of crushed glass

Specific gravity

Specific gravity of two sources of cullet were obtained in the Glass Feedstock Evaluation Project [25]. The specific gravities of coarse cullet and fine cullet are in the range of 1.96 to 2.41 and 2.49 to 2.52 respectively. The differences in these ranges appeared to be caused by the difference in the debris levels of cullet samples. Debris was defined as any deleterious material that could affect the performance of engineered fill, generally nonceramic materials. Types of debris observed in cullet samples included paper, foil, and plastic labels, plastic and metal caps, cork, paper bags, wood debris, food residue, and grass. Malisch et al [20] carried out the first experiment using cullet in a bituminous mixture and according to their report, the specific gravity of cullet was 2.50.

Blewett and Woodward [24] reported the specific gravity of three samples of crushed glass; fine crushed glass, coarse crushed glass and raw crushed glass. Fine and coarse crushed glass comprise clear and green glass and they were ground to produce smooth particles. The specific gravity of fine and coarse crushed glass was 2.45 and 2.46, respectively, while the specific gravity of raw crushed glass, derived from brown glass and obtained without grinding, was 2.59. Based on this research, it is obvious that the specific gravity of crushed glass is lower than that of conventional aggregate, such as limestone of which the specific gravity is typically 2.7.

Strength

The L.A. abrasion test was conducted on coarse and fine cullet samples in the Glass Feedstock Evaluation Project [25]. The results of fine and coarse cullet were approximately 30% and 42% respectively. The result obtained from crushed rock, which was tested at the same time, was 14%.

Blewett and Woodward [24] conducted a modified Aggregate Crushing Value test. Instead of using sieved samples, continuous distribution sized samples were used. Using the results of before and after crushing size distribution charts, a coefficient of uniformity was obtained as the ratio of d_{60} and d_{10} (particle size at which percent passing is 60% and 10% respectively) and the modified ACV was calculated as the ratio of crushed and uncrushed coefficient of uniformity. According to their results, the behaviour during crushing was that the coarse fraction of glass aggregate was ground and the fine fraction of aggregate increased. As a result of this, the values of d_{60} of crushed and uncrushed were approximately the same, while the d_{10} of crushed material had doubled. The main change of particle size was due to the grinding of coarse particles rather than the splitting of particles and a similar result was obtained from gravel.

Particle shape and other properties

Angular, flat and elongated particles may be contained in glass aggregate [26]. In the Glass Feedstock Evaluation Project [25], particle shapes were evaluated in accordance with ASTM D2488. According to this, all particles were angular, 20 to 30% of 3/4-inch minus particles were of flat shape, although only 1% of 1/4-inch minus were flat. Low percentages of flat and elongated particles were observed.

Glass does not absorb measurable amounts of water, therefore, the water absorption ratio is very low [20,26].

2.2.3 Properties of bituminous mixtures containing crushed glass

Marshall stability

Regarding the properties of bituminous mixtures containing glass aggregate, the Marshall stability test and the stripping test were mainly employed to assess the properties of the mixture. Although it has been reported that the Marshall stability could be better than for conventional mixtures [26], it seems that the stability depends on the replacement ratio of glass to aggregate. West et al [27] evaluated the feasibility of using crushed glass as an aggregate in bituminous mixtures. A limestone aggregate mixture was selected as the control, and a coarse glass mixture, which contained 15%

of coarse glass aggregate, and a fine glass mixture which contained 15% of fine glass aggregate were tested for Marshall stability. The result showed that introducing glass aggregate leads to the reduction of Marshall stability. The stability of the coarse glass mixture and fine glass mixture were 15% and 12% lower than the control mixture, respectively.

Chesner [28] evaluated mixtures, in which aggregate was replaced with 15%, 32% and 43% of glass aggregate. The glass aggregate mixtures and the control mixture were the same with respect to the grading by mass. The result showed that the Marshall stability decreased along with the increase of the replacement ratio of glass to aggregate. The reduction in stability was significant (31% to 47% lower than the control mixture). The author noted that the decrease of angular shaped aggregates contributing to the stability and the increase of rounded sand (necessary to achieve the required grading) had a negative impact on the stability, as did the increased glass aggregate quantity.

Stripping

Since glass aggregate does not absorb any bitumen, stripping could be a problem. Malisch et al [20] reported that significant stripping was observed in glass aggregate mixtures without anti-stripping additive, such as hydrated lime. A high replacement ratio of glass aggregate and coarser glass particles caused a stripping problem, therefore, in the case of New York City, a smaller replacement ratio (5 to 10% by weight of the mixture) and lower gradation (3/8-inch minus) is applied for Glasphalt mixtures [23].

West et al [27] conducted tensile strength tests on the fine and coarse glass aggregate mixtures mentioned above. According to their report, the mixture containing fine glass aggregate was more susceptible to moisture than the mixture containing coarse glass aggregate. However, it was noted that 15% by mass of the fine glass aggregate or coarse aggregate simply replaced the limestone, and the fine glass mixture had greater surface area of glass than the coarse glass mixture. This difference in surface area appeared to cause the moisture susceptibility. Moreover, as the result of a boiling test, they also reported that the potential for stripping of coarse glass aggregate was actually greater than that of fine aggregate. Therefore, it can be deduced that the amount of surface area in contact with bitumen is a key factor determining the effect of stripping.

Maupin [29,30] reported that the Tensile Strength Ratio (TSR) of a mixture containing 15% of glass fine aggregate was lower than the specification value (0.9), with an increase in the glass aggregate ratio leading to a decrease in the TSR, and some stripping observed from glass particles in the boiling test. He also reported the result of a field investigation. According to the investigation, some loss of glass particles was observed, although the Glasphalt still seemed to perform adequately. However, ravelling of glass particles caused some problems, such as cutting vehicle tyres. Therefore, the author recommended that surface mixture might not be a suitable for using glass aggregate.

If crushed glass is used in a road base mixture, the problem of stripping is likely to be less serious. In the U.K., road base / base course material containing crushed glass as aggregate has been evaluated by the Highway Agency and bituminous mixture was placed in Warwickshire in 2000 as a field test, containing approximately 25% of crushed glass [31].

Stiffness and Permanent Deformation

Mechanical properties of 20mm DBM mixtures containing glass aggregates were reported by Nicholls et al [32]. 30% of total weight of aggregate were replaced with glass aggregate and 50pen of binder was used in the mixture. The stiffness modulus of mixture containing glass aggregate and control mixture (limestone aggregate) were 2600MPa and 2800MPa, respectively. Water sensitivity ITSM tests were also performed and the results showed that both mixtures exhibited similar retained stiffness ratio (123% and 126%). Permanent deformation characteristics of these mixtures were evaluated using Repeated Load Axial Test (RLAT) and Wheel Tracking test. The mixtures containing glass showed slightly lower axial strains than the control mixture in the RLAT. Wheel Tracking tests did not show a significant difference between the performance of these mixtures.

2.3 Conclusions

2.3.1 Summary of the literature review

Steel Slag

1) The physical property of steel slag aggregate seems to be appropriate for aggregate use in comparison with conventional aggregate. The specific gravity is much higher than that of conventional aggregate.
2) Steel slag has an expansive nature caused by the presence of CaO and MgO reacting with moisture. Weathering, therefore, is essential for steel slag aggregate.
3) It is thought that the premature deterioration (map cracking) observed in 100% steel slag mixtures was caused by expansion of the aggregate. However, it is possible that a chemical reaction between the binder and the steel slag might facilitate the ageing of binder and cause the cracking.
4) Steel slag will enhance the properties of mixtures, such as Marshall stability and skid resistance.

Crushed Glass

1) The physical properties, such as strength, of glass aggregate seems to be adequate for aggregate use. The specific gravity of glass aggregate is lower than conventional aggregate.
2) A near 0% water absorption ratio of glass aggregate leads to a stripping problem.
3) In general, introducing glass aggregate leads to a reduction of Marshall stability.

2.3.2 Research addressed in this project

Volumetric mixture design

As the literature review shows, bituminous mixtures containing steel slag or glass aggregates have been tested and evaluated. However, it seems that most research has been carried out on mixtures having different volumetric characteristics from conventional mixtures. It was found from the literature review that the specific gravities of secondary aggregates evaluated in this project are different from those of conventional aggregates. Besides, secondary aggregates tend to be incorporated with conventional aggregate in a mixture. For example, a 100% steel slag aggregate mixture is not commonly used because of its high specific gravity and, as the literature review showed, deterioration was found in 100% steel slag aggregate mixtures. Crushed glass aggregate is also mixed with another aggregate. In the U.S.A., usually less than 15% of total mass of aggregate is replaced with glass aggregate in mixtures. A difference in specific gravity of aggregate will lead to difference in volumetric characteristics of mixtures (this is explained in more detail in Chapter 3). Therefore, the results might be influenced by not only the characteristics of the secondary aggregate itself, but also the difference in volumetric characteristics, such as grading and binder content. To eliminate the difference in volumetric characteristics, volumetric grading of aggregate and effective binder content, which is influenced by the specific gravity and binder absorption of aggregate, needs to be considered. In this project, tests will be carried out on control mixtures and secondary aggregate mixtures, which have nominally similar volumetric characteristics and the mechanical properties evaluated.

Evaluation of test methods

It was found that steel slag aggregate mixture has potential for cracking if unweathered steel slag aggregate is incorporated in a mixture. Also, glass aggregate mixture has potential for stripping. It is necessary to know how these characteristics are reflected in the results obtained from tests carried out in this project. In other words, test methods need to be able to evaluate the potential for the poor performance of mixtures. Therefore, in this project, apart from evaluating the mechanical properties of practical mixtures, experimental mixtures, which can be expected to perform poorly, such as an unweathered steel slag mixture and a 100% glass aggregate mixture, will be tested to make sure whether the conventional test methods are valid for assessing these mixtures or not.

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Chapter 3 Mixture Design & Sample Preparation

3.1 Mixture design

3.1.1 Design factors affecting test results

Volumetric grading

The mixtures evaluated in this project are designed in accordance with prEN 13108-5 [1] for the SMA mixtures and BS 4987 [2] for the DBM mixtures. However, even if identical aggregate gradings are used, mixtures containing different types of aggregate with different specific gravities will have different volumetric proportions which will influence the mechanical properties of mixture. For example, an SMA mixture that incorporates steel slag coarse aggregate (with a specific gravity of approximately 3.0) and BFS fine aggregate (with a specific gravity of approximately 2.5) will have a volumetric grading that is 3-5% different compared to the volumetric grading of a control mixture (both coarse and fine aggregates having the same specific gravity) when the gravimetric gradings of those mixtures are the same (Figure 3-1). If the grading of aggregate is designed only by mass, the slag aggregate mixture will have a volumetrically finer grading than the control mixture. Therefore, even if the grading of the aggregate is the same as the control mixture, the arrangement of the aggregate particles in the mixture would be different and this will significantly influence the mechanical properties. To clarify the effect of an aggregate in a bituminous mixture, it is important to design mixtures to be volumetrically the same. Therefore, the mixtures used here were designed using volumetric grading.

The procedure of volumetric grading design follows. After obtaining the grading of the control mixture, the grading is converted to percentage passing by volume, then the other mixtures, which contain secondary aggregate, are designed to obtain the same volumetric grading as the control mixture. The volumetric grading is converted to the gramvietric grading to check where the grading is located in the specification.

Binder content

To make the mixtures volumetrically similar, it is also necessary to consider the amount of binder. This is influenced by not only the specific gravity (particle density) of combined aggregate but also the degree of binder absorbed by the aggregate. The binder that is not absorbed is called the effective binder content and is calculated using the result of a Rice Density test [3]. Figure 3-2 shows schematically the state of aggregates, binder and air void in a bituminous mixture. The effective binder content can be determined by obtaining the effective specific gravity of aggregate and binder absorption ratio. The effective specific gravity of aggregate is influenced by the degree of binder absorption. For example, if the binder is not absorbed by the aggregate, the effective specific gravity of aggregate is equal to the bulk specific gravity (oven dried particle density). If the pores of an aggregate are filled with binder fully, the effective specific gravity of the aggregate is equal to the apparent specific gravity. Therefore, it is obvious that the effective specific gravity of an aggregate should be somewhere between the bulk specific gravity and the apparent specific gravity of the aggregate.

The volume relationship of a bituminous mixture is expressed as,

$$\frac{\%\ of\ Aggregate\ by\ mass}{Aggregate\ S.G.} + \frac{\%\ of\ Binder\ Content\ by\ mass}{Binder\ S.G.} = \frac{\%\ of\ Total\ mixture\ by\ mass\ (=100\%)}{Mixture\ S.G.\ (=Maximum\ Density)} \tag{3.1}$$

The binder content of the mixture and the binder S.G. are known and do not change before and after mixing. Percentage of aggregate by mass also does not change if the absorbed binders are not regarded as the part of aggregates. On the other hand, the free pore volume of the aggregate would change with the degree of absorbing binders. The result obtained from a Rice Density test designates the maximum density of the mixture using the mass and volume relationship of the mixture. The volume of the mixture can be interpreted as the total of binder volume and aggregate volume from which the volume of porosity absorbed by binder is subtracted. Therefore, using the result of Rice Density, the effective S.G. (G_{se}) of the aggregate is designated as,

$$G_{se} = \frac{\%\ of\ Total\ Mixture\ by\ mass - \%\ of\ Binder\ Content\ by\ mass}{\frac{\%\ of\ Total\ Mixture\ by\ mass}{Maximum\ Density} - \frac{Binder\ Content\ \%}{Binder\ S.G.}} \tag{3.2}$$

Binder absorption ratio is expressed as the percentage of absorbed binder against mass of aggregate. Using bulk S.G. and effective S.G. of aggregate, the volume of binder absorbed in the aggregate is designated as,

$$Absorbed\ \ Binder\ \ volume = \frac{mass\ \ of\ \ aggregate}{Bulk\ \ S.G.} - \frac{mass\ \ of\ \ aggregate}{Effective\ \ S.G.} \tag{3.3}$$

Therefore, the binder absorption ratio (P_{ba}) is expressed as,

$$P_{ba} = \frac{Absorbed\ \ Binder\ \ volume \times Binder\ \ S.G.}{Mass\ \ of\ \ Aggregate} \times 100$$

$$= \left(\frac{Mass\ \ of\ \ Aggregate}{Bulk\ \ S.G.} - \frac{Mass\ \ of\ \ Aggregate}{Effective\ \ S.G.} \right) \times \frac{Binder\ \ S.G.}{Mass\ \ of\ \ Aggregate} \times 100$$

$$= \left(\frac{Effective\ \ S.G. - Bulk\ \ S.G.}{Bulk\ \ S.G. \times Effective\ \ S.G.} \right) \times Binder\ \ S.G. \times 100 \tag{3.4}$$

The effective binder content (P_{be}) is designated as the subtraction of a percentage of absorbed binder from a percentage of total binder content.

$$P_{be} = Total\ \ Binder\ \ Content - \frac{P_{ba}}{100} \times \%\ of\ \ Aggregate\ \ by\ \ mass \tag{3.5}$$

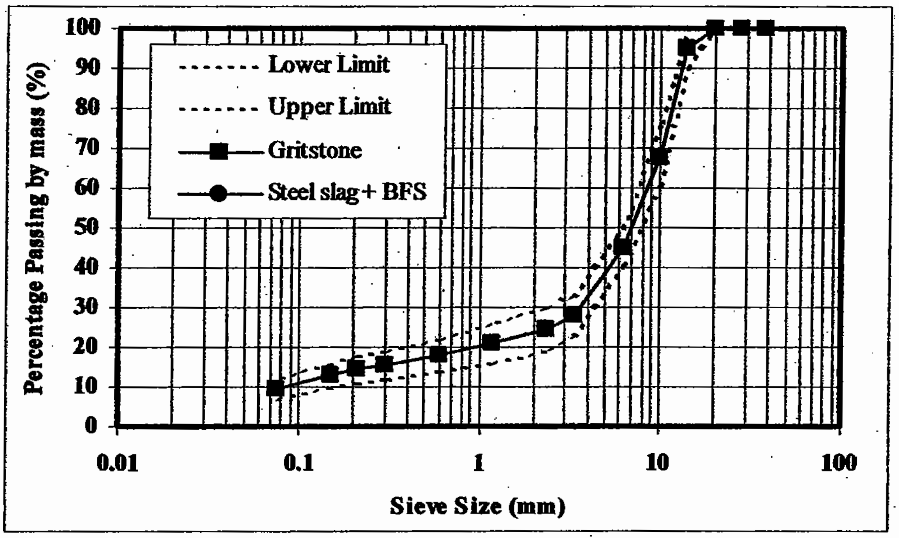
Pbe expresses the mass relationship of the mixture. Volumetric effective binder content (P_{bev}) is designated as,

$$P_{bev} = \frac{Effective\ \ binder\ \ by\ \ volume}{Total\ \ volume} \times 100$$

$$= \frac{\dfrac{P_{be}}{Binder\ \ S.G.}}{\dfrac{100\ \%}{Maximum\ \ Density}} \times 100$$

$$= \frac{P_{be}}{Binder\ \ S.G.} \times Maximum\ \ Density \tag{3.6}$$

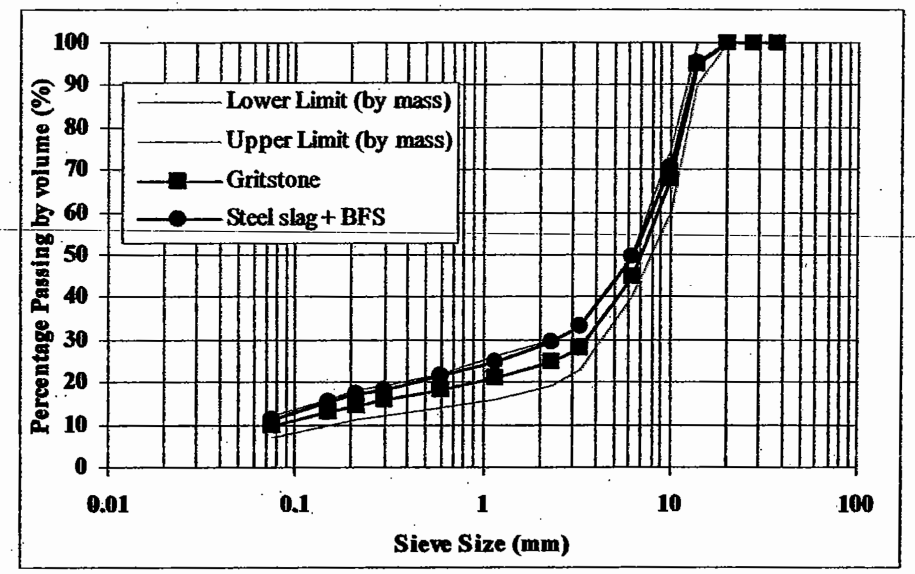
Finally, the binder content of the mixture containing secondary aggregates is determined in order to obtain the same volumetric effective binder content as the control mixture.



Gravimetrical Grading Curves

Convert to Volumetric Grading

⇓



Volumetrical Grading Curves

Figure 3-1 Volumetric Difference in Grading Curves

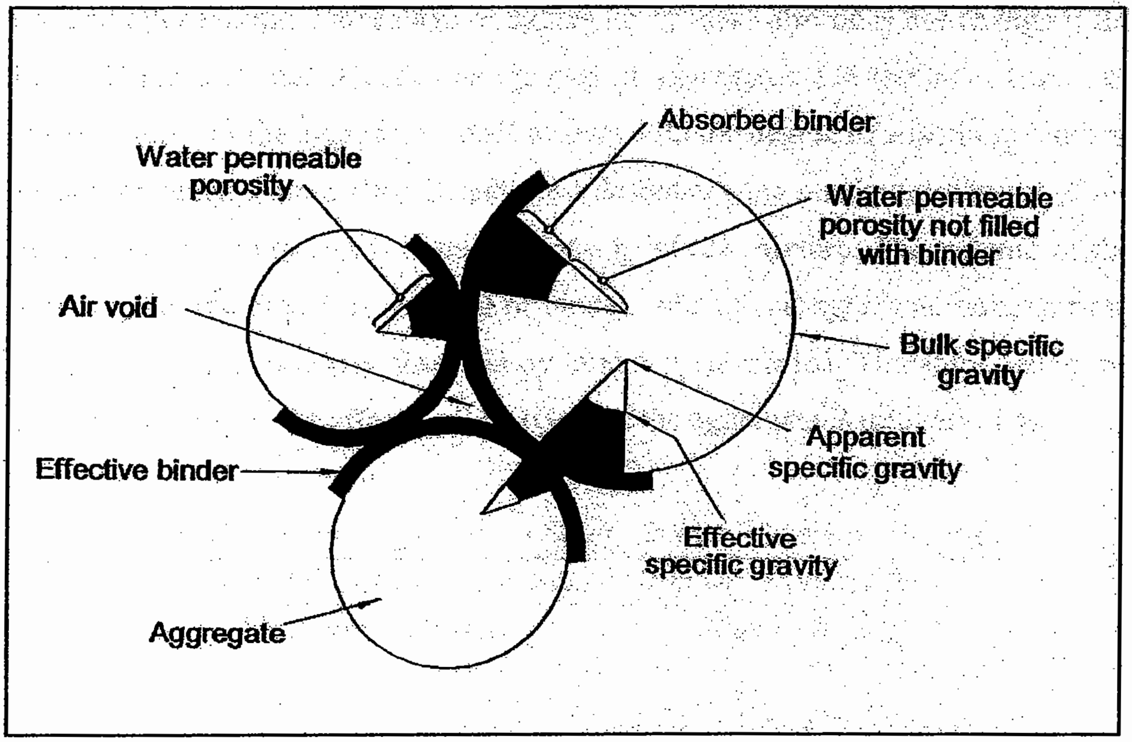


Figure 3-2 Schematic State of Aggregates and Binder in a Mixture [4]

3.1.2 Mixture design results

14mm SMA

Table 3-1 shows the materials used for making 14mm SMA mixtures. In this investigation, there were three types of bituminous mixtures with different aggregate compositions. Gritstone coarse and fine aggregates were used for the control mixtures. Two different types of slag mixtures were made distinguished by their filler types; BFS filler and limestone filler. Steel slag coarse aggregate and BFS fine aggregate were used for both slag mixtures.

Table 3-1 Mixture Types and Materials

	Control	Slag (BFS filler)	Slag (limestone filler)
Bitumen	50pen	50pen	50pen
Coarse aggregate	Gritstone (Bayston Hill)	Steel slag (Llanwern)	Steel slag (Llanwern)
Fine aggregate	Gritstone (Bayston Hill)	BFS (Port Talbot)	BFS (Port Talbot)
Filler	Limestone	BFS (Llanwern)	Limestone
Additive	Cellulose fibre	Cellulose fibre	Cellulose fibre

Penetration test, softening point test results and the specific gravity of bitumen are listed in Table 3-2.

Table 3-2 Test results of bitumen

	Penetration Test	Softening Point	Specific Gravity
50pen	50	50.2 °C	1.03

Table 3-3 shows the particle density and water absorption of aggregates employed in the SMA mixture. As can be seen, the particle density of steel slag aggregate is much higher than that of gritstone and BFS aggregates. Also, the water absorption ratio of BFS aggregate is much higher than other aggregates.

Table 3-3 Particle Density and Water Absorption of aggregates

	Particle Relative Density			Water Absorption (%)
	Oven Dried	Saturated & Surface Dried	Apparent	
Gritstone (Coarse and fine)	2.76	2.78	2.81	0.7
Steel slag Coarse Aggregate	3.27	3.33	3.46	1.7
BFS Fine aggregate	2.47	2.65	2.98	6.9

Grading

The volumetric and gravimetric grading curves for the SMA mixture are shown in Figure 3-3 and Figure 3-4, respectively. As can be seen, the volumetric grading shows that the control and slag aggregate mixtures have approximately the same size distribution. The gravimetric grading, on the other hand, indicates that the grading of the slag mixture is located near the lower limit of the specification, although the grading of the control mixture is nearly in the middle.

Binder content

The binder content for the control mixture was originally selected as 6.2% with a target air void of 4%. However, specimens obtained from the mixtures had very low air void ratio (approximately 1.0%). Therefore the binder content of control mixture was reduced by 6.0% to obtain specimens having 2 - 4% air void ratio, and also the slag mixtures were made using 6.0% of binder content. Figure 3-5 shows the volumetric binder content of these mixtures. As can be seen, slag mixtures have higher volumetric binder content than gritstone mixture due to the higher combined aggregate specific gravity. Nevertheless the results of Rice density tests indicated that the effective volumetric binder content of slag mixture incorporating limestone filler is similar to that of gritstone mixture, as shown in Figure 3-6. The calculated effective binder content of the gritstone mixture was the same as the design binder content since gritstone aggregate has a very small water absorption ratio (0.7%) which resulted in not absorbing bitumen. On the other hand, the steel slag and, especially BFS aggregates have higher water absorption ratios and this resulted in 0.63% of binder absorption ratio and this made the slag mixture have a similar volumetric effective binder content to that of the gritstone mixture. Based on these results, the gravimetric binder content for SMA mixtures was selected at 6.0%, although a 6.2% binder content of the gritstone mixture and a 7.0% binder content of the slag mixture containing BFS filler were also evaluated using some test methods as described in Chapter 4.

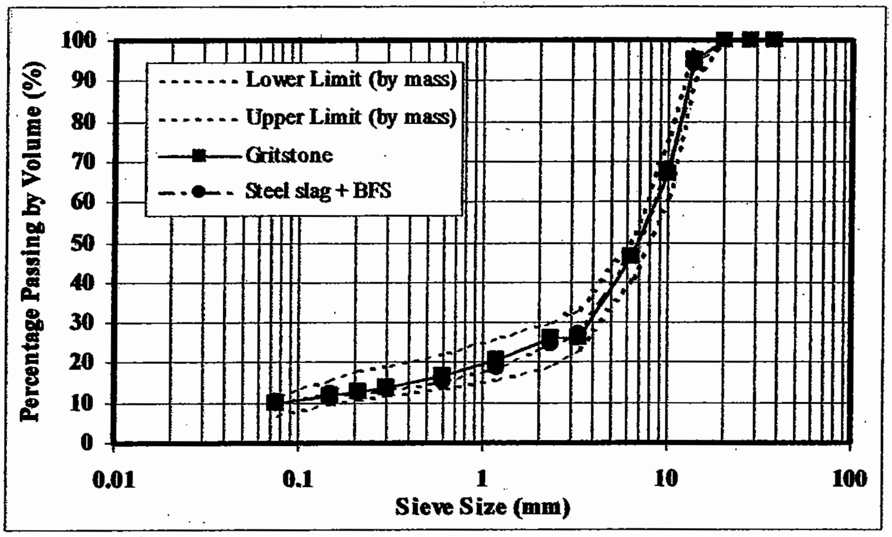


Figure 3-3 Volumetric Grading of SMA mixtures

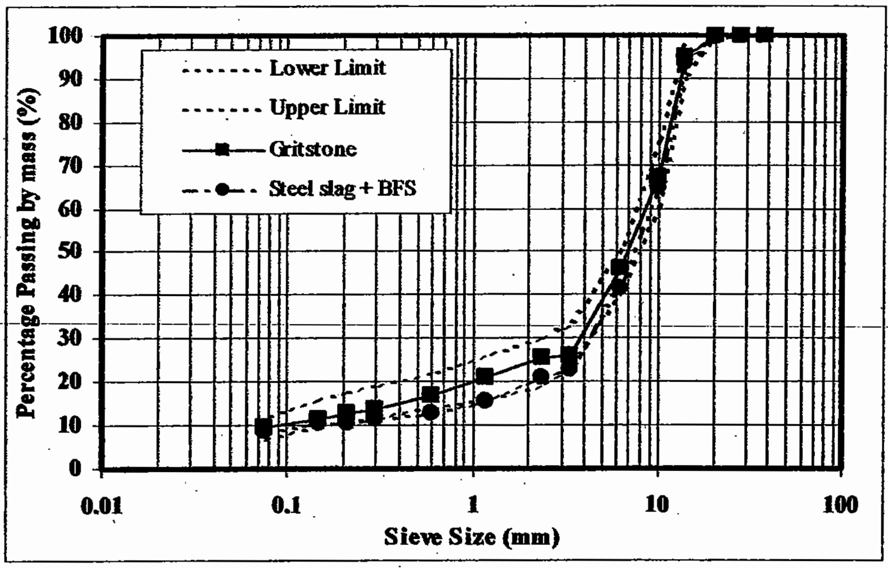


Figure 3-4 Gravimetric Grading of SMA mixtures

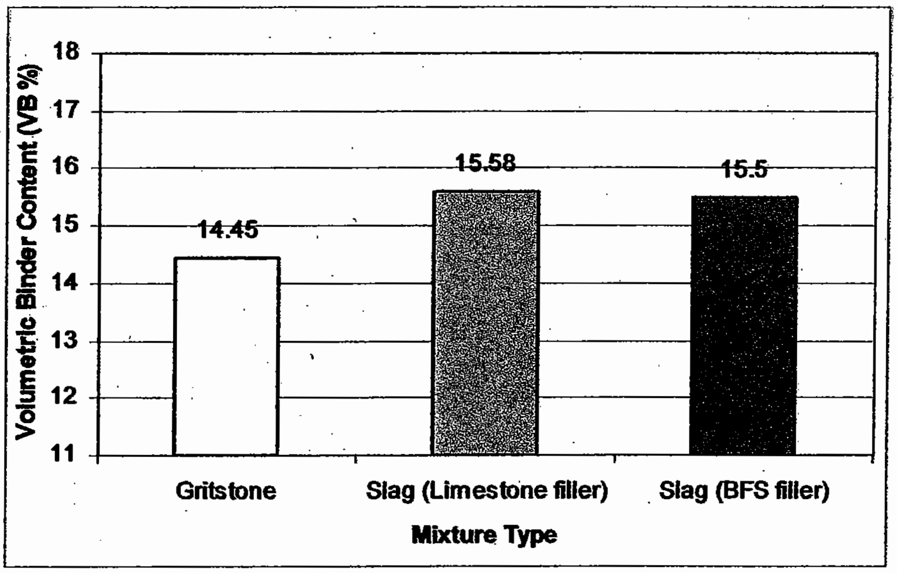


Figure 3-5 Volumetric Binder Content of SMA mixtures

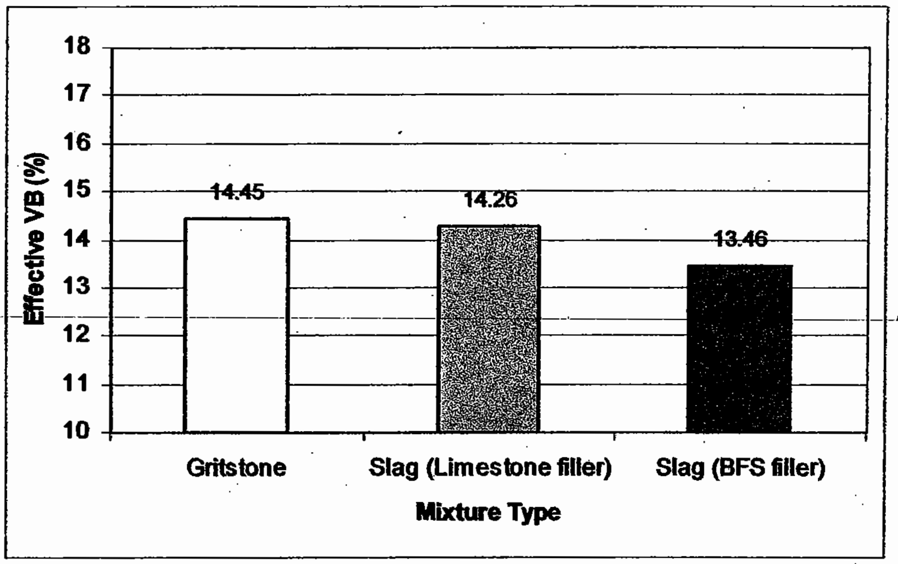


Figure 3-6 Effective Volumetric Binder Content of SMA mixtures

28mm DBM

Table 3-4 shows the materials used for making 28mm DBM mixtures. There were four types of bituminous mixtures distinguished by different aggregate compositions. Limestone coarse and fine aggregates were used for control mixture. There were two types of mixtures which incorporating glass fine aggregate; one is limestone coarse aggregate + glass fine aggregate, the other is steel slag coarse aggregate + glass fine aggregate. The slag mixture consists of steel slag coarse aggregate and BFS fine aggregate.

Table 3-5 shows the particle density and water absorption of aggregates employed in the DBM mixture. As can be seen, the particle density of glass aggregate is slightly lower than that of limestone aggregate.

Table 3-4 Mixture Types and Materials for DBM mixtures

	Limestone (control)	Limestone + glass	Slag	Steel slag + glass
Bitumen	50pen	50pen	50pen	50pen
Coarse aggregate	Limestone (Ballidon)	Limestone (Ballidon)	Steel slag (Llanwern)	Steel slag (Llanwern)
Fine aggregate	Limestone (Ballidon)	Glass	BFS (Port Talbot)	Glass
Filler	Limestone	Limestone	Limestone	Limestone

Table 3-5 Particle Density and Water Absorption of aggregates

	Particle Relative Density			Water Absorption (%)
	Oven Dried	Saturated & Surface Dried	Apparent	
Limestone (Coarse and fine)	2.61	2.64	2.68	1.0
Glass Fine aggregate	---	---	2.51	0.0
Steel slag Coarse aggregate	3.27	3.33	3.46	1.7
BFS Fine aggregate	2.47	2.65	2.98	6.9

Grading

The volumetric and gravimetric grading curves for the DBM mixtures are shown in Figure 3-7 and Figure 3-8, respectively. As can be seen, the volumetric gradings show that all mixtures have approximately the same size distribution. The gravimetric gradings indicates that the grading of the limestone mixture and limestone + glass mixtures are similar because there is not much difference between limestone and glass with respect to specific gravity. The gradings of the mixtures containing steel slag aggregate are located closer to the lower limit of the specification than the control mixture.

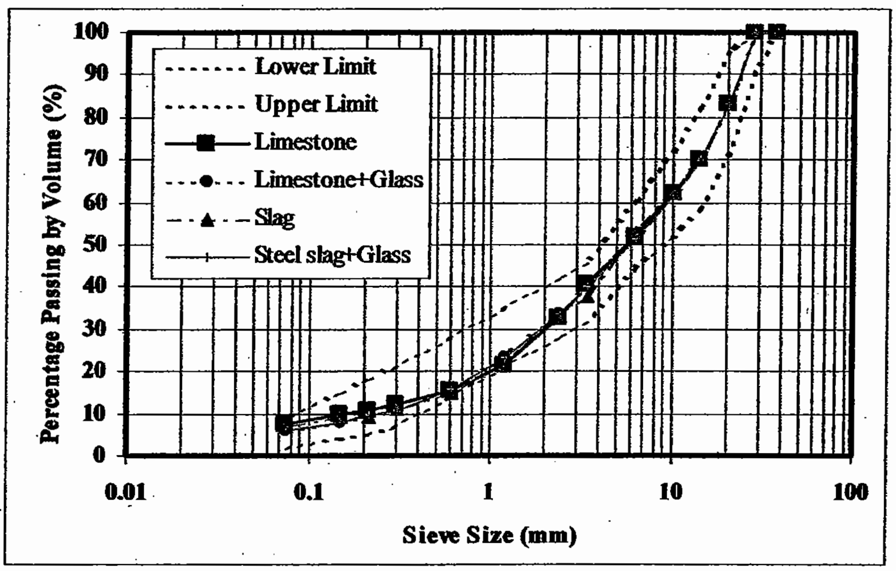


Figure 3-7 Volumetric Gradings of DBM mixtures

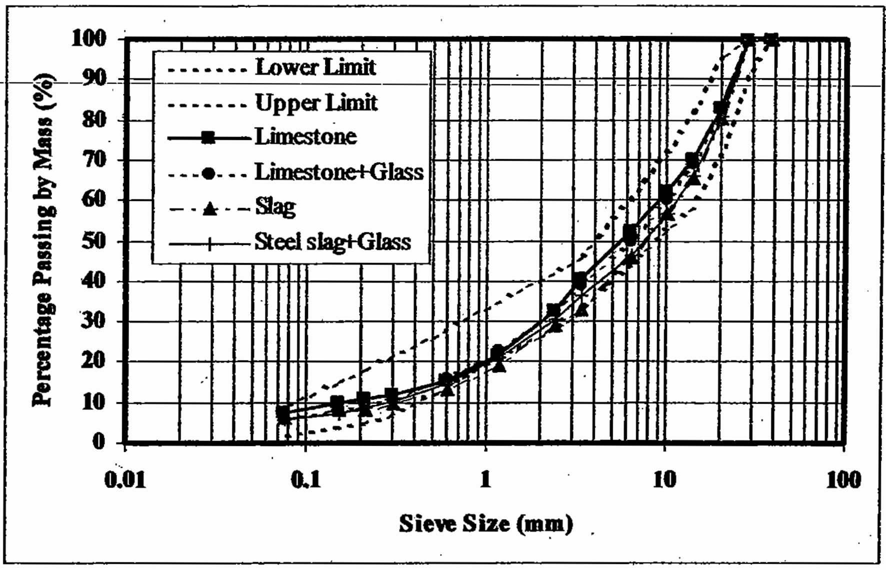


Figure 3-8 Gravimetric Gradings of DBM mixtures

Composition

Figure 3-9 shows the size distribution of glass and BFS fine aggregates. Table 3-6 shows the detailed mixture composition for all DBM mixtures. All mixtures have similar volumetric characteristics in terms of aggregate composition. The ratio of glass aggregate incorporating in the limestone + glass mixture is approximately 51% by volume.

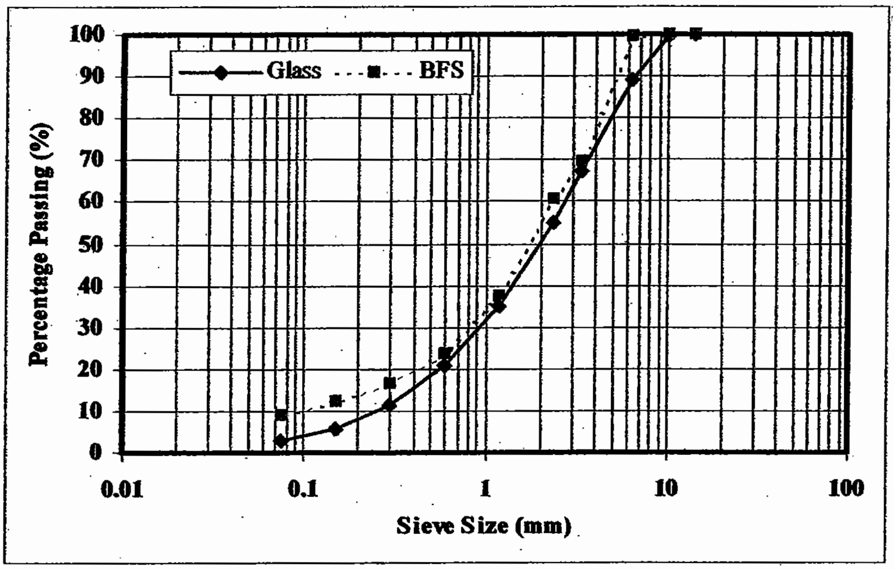


Figure 3-9 Size Distribution Curves for Glass and BFS fine aggregates

Table 3-6 Aggregate Compositions of DBM mixtures

	Limestone		Limestone+Glass		Slag		Steel slag+Glass	
Size	Gravi.	Vol.	Gravi.	Vol.	Gravi.	Vol.	Gravi.	Vol.
Coarse ~3.35mm	59.5%	59.5%	61.0% 44.7%:Lime. 16.3%:Glass	59.9% 43%:Lime. 16.9%:Glass	67.1% 53.9%:S.S. 13.2%:BFS	62.3% 47.0%:S.S. 15.3%:BFS	63.8% 48.6%:S.S. 15.1%:Glass	59.9% 43.0%:S.S. 16.9%:Glass
Fine ~0.075mm	32.9%	32.9%	32.7% (all glass)	34.0% (all glass)	26.6% (all BFS)	30.5% (all BFS)	30.4% (all glass)	34.0% (all glass)
Filler 0.075mm~	7.6%	7.6%	6.3% 4.9%:Lime. 1.4%:Glass	6.1% 4.7%:Lime. 1.4%:Glass	6.6% 2.8%:Lime. 3.8%:BFS	7.2% 2.8%:Lime. 4.4%:BFS	5.8% 4.6%:Lime. 1.2%:Glass	6.1% 4.7%:Lime. 1.4%:Glass

Binder Content

According to BS 4987-1, the binder content for a 28mm DBM mixture incorporating crushed rock or steel slag aggregate would be designated at 4.0% but the binder content for the mixture containing BFS aggregate will need to be designated depending on the bulk density of the BFS aggregate. Therefore, the binder content was selected as 4.0% apart from the slag mixture. Because only BFS fine aggregate was incorporated in the slag mixture used in this research, the procedure for determining the binder content for the slag mixture did not comply with BS 4987 but was achieved by evaluating the volumetric binder content of the mixture.

Figure 3-10 shows the volumetric binder content of the DBM mixtures having 4.0% binder content by mass. Because the slag mixture contains steel slag aggregate with a high specific gravity, the amount of binder by volume in the slag mixture is higher than in that of control mixture. Taking account of the volumetric binder content and that the slag mixture only contains BFS fine aggregate, the binder content of the slag mixture was selected as 4.0% by mass, which is as same as the other mixtures. Figure 3-11 shows the volumetric effective binder content of DBM mixtures, which were derived from the Rice Density test results. Only the mixture incorporating BFS aggregate that has a high water absorption ratio exhibited a significant reduction of effective binder content.

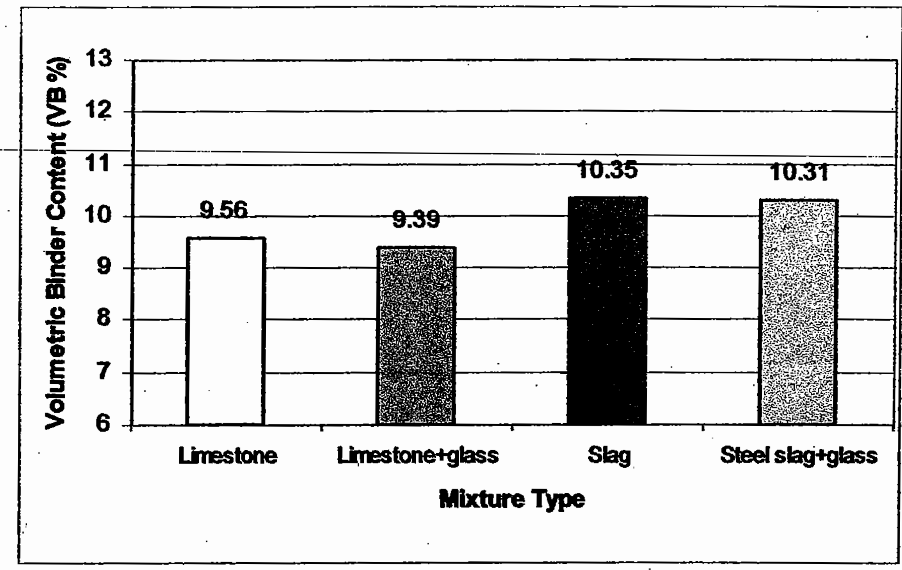


Figure 3-10 Volumetric Binder Content of DBM mixtures

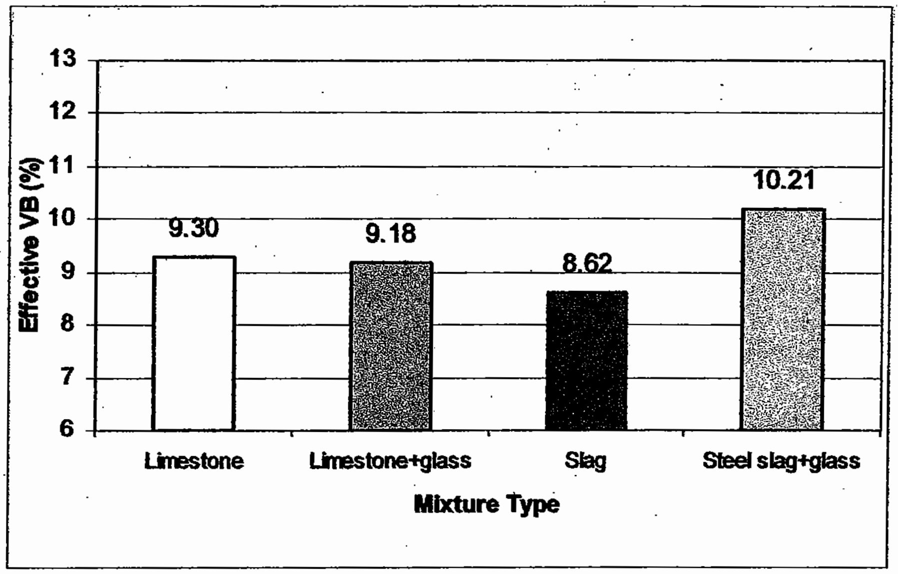


Figure 3-11 Volumetric Effective Binder Content of DBM mixtures

In addition to the mixtures having 4.0% gravimetric binder content, slag mixture was evaluated using 5.0% gravimetric binder content because the water sensitivity test results described in Chapter 4 indicated that the slag mixture (M_B=4.0%) is susceptible to moisture induced damage.

3.2 Sample preparation

3.2.1 Mixing

Materials

Single sized coarse aggregates were used throughout this research work. Aggregates were dried at a temperature of 105℃ and preheated before mixing at a temperature of 150℃ because 50pen binder was used in all mixtures.

50pen of binder was used for both SMA and DBM mixtures. Bitumen was preheated before mixing at a temperature of 150℃ for 2 hours.

Procedure

A mechanical mixer was used for mixing the materials and the mixing temperature was selected as 150℃. At first, aggregates were placed in the mixer and mixed for 2 minutes. Then, the bitumen was poured into the hole made in the centre of aggregates.

Mixing was continued until the aggregates were covered by bitumen properly (approximately 2 minutes). After finishing mixing, mixed materials were placed into a square mould to fabricate a slab sample.

3.2.2 Sample fabrication

Firstly, a slab sample is made using mixed materials. A square mould, having 305mm side length and 140mm depth, was used for making the slab. A slab compactor was used for compacting the sample. After the compaction, the slab sample was left in the room overnight.

Core samples were then cut from the slab sample. 100mm diameter and 65mm height of core specimens were used in this research. 4 core specimens were cut from 1 slab sample.

Number of specimens

Table 3-7 shows the number of specimens used for NAT and Splitting tests. After conducting ITSM tests, specimens were used for the other tests.

Table 3-7 Number of core specimens used for NAT and Splitting test / mixture

	Unconditioned	Aged	Moisture conditioned
ITSM	(11)	(8)	(11)
ITFT	5	5	5
CRLAT	3	0	3
Splitting	3	3	3
Total (performed)		60	
Total (fabricated)		30	

Therefore, a total of 60 specimens * 8 mixtures = 480 specimen tests were performed and a total of 30*8=240 specimens were fabricated.

3.3 References

1. British Standards Institution, "Bituminous mixtures. Material specification. Part 5. Stone mastic asphalt, (BS EN 13108-5)", March 2000.

2. British Standards Institution, "Coated macadam for roads and other paved areas, Part 1. Specification for constituent materials and for mixtures (BS 4987 Part 1)", 2001.

3. Asphalt Institute, "Superpave Level 1 Mix Design", Superpave series No.2 (SP-2), pp37-45, 1995

4. Richardson, J. T. G., Elliot, R. C., Mercer, J. and Williams, J., "Laboratory Performance-Based Testing of Asphalt Mixtures in the United Kingdom", (unpublished paper), 2000.

Chapter 4 Mechanical Properties of Bituminous Mixtures Containing Secondary Aggregates

4.1 Indirect Tensile Stiffness Modulus

4.1.1 Factors affecting Stiffness Modulus

Stiffness modulus, determined by the relationship between stress and strain of a bituminous mixture, is an important factor for load spreading capability of a pavement. Stiffness of a pavement is dependent on loading time and temperature because of the visco-elastic behaviour of the bituminous binder, therefore, different types of stiffness which are called elastic stiffness and viscous stiffness, are obtained in different loading time and/or temperature conditions. Elastic stiffness is determined by short loading time / low temperature conditions. This would express the stiffness modulus of the actual pavement under moving traffic loading. The elastic stiffness is mainly influenced by the stiffness of binder and volumetric characteristics of the bituminous mixture, such as binder content, air void content and VMA (Voids in Mineral Aggregates). Viscous stiffness is determined by long loading time / high temperature conditions. This could express the stiffness modulus of the pavement under low speed traffic load, e.g. the road where traffic congestion would be likely to occur. Factors influencing the viscous stiffness are not only the stiffness of binder and volumetric characters of the mixture, but also aggregate type, shape and grading and so on.

4.1.2 Test Procedure

ITSM test

There are several test methods that can be used for determining the stiffness modulus of bituminous mixtures. Those are repeated load beam (simple beam, trapezoidal beam), uniaxial repeated load and indirect tensile tests. In the U.K., the indirect tensile test is commonly applied using the Nottingham Asphalt Tester (NAT) and the NAT was used through out this project. During the test a load pulse is applied along the vertical diameter of a cylindrical specimen and the resultant peak transient deformation measured along the horizontal diameter. The stiffness modulus is then a function of load, deformation, specimen dimensions and an assumed Poisson's ratio of 0.35.

$$Sm = L / (D \times t) \times (\nu + 0.27) \quad (4.1)$$

Sm : Stifness Modulus

L = Peak value of the applied vertical load (N)

D = Peak horizontal diamentral deformation (mm)

t = Thickness of the test specimen (mm)

ν = Poisson's ratio (0.35 is assumed for bituminous mixture)

Temperature, loading time and Poisson's ratio are designated in accordance with BS draft DD213 [1]. Namely, a test temperature of 20°C, a rise time of 124ms and a Poisson's ratio of 0.35 were selected. 100mm diameter and 65mm thickness specimens were used for the test. Specimens were cored from slab samples fabricated in the laboratory.

Conditioning (Ageing & Moisture conditioning)

Ageing

Specimens were conditioned in accordance with the LINK BITUTEST Project procedure [2]. Namely, after determining the unaged stiffness modulus, specimens were placed in an oven at a temperature of 85°C for 120h. After that, the specimens were cooled to room temperature, then an aged stiffness modulus is determined by the ITSM test.

Moisture conditioning (Water sensitivity ITSM test)

Water sensitivity tests were also carried out in accordance with the LINK BITUTEST Project procedure [2]. Firstly, specimens were immersed in water and vacuum was applied for 30minutes. The percentage saturation is determined using the weights of dry and wet specimens. Then the specimens were conditioned routinely as below,

a) specimens were placed in a hot water bath (60°C) for 6h,

b) specimens were moved to a cold water bath (5°C) and placed for 16h,

c) specimens were moved to a 20°C water bath (test temperature) and placed for 2h.

Then, the stiffness modulus was determined by the ITSM test immediately after taking specimen out of the water bath. After testing, the specimens were subjected to the conditioning cycle (a to c) and stiffness modulus was determined after every conditioning cycle. In this project specimens were conditioned for 4 cycles, although the standard test method finishes after 3 cycle conditionings.

4.1.3 Test Results

14mm SMA

Unconditioned

Unconditioned ITSM tests were carried out using the gritstone mixture and two types of slag mixtures, which are distinguished by limestone filler and BFS filler. Table 4-1 shows the results obtained from those mixtures. As can be seen, the stiffness modulus of the slag mixtures are higher than that of the gritstone mixture at the same gravimetric binder content. To consider these results, it is important to check the volumetric characteristics of these mixtures.

Figure 4-1 shows the volumetric binder content of each mixture. Although the gravimetric binder content is the same in each mixture, the volumetric binder contents are different because of the difference in specific gravity of aggregates. From this figure, it was found that slag mixtures would have a higher binder content compared to the gritstone mixture. Figure 4-2 also shows the volumetric effective binder content of these mixtures, which takes account of binder absorption of aggregates. As can be seen, similar results were obtained from gritstone and slag with limestone filler mixtures. Thus, the amount of binder existing between aggregates is the same in both mixtures. However, differences in surface texture of aggregates would lead to different binder thickness. Namely, binder film thickness of slag mixture might be thinner than that of gritstone mixture. Therefore, the difference in stiffness modulus of these mixtures might be given by the difference in surface texture of aggregates, especially the porous material of BFS. It could be thought that the aggregate contacts in slag mixtures would be more efficient than those in the gritstone mixture.

Table 4-1Unconditioned ITSM test results

Mixture type	Binder Content (%)	Average Air void % of specimens	Number of Specimens tested	Stiffness Modulus (MPa)	Standard Deviation
Gritstone	6.0	2.4	30	3413	232
Slag (with Limestone filler)	6.0	2.6	30	4351	337
Slag (with BFS filler)	6.0	4.1	4	4734	447
	7.0	2.8	4	3401	311

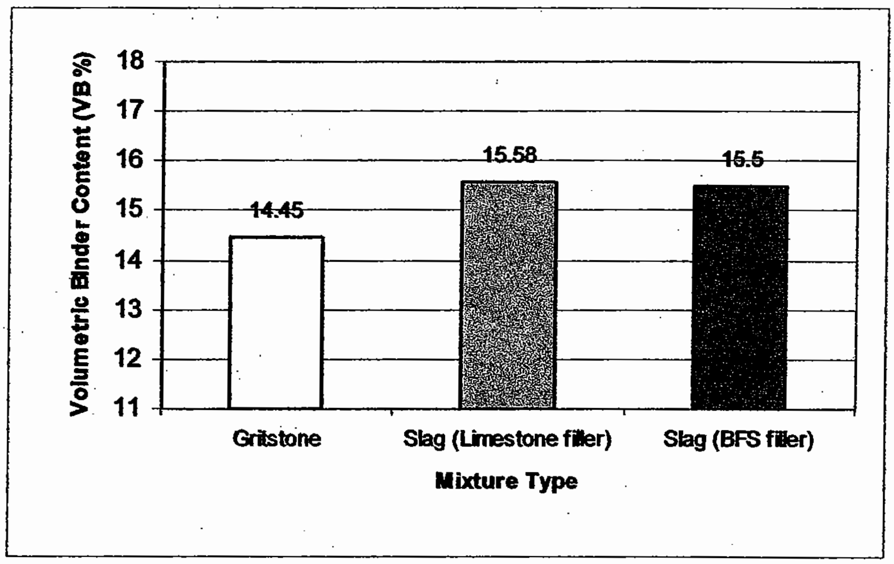


Figure 4-1 Volumetric Binder Content of SMA mixtures

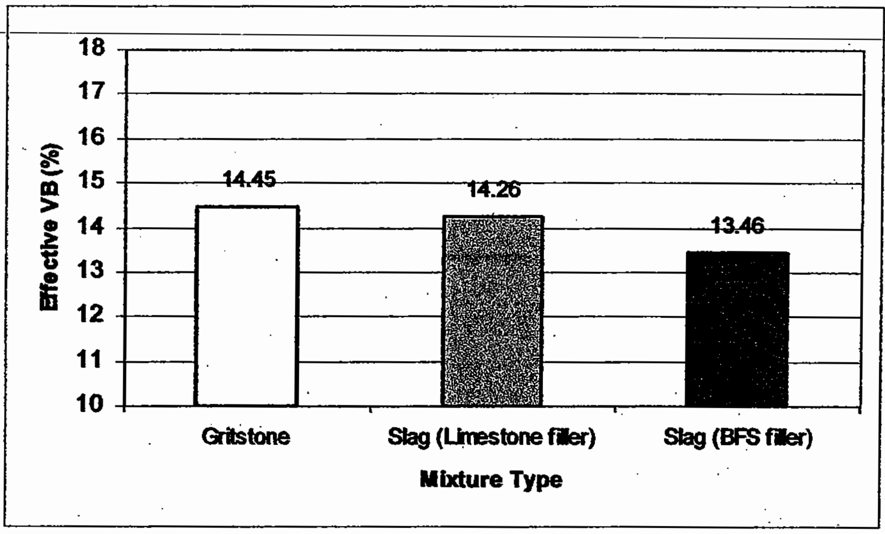


Figure 4-2 Effective Volumetric Binder Content of SMA mixtures

Aged Results

Aged ITSM tests were carried out using gritstone and slag (limestone filler) mixtures. Figure 4-3 shows the ITSM test results obtained from these mixtures. It was found that the increase in aged stiffness modulus of slag mixture is much higher than that of gritstone mixture. One of the reasons for the result is thought to be that the porous BFS aggregate facilitates the volatility or absorption of oily component of bitumen [3]. The other reason could be that different chemical composition of aggregates. Thus, CaO and free lime contained in steel slag aggregates may have facilitated the stiffening of the binder.

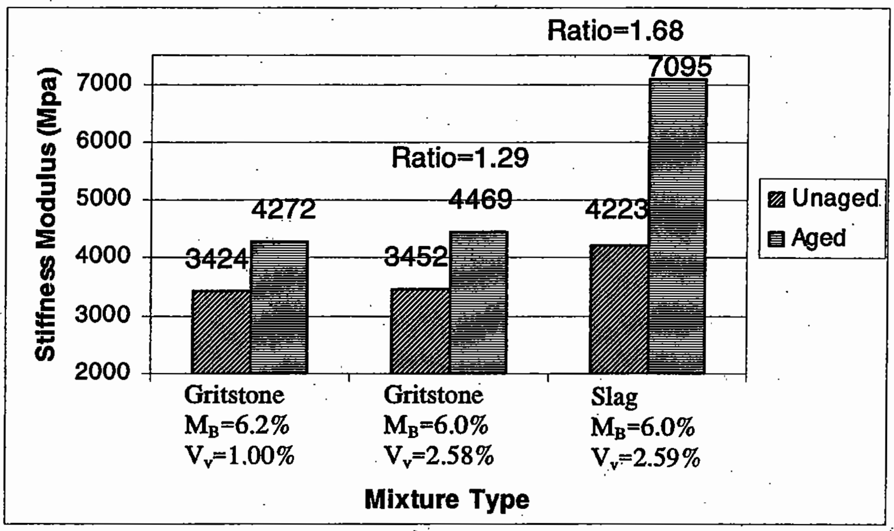


Figure 4-3 Ageing ITSM Test Results for SMA Mixtures

Dynamic Shear Rheometer (DSR) tests were carried out on the binders recovered from those aged gritstone and slag mixtures to investigate the results of aged ITSM tests. Figure 4-4 shows the master curve of complex modulus for both binders. The results indicated that there was not much difference between the properties of both binders. Small differences in complex modulus were found at a particular temperatures and frequency. Figure 4-5 shows the isochronal plot of the complex modulus at 1.2Hz. The ITSM tests were carried out at a temperature of 20°C, therefore, the ratio of difference in complex modulus at this temperature was calculated. It was found that the rate is pretty similar to the rate of increasing rate of ITSM test results. Together with those results, it was confirmed that the binder of slag mixtures is stiffened by the presence of slag aggregates, although the detailed process is unclear.

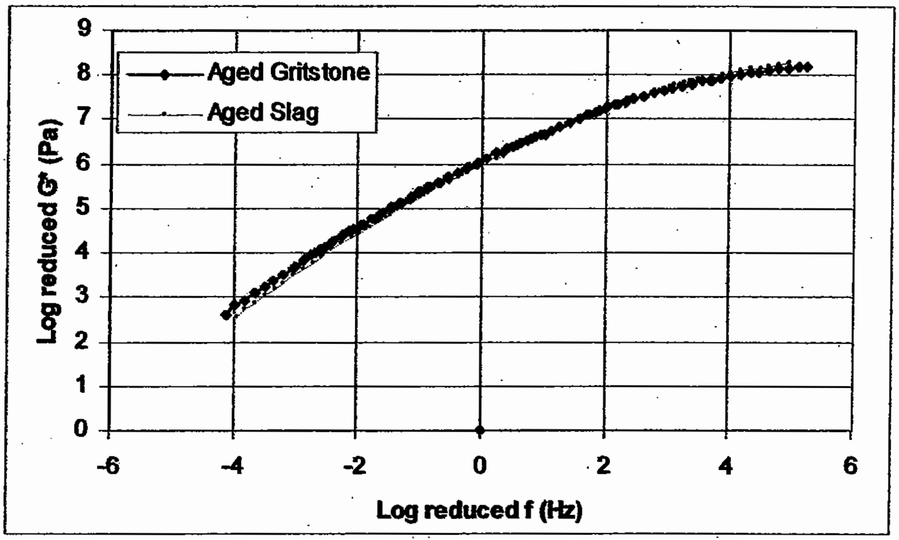


Figure 4-4 Master Curve of Complex Modulus for Recovered Binders

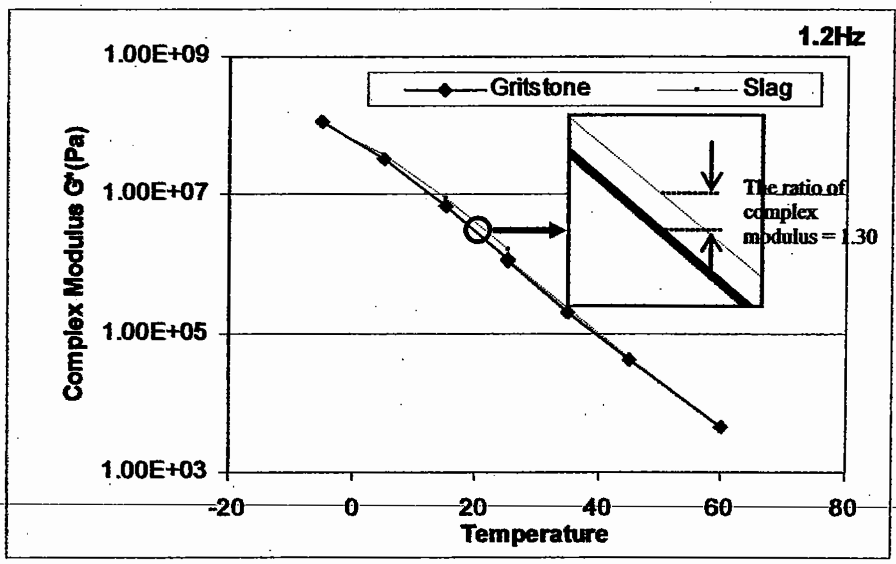


Figure 4-5 Isochronal Plot of Complex Modulus at 1.2Hz

Moisture conditioned

Water sensitivity ITSM tests were carried out using the gritstone mixture and two types of slag mixtures. Figure 4-6 shows the results obtained from these mixtures. The results showed that the two slag mixtures incorporating BFS filler (M_B=6% and 7%) deteriorated significantly due to moisture conditioning. On the other hand, the slag mixture incorporating limestone filler showed good performance. Therefore, it seems that the use of BFS filler might affect the results. The gritstone mixtures of higher density specimens (V_v=1.0%) did not show a decrease in stiffness modulus and the lower density of the gritstone mixtures (V_v=2.5%) allowed the stiffness modulus to reduce gradually as the specimens were moisture conditioned. Comparing gritstone mixture (lower density) and slag mixture (limestone filler), both of which had similar volumetric characteristics, slag mixtures resulted in better performance than gritstone mixtures. It could be thought that the rough and porous surface texture of slag aggregates contribute to the resistance to moisture susceptibility.

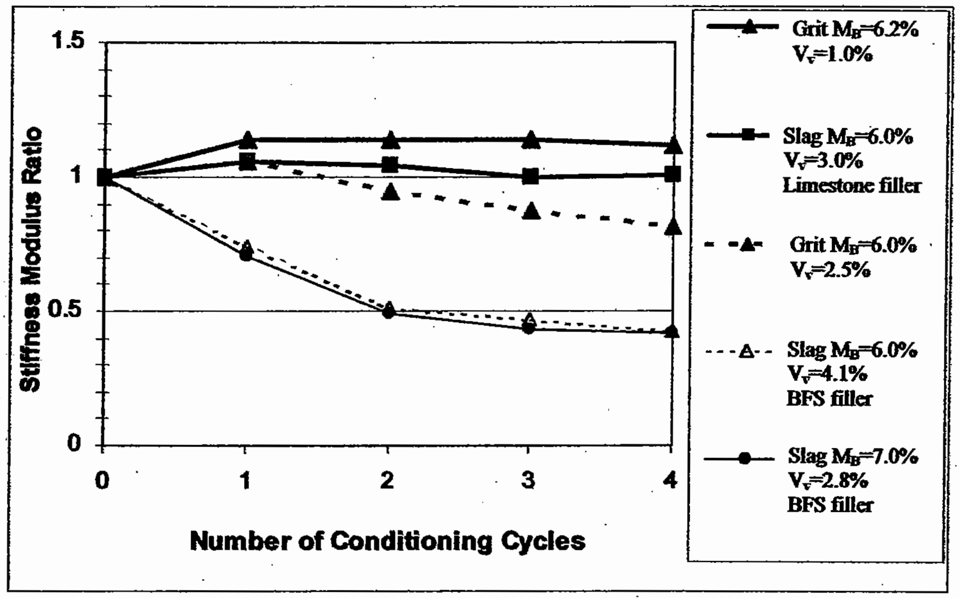


Figure 4-6 Water Sensitivity Test Results for SMA mixtures

28mm DBM

Unconditioned

Unconditioned ITSM tests were carried out using limestone, limestone + glass, slag (BOS + BFS), and steel slag (BOS) + glass mixtures. Table 4-2 shows the results obtained from these mixtures. As can be seen, results are similar apart from that of slag mixtures. Two different density of slag mixtures were used in the test. The reason for this is that the initial slab samples for the slag mixture were fabricated not using the maximum density of the mixture from the Rice density test but using the assumed maximum density by calculation, because the Rice density test results of the 4% binder content of slag mixture came out with an incorrect value. After fabricating the initial slabs, further Rice density tests were conducted using 6% and 7% binder content slag mixtures. Then the maximum density of the 4% binder content slag mixture was determined using these results. Figure 4-7 shows the Rice density results and theoretically calculated maximum density of the slag DBM mixtures. In theory, maximum density increases/decreases at the same ratio as the binder content increases/decreases. However, the results obtained from lower binder content (4 and 5%) do not comply with the theory. It could be thought that the aggregates are not covered by binder sufficiently because of vesicular surface of BFS aggregates and during testing, water could get into aggregate particles. Therefore, results would be slightly higher than actual density.

Figure 4-8 and Figure 4-9 show the volumetric binder content and effective volumetric binder content of DBM mixtures respectively. Mixtures containing steel slag aggregate have a higher binder content compared to the other mixtures because of its high specific gravity. However, the slag mixture has the least effective volumetric binder content in these mixtures because of the high binder absorption of BFS aggregates.

Table 4-2 Unconditioned ITSM test results for DBM mixtures

Mixture type	Binder Content (%)	Average Air void % of specimens	Number of Specimens tested	Stiffness Modulus (MPa)	Standard Deviation
Limestone	4.0	4.3	30	4587	487
Limestone + Glass	4.0	3.2	30	4706	478
Slag	4.0	4.0	30	5615	529
	4.0	6.5	4	4691	435
Steel slag +Glass	4.0	4.4	12	4288	336

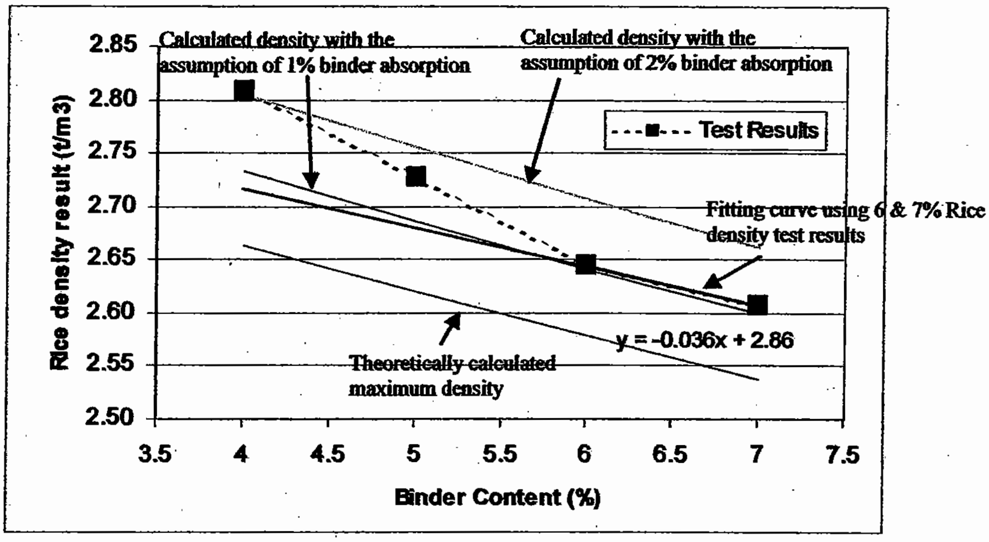


Figure 4-7 Rice Density Test Results for Slag Mixtures

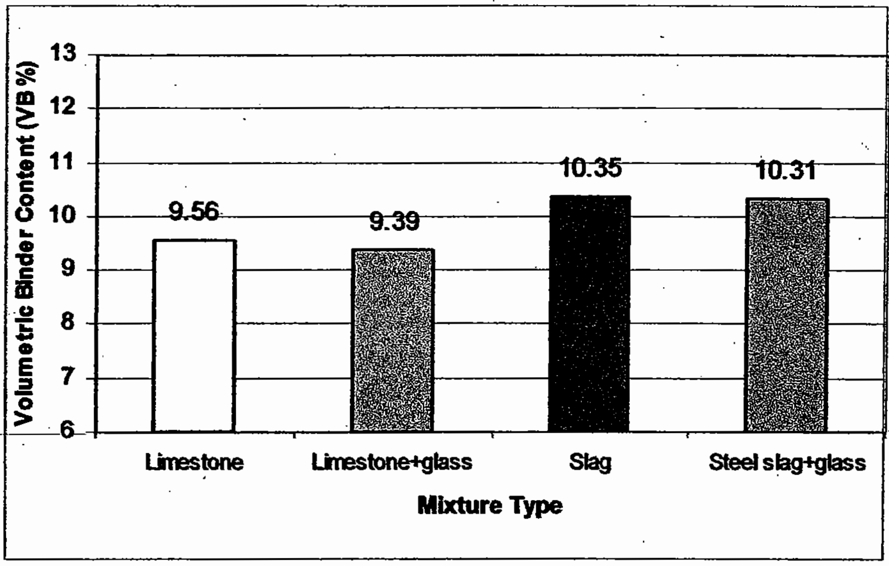


Figure 4-8 Volumetric Binder Content of DBM mixtures

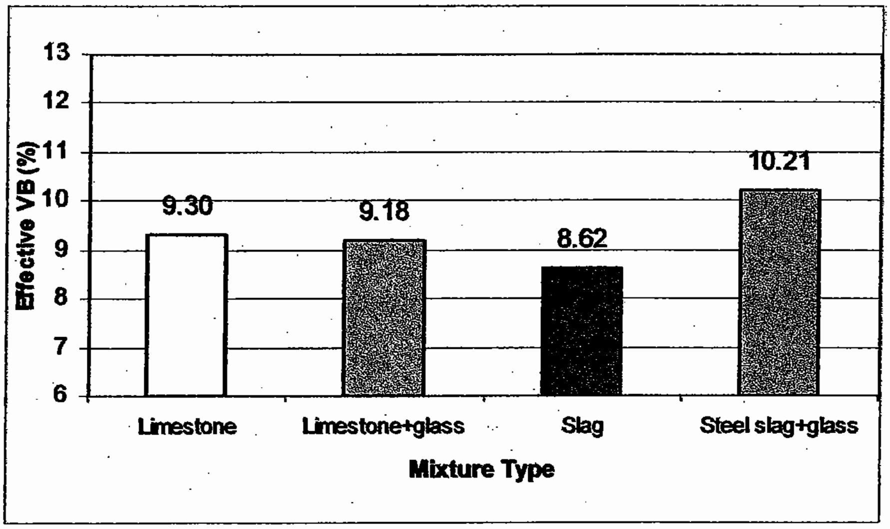


Figure 4-9 Effective Volumetric Binder Content of DBM Mixtures

Aged

Aged ITSM tests were carried out using those mixtures used for unconditioned ITSM tests. Figure 4-10 shows the results obtained from these mixtures. As expected, and similar to the results of SMA mixtures, a much higher ITSM ratio was obtained from the slag mixture. The lowest ITSM ratio was obtained from the limestone + glass mixture. The limestone mixture and the steel slag + glass mixture are ranked between them. The factors that affect the stiffening action of binder could be the chemical composition and surface texture or binder absorption of aggregates. From this point of view, steel slag and BFS slag aggregates contribute greatly to the stiffening. On the other hand, the glass aggregate seems not to affect the binder hardening because of its smooth surface texture and nearly 0% binder absorption. Limestone aggregates would affect the hardening slightly due to the absorption of binder.

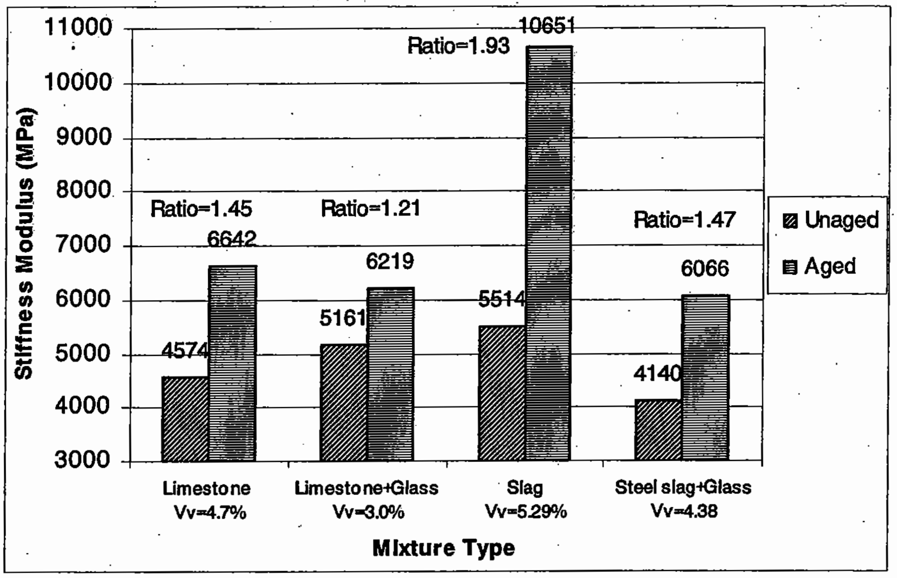


Figure 4-10 Aged ITSM Test Results for DBM mixtures

Moisture conditioned

Water sensitivity ITSM tests were carried out on the mixtures used for unconditioned ITSM tests. Figure 4-11 shows the results obtained from these mixtures. Different behaviour was observed in different mixtures. Stiffness modulus of limestone mixture increased after the 1st conditioning and then did not decrease with moisture conditioning. The limestone + glass mixture also seemed to perform well during the moisture conditioning. More than 95% initial stiffness was retained after 4 conditioning cycles. The slag mixture exhibited less resistance to moisture than the other mixtures. Two different density samples were tested and, although both mixtures behaved differently during the 1st conditioning cycle, the slag mixtures lost stiffness modulus at a similar ratio after the 2nd conditioning cycles. The results obtained from the steel slag + glass mixture is ranked between the limestone and slag mixtures. To clarify the difference in these mixtures after conditioning, Figure 4-12 shows the results in which the data is rearranged to be normalised with respect to the 1st conditioning. As can be seen, the two slag mixtures decreased at nearly the same ratio. The limestone, limestone + glass, and steel slag + glass mixtures decreased their stiffness modulus ratio at a different ratio, but similar to each other.

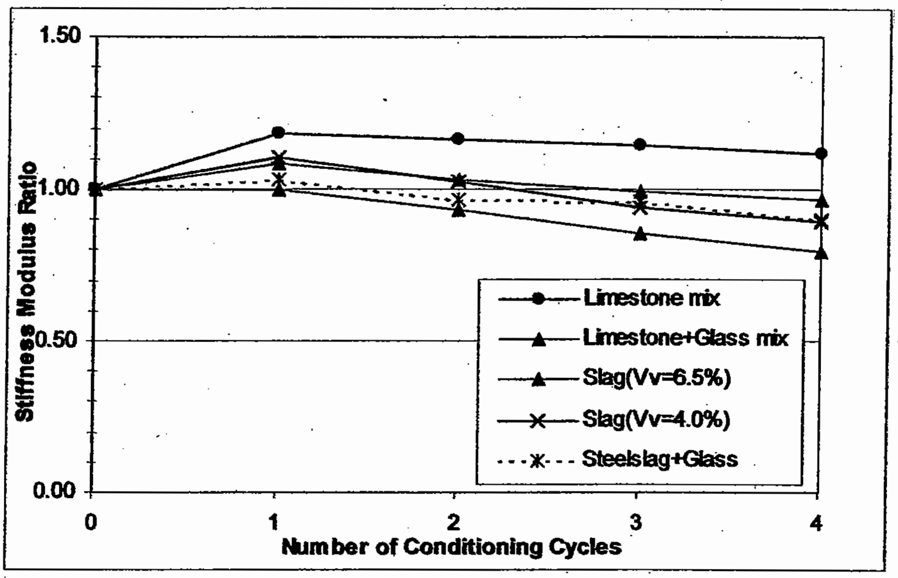


Figure 4-11 Water Sensitivity ITSM Test Results for DBM mixtures

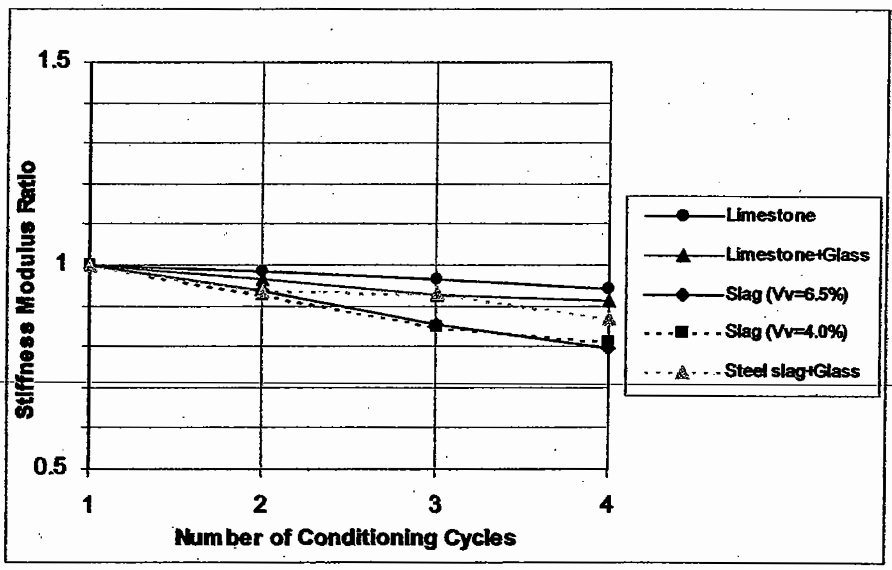


Figure 4-12 Water Sensitivity ITSM Test Results for DBM mixtures Normalised at 1st Conditioning

4.1.4 Conclusion

The results obtained from the ITSM tests show that the unconditioned ITSM result of bituminous mixtures containing slag and/or glass aggregates were satisfactory because these mixtures have a level of stiffness modulus more than equal to that of conventional mixtures. The higher stiffness of slag mixture would be derived from the different volumetric characteristics caused by the vesicular surface texture of BFS aggregates. SMA slag mixture and DBM slag mixture indicate contradictory results with respect to water sensitivity test. The reason could be that the binder content of the SMA mixture is very high while that of DBM mixture is low, and also the BFS aggregate content of SMA mixture is lower than that of DBM mixture. Therefore, there could be adequate binder to cover aggregate sufficiently in the SMA mixture, while there might not be in the DBM mixture. This could lead to the poor performance in the water sensitivity test of the slag DBM mixture.

To investigate this, a slag DBM mixture which binder content increased to 5% was used for a water sensitivity test. Figure 4-13 and Figure 4-14 show the results of unconditioned ITSM and water sensitivity ITSM tests obtained from all the slag DBM mixtures. An improvement of resistance to moisture induced damage of the slag mixtures as binder content increases is evident, although the initial stiffness modulus of slag (M_B=5%) mixtures is much lower than that of slag (M_B=4%) mixtures. Splitting test results, which will be discussed later in the chapter 5, also show less moisture induced damage.

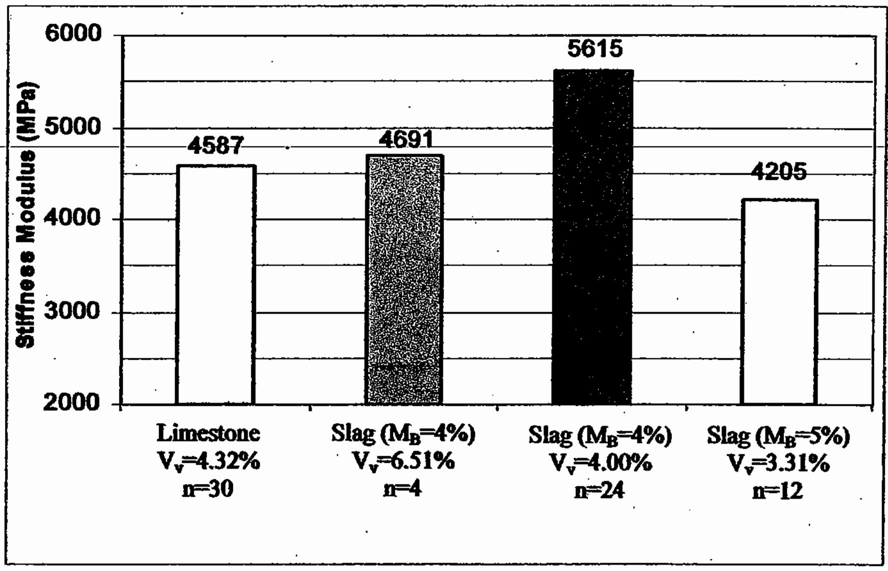


Figure 4-13 Unconditioned Stiffness Modulus for slag DBM Mixtures

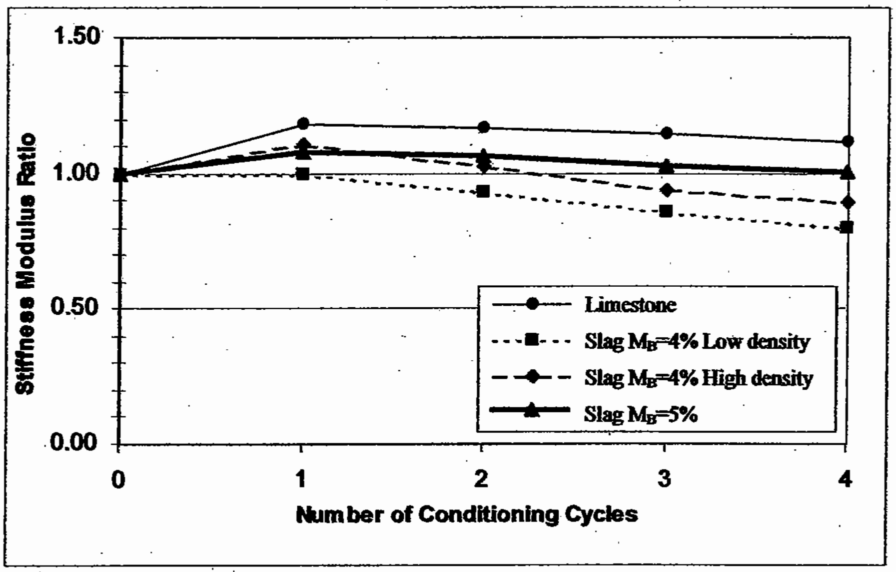


Figure 4-14 Water Sensitivity ITSM Test Results for Slag DBM mixtures

As indicated in the literature review, a bituminous mixture incorporating glass aggregate has a potential susceptibility to moisture induced damage. Although the data obtained from ITSM tests indicated that the limestone + glass mixture exhibited a rather good performance for moisture susceptibility in terms of stiffness modulus, the mixture was also evaluated using anti-stripping agent. 0.3% by weight of bitumen of anti-stripping agent was added to the binder before mixing. Unconditioned stiffness modulus of limestone + glass mixture without anti-stripping agent and incorporating anti-stripping agent are 4706 (MPa) and 4259 (MPa), respectively. Figure 4-15 shows the water sensitivity ITSM test of these mixtures. The results indicate that the mixture incorporating anti-stripping agent had a slightly improved resistance to moisture susceptibility. The effect of the anti-stripping agent will be discussed in a latter chapter.

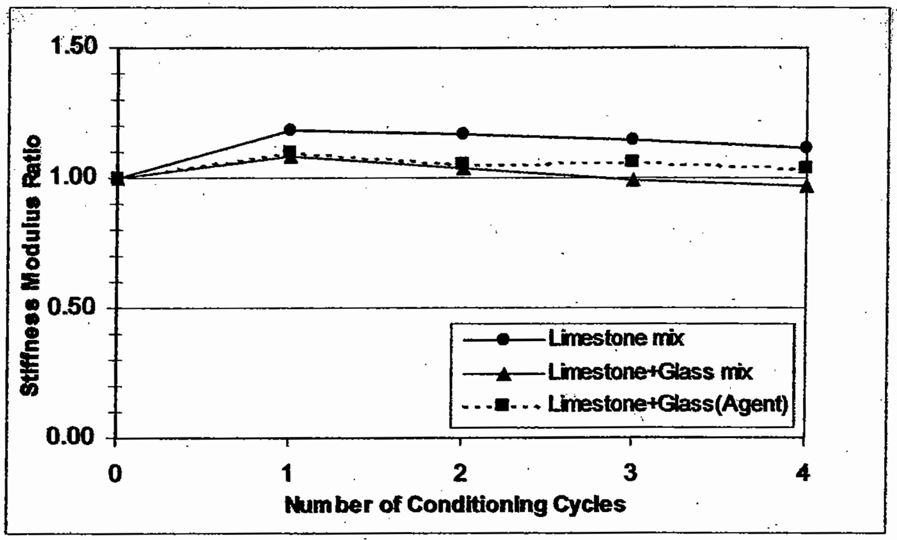


Figure 4-15 Water Sensitivity ITSM Test Results for Limestone + Glass DBM mixtures (with/without anti-stripping agent)

Ageing ITSM tests suggest that the binder hardening in a slag mixture would be accelerated by the vesicular surface texture of BFS aggregates and chemical composition of steel slag aggregates. As a result of the hardening of the binder, the mixture would become more brittle material and this will be discussed in a later section.

4.2 Permanent Deformation

4.2.1 Factors affecting Permanent Deformation

The resistance to permanent deformation would be influenced by the grading, particle shape and surface texture of aggregates. Generally, DBM and SMA mixtures would have good resistance to permanent deformation because the inter-particle contact is well established. To increase the interlocking of aggregates, particle shape could be an important factor. Angular shaped aggregates could provide better interlocking than rounded particle aggregates. Also, the surface texture of aggregates would be another important factor. Rough texture would be better than smooth texture, the latter being associated with loss of adhesion which will result in poor performance in terms of permanent deformation.

4.2.2 Test Procedure

Confined Repeated Load Axial Test (CRLAT)

The unconfined Repeated Load Axial Test (RLAT) was developed to evaluate the permanent deformation characteristics of bituminous mixtures. The methodology of this test can be found in the BS draft DD226 [4]. A 1 second period of 100kPa axial stress is applied vertically to the specimen followed by a 1 second rest period. 3,600 loads are applied to the specimen. The axial deformation is measured during the test. The test result is expressed as the relationship between accumulated axial strain and test duration (number of load cycles). However, in the RLAT, the lateral confinement, which exists in the actual road, is ignored. To take account of the effect of lateral confinement, a modified version of the RLAT was developed. Thus, the specimen is covered by a membrane and vacuum is applied during testing to simulate actual road conditions. Previous research investigating the effect of confining pressure [5] showed that a low confining pressure may be enough to simulate the lateral confinement effect. Although this modified version of the RLAT has not been standardised, 50kPa of confining pressure has been selected in this project. The test temperature has been selected as 40°C, and 100mm diameter and 65mm thickness specimens were used.

Wheel Tracking Test

A wheel tracking test, previously developed, is widely used to evaluate the resistance to permanent deformation of bituminous mixtures using a more realistic wheel load. A single wheel load which is normally 520N is applied to a test specimen with a frequency of 21 load cycles per minute. Tests are carried out at a temperature of 45/60℃ and during testing the vertical deformation is monitored. The test will finish if the deformation reaches a depth of 15mm or for 45 minutes, whichever occurs first. Test results are expressed as the wheel tracking rate and wheel tracking depth.

4.2.3 Test Results

CRLAT

14mm SMA

Tests were carried out using gritstone mixtures and slag mixtures, and unconditioned and moisture conditioned specimens were prepared for the test. Figure 4-16 and Figure 4-17 show the results obtained from these mixtures. These graphs express the development of vertical strain, which is accumulated during testing. As can be seen, both unconditioned and moisture conditioned results indicate that the slag mixtures would be more susceptible to rutting. Figure 4-18 and Figure 4-19 show the total strain and strain rate obtained from these results. Strain rate is expressed as the rate between 2700 and 1800 load cycles. It was confirmed from these results that the slag mixtures performed poorly in the CRLAT. In theory, as mentioned above, slag aggregate having rough and vesicular surface texture would improve the resistance to permanent deformation, however the results are opposed to this theory.

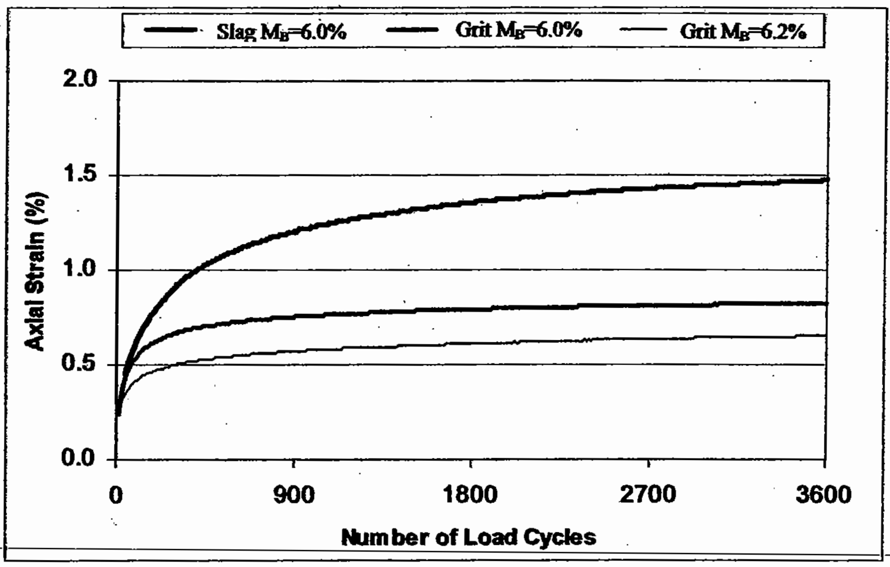


Figure 4-16 CRLAT Results for Unconditioned SMA mixtures

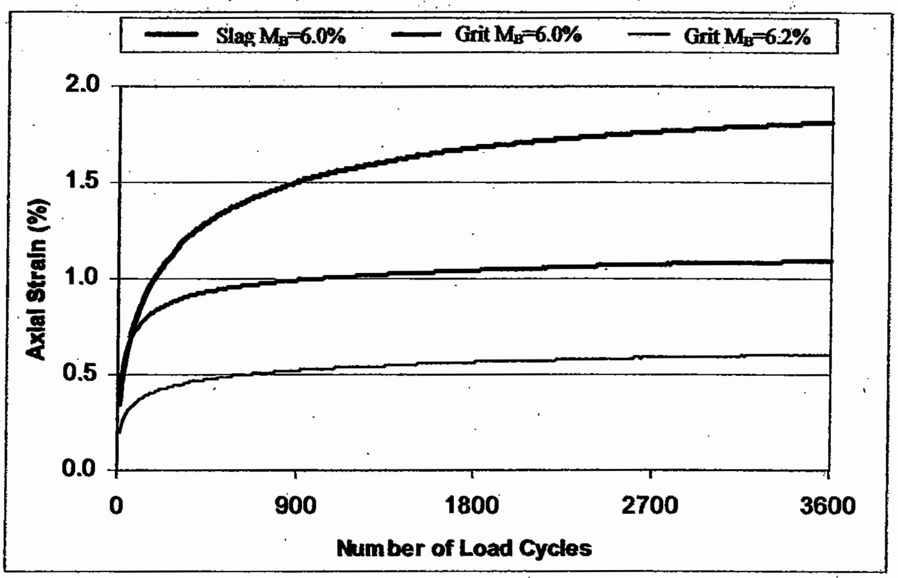


Figure 4-17 CRLAT Results for Moisture Conditioned SMA mixtures

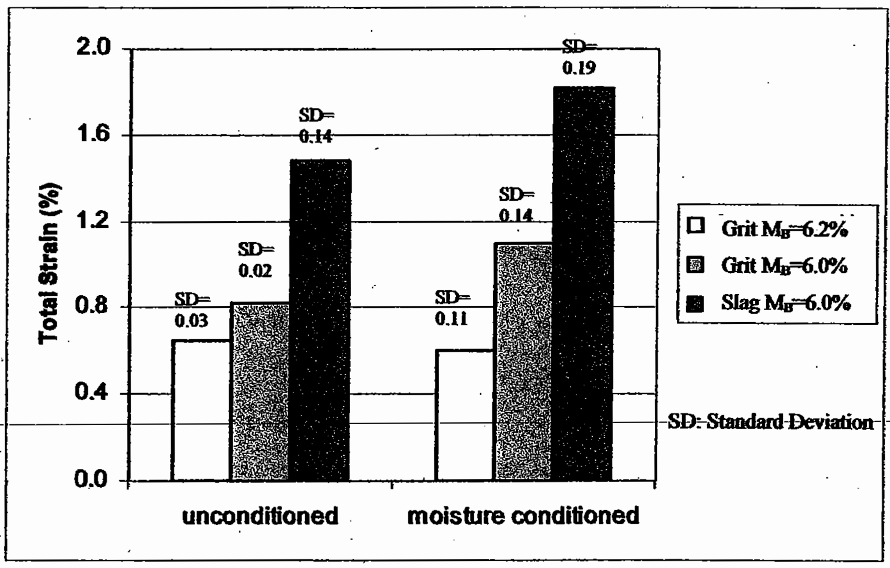


Figure 4-18 CRLAT Results for SMA mixtures (Total Strain)

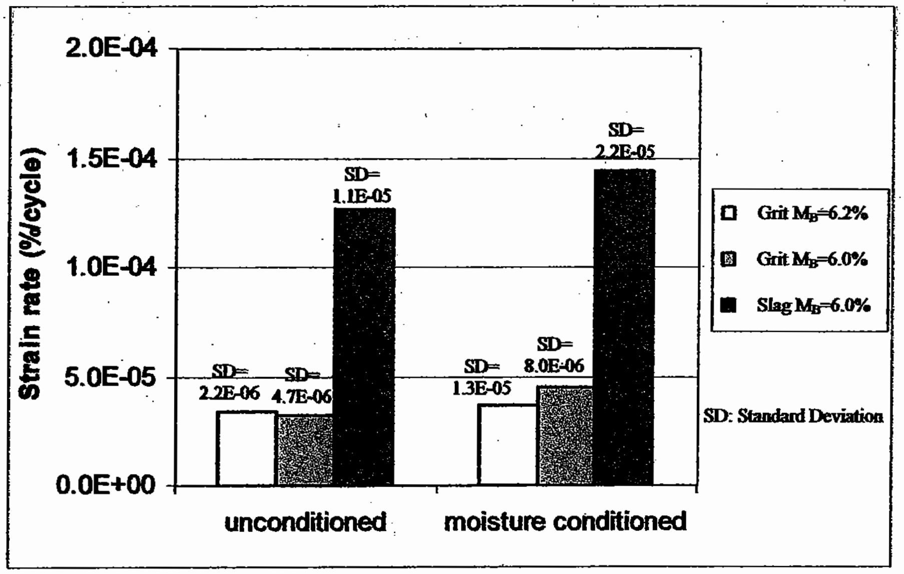


Figure 4-19 CRLAT Results for SMA mixtures (Strain Rate)

One of the factors affecting the poor results of slag mixture could be the amount of binder in the mixture. As mentioned above, the volumetric binder content of the slag mixture is higher than that of gritstone mixture. Gravimetric binder content of slag mixture needs to be 5.5% instead of 6.0% to obtain similar volumetric binder content to the gritstone mixture, if binder absorption is not taken account. Therefore, specimens were fabricated using 5.5% binder content slag mixture and tested by CRLAT. Figure 4-20 and Figure 4-21 show the results obtained from both slag mixtures (M_B=6.0% and M_B=5.5%) and gritstone mixture (M_B=6.0%). As can be seen, the slag (M_B=5.5%) mixture performed slightly better than slag (M_B=6.0%) mixture in moisture conditioned specimens, however, still there is a gap relative to the gritstone mixture.

CRLAT tests were also performed at a temperature of 60°C using unconditioned gritstone (MB=6.0%) and slag (MB=5.5%) mixtures because the influence of physical characteristics of aggregates would be clarified at a high temperature. Figure 4-22 shows the results from the gritstone mixtures. As expected, poorer results were obtained at higher temperature. However, the slag mixture results, which are shown in Figure 4-23, show that resistance to rutting would be better at higher temperature. Although the reason for the interesting behaviour of slag mixture is not clear, the gritstone and slag mixtures performed similarly at the high test temperature, as shown in Figure 4-24 to Figure 4-26.

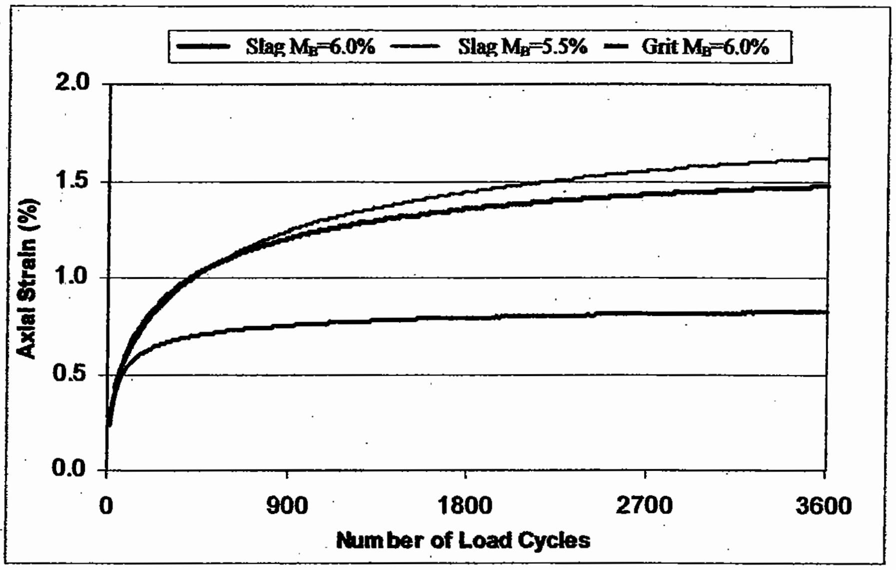


Figure 4-20CRLAT Results for Different Binder Content Slag SMA mixtures (Unconditioned)

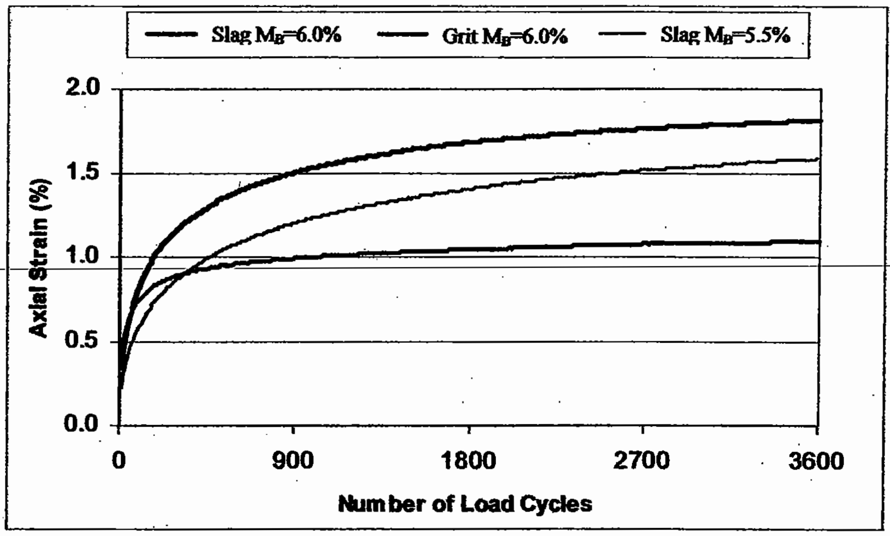


Figure 4-21CRLAT Results for Different Binder Content Slag SMA mixtures (Moisture Conditioned)

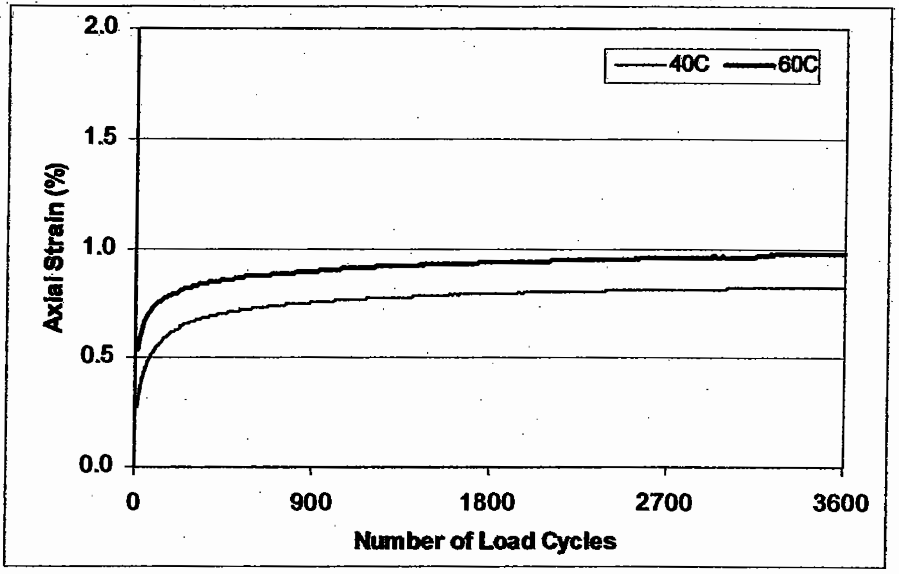


Figure 4-22 CRLAT Results for gritstone mixture (M_B=6.0%) at Different Temperature

B

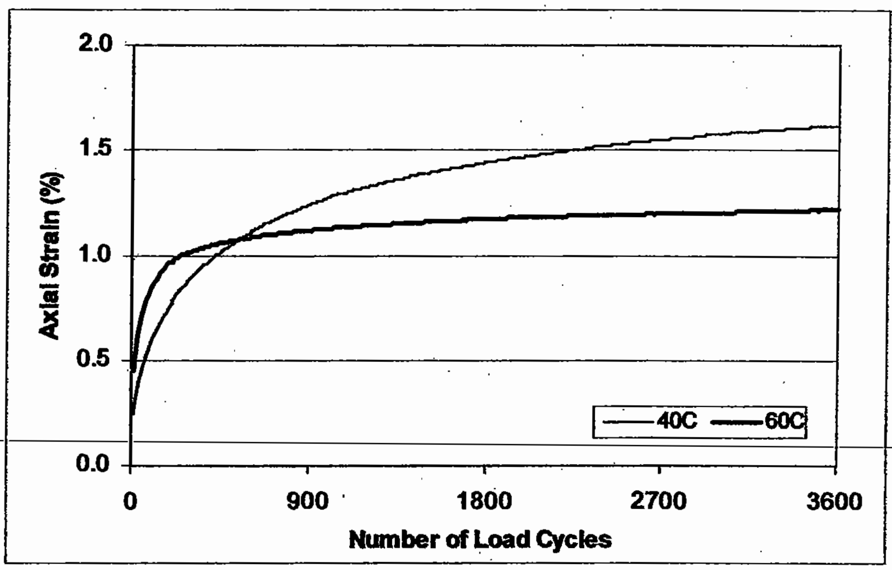


Figure 4-23 CRLAT Results for slag mixture (M_B=5.5%) at Different Temperature

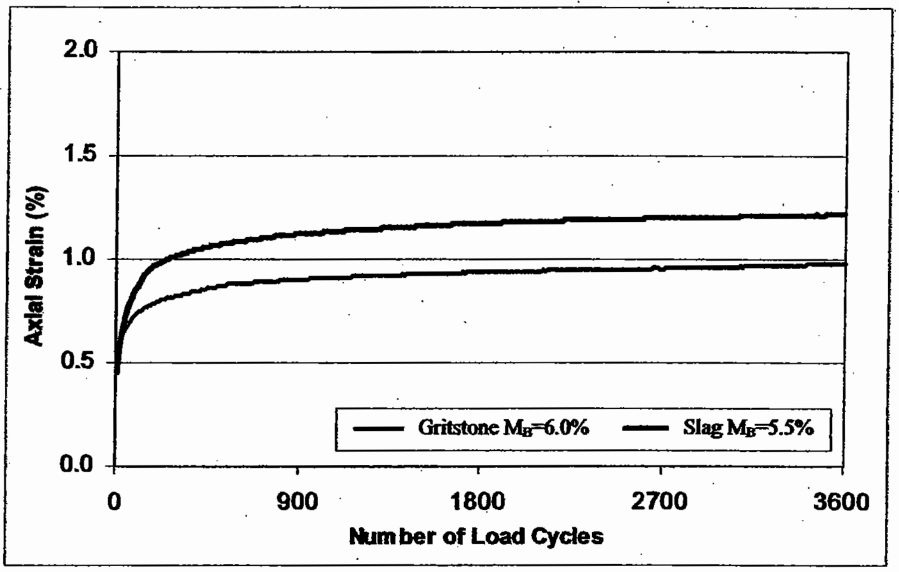


Figure 4-24 CRLAT Result at 60°C (gritstone and slag mixtures)

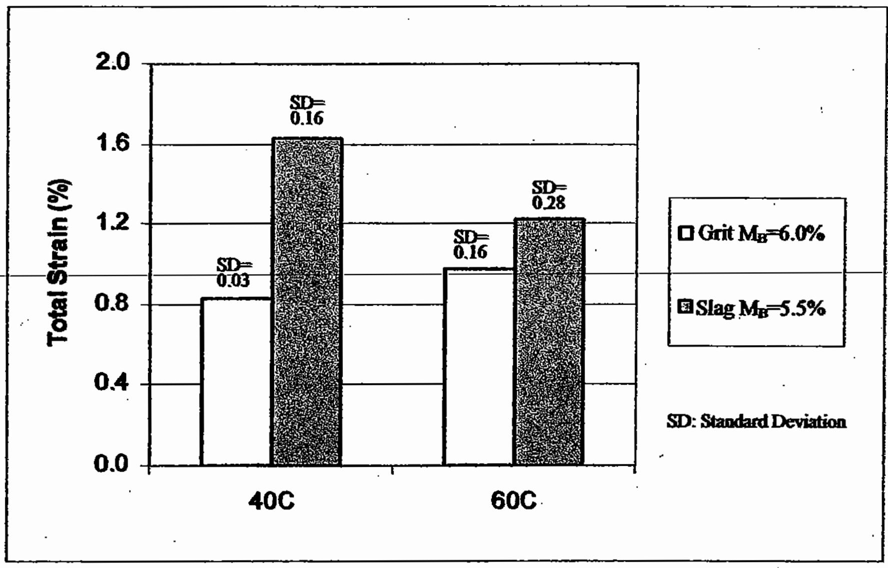


Figure 4-25 Total Strain at Different Temperature

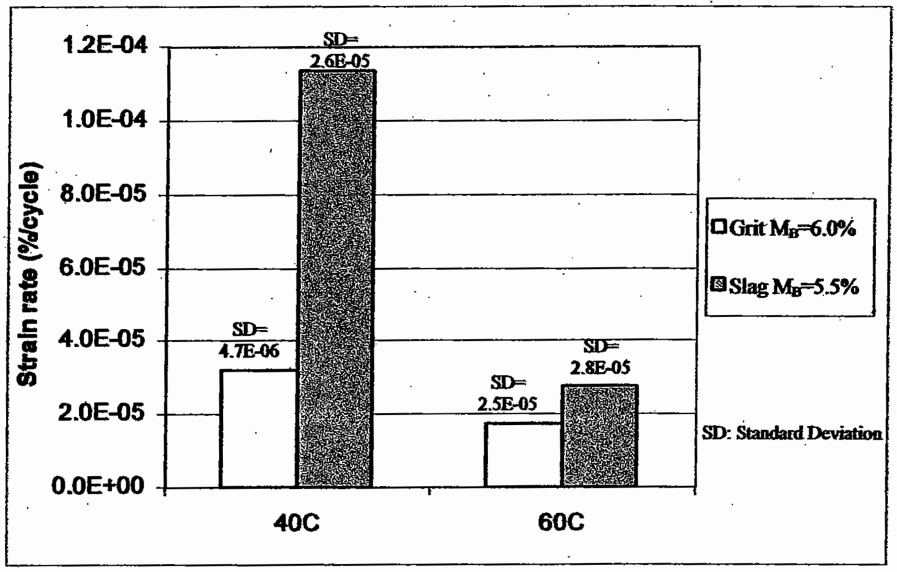


Figure 4-26 Strain Rate at Different Temperature

28mm DBM

Tests were carried out using limestone, limestone + glass, slag, and steel slag + glass mixtures, and unconditioned and moisture conditioned specimens were prepared for the tests apart from the steel slag + glass mixture on which tests were conducted only using moisture conditioned specimens. Figure 4-27 and Figure 4-28 shows the results obtained from unconditioned and moisture conditioned specimens of these mixtures, respectively. As can be seen, limestone mixtures and slag mixtures performed similarly and exhibited good resistance to rutting, on the other hand, mixtures containing glass aggregate (limestone + glass and steel slag + glass mixtures) exhibited susceptibility to permanent deformation. Figure 4-29 and Figure 4-30 show the total strain and strain rate obtained from these data, respectively. Again, it was confirmed that the mixtures incorporating glass aggregates have potential for poor resistance to permanent deformation. The reason for this could be that the smooth surface texture of glass aggregates contributes to reduced aggregate interlocking and less adhesion of binder. It was also confirmed that slag mixtures exhibited good performance, which resulted in an opposite result to that of the SMA Slag mixture. This indicates that the poor performance obtained from SMA slag mixtures could not be due to the properties of slag aggregates but to factors of mixture design, e.g. binder content.

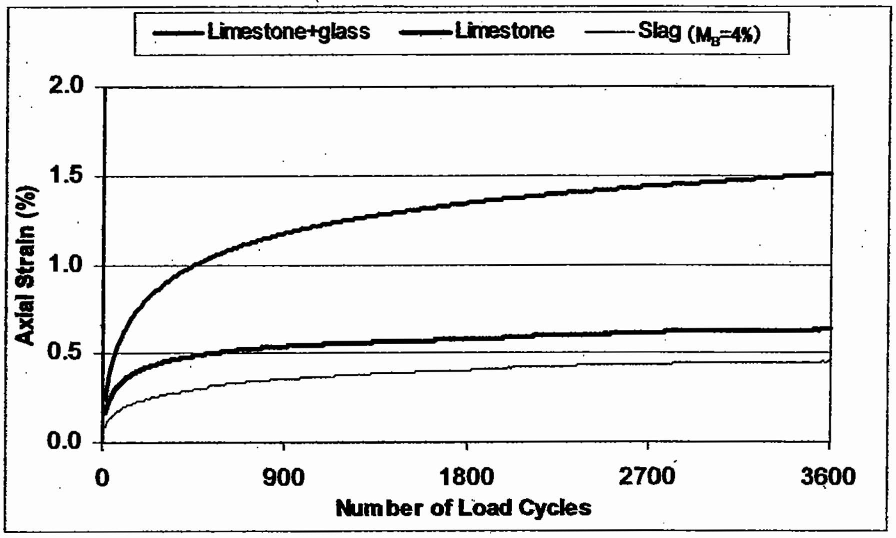


Figure 4-27 CRLAT Results for Unconditioned DBM mixtures

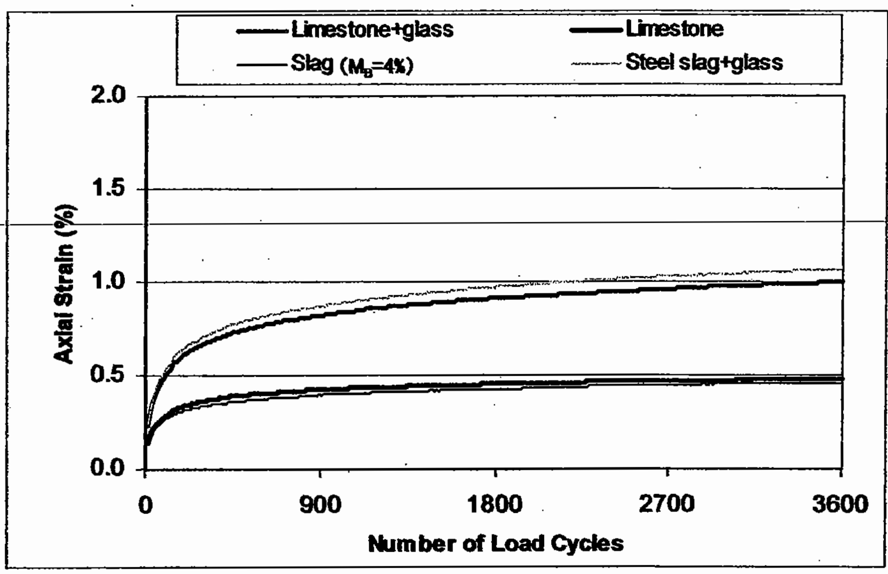


Figure 4-28 CRLAT Results for Moisture Conditioned DBM mixtures

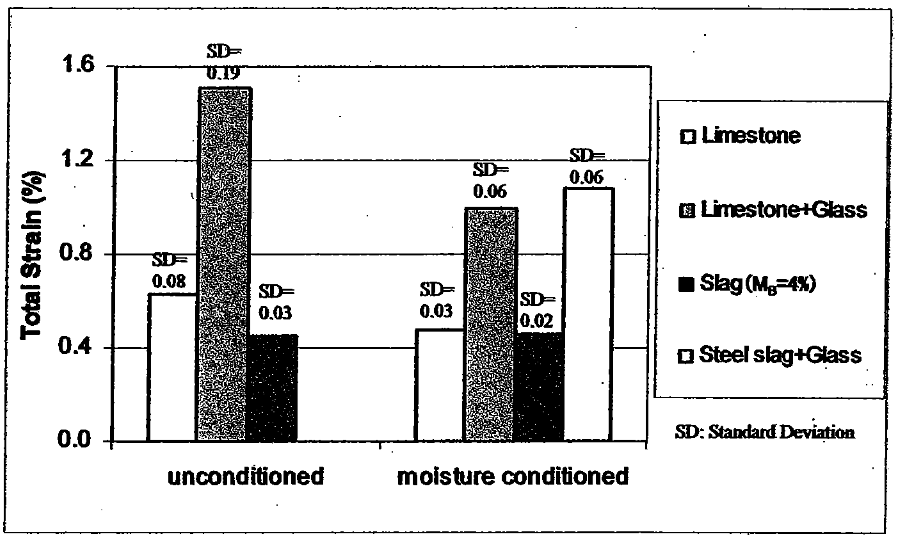


Figure 4-29 CRLAT Results for DBM Mixtures (Total Strain)

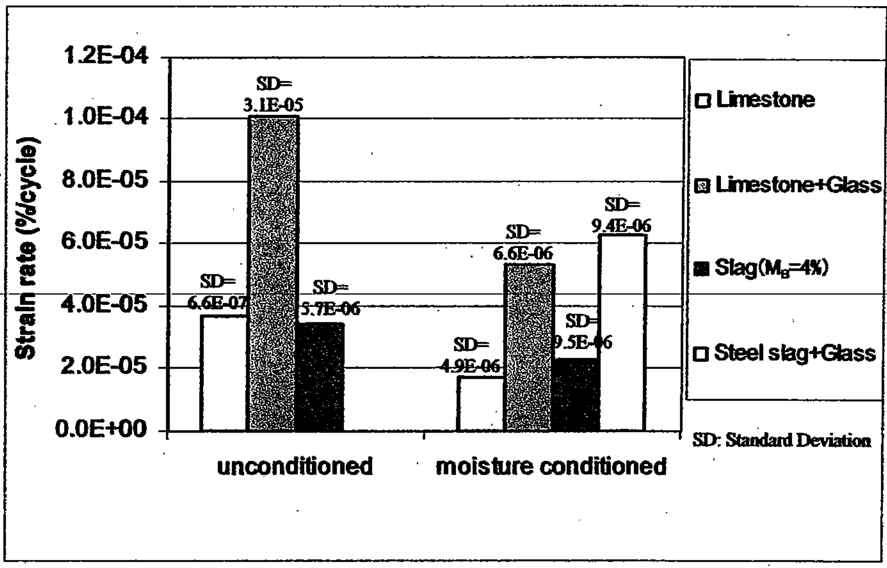


Figure 4-30 CRLAT Results for DBM Mixtures (Strain Rate)

As mentioned above, the slag mixture which had its binder content increased to 5% was also evaluated because the 4% binder content slag mixture was found to be susceptible to moisture damage. CRLA tests were also carried out using these 5% binder content slag mixtures. These results are shown in Figure 4-31 to Figure 4-34. The results indicated that the total strain of the slag (M_B=5%) mixture is slightly higher than that of the slag (M_B=4%) mixture, however, the mixture still seems to have good characteristics for permanent deformation. Together with the results obtained from ITSM tests, it could be thought that the optimum binder content for the slag mixture should be 5% instead of 4%.

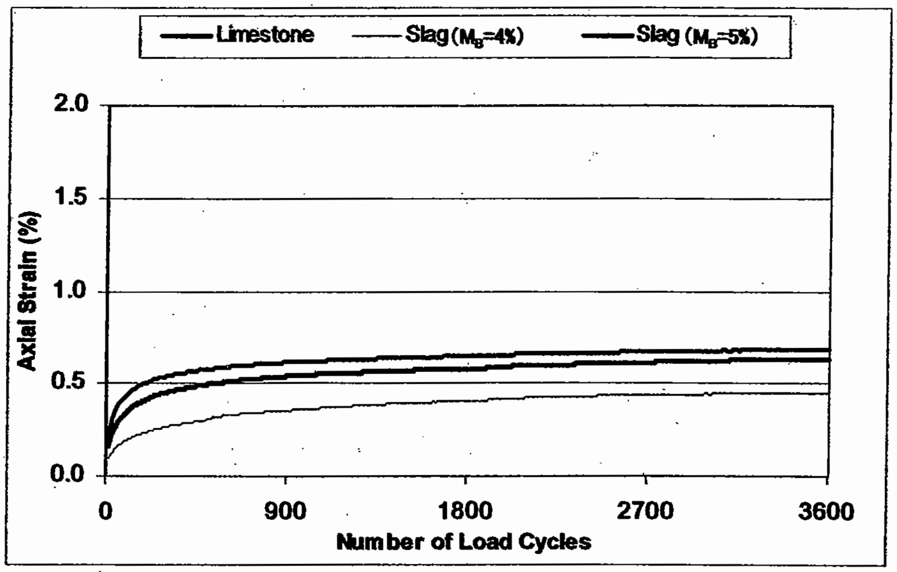


Figure 4-31CRLAT Results for Different Binder Content of Slag DBM mixtures (Unconditioned)

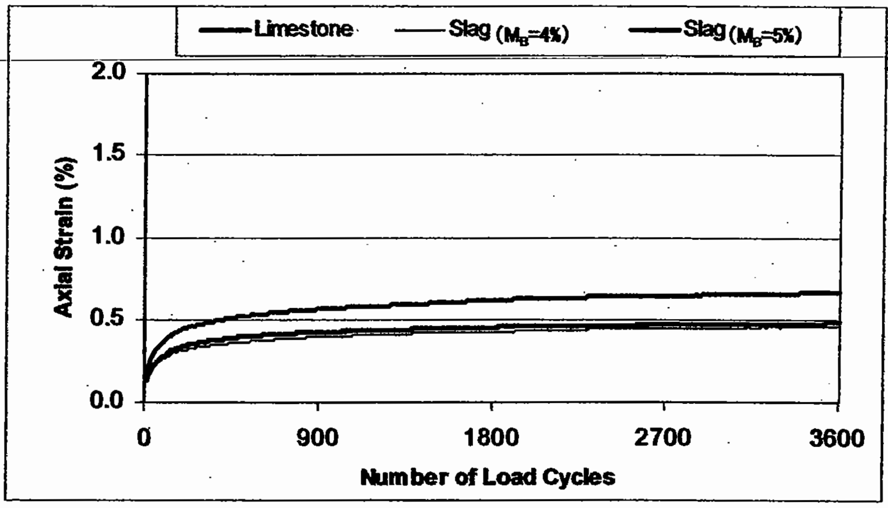


Figure 4-32 CRLAT Results for Different Binder Content of Slag Mixtures (Moisture Conditioned)

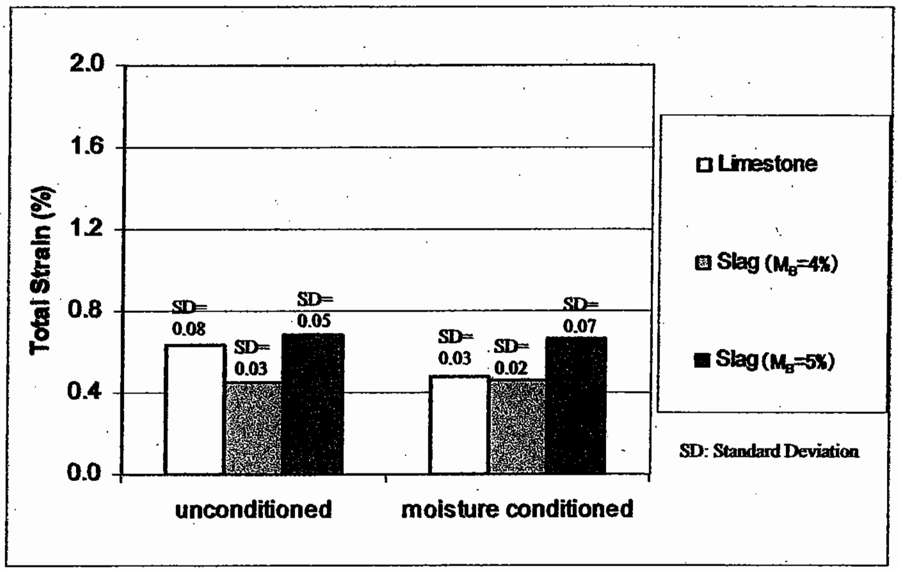


Figure 4-33CRLAT Results for Different Binder Content of Slag Mixtures (Total Strain)

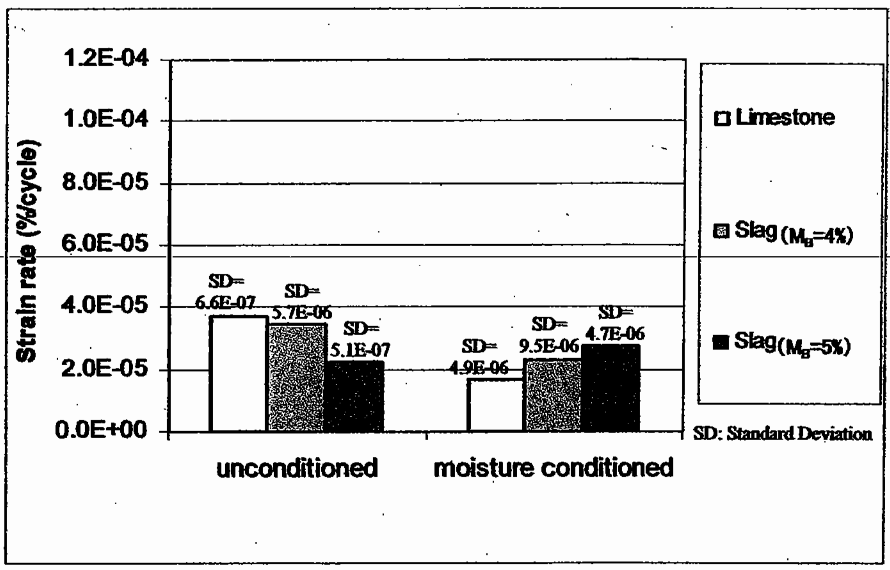


Figure 4-34 CRLAT Results for Different Binder Content of Slag Mixtures (Strain Rate)

In addition, the limestone + glass mixture which incorporates anti-stripping agent was used for CRLAT. As shown in Figure 4-35, the use of anti-stripping agent did not improve the resistance to permanent deformation.

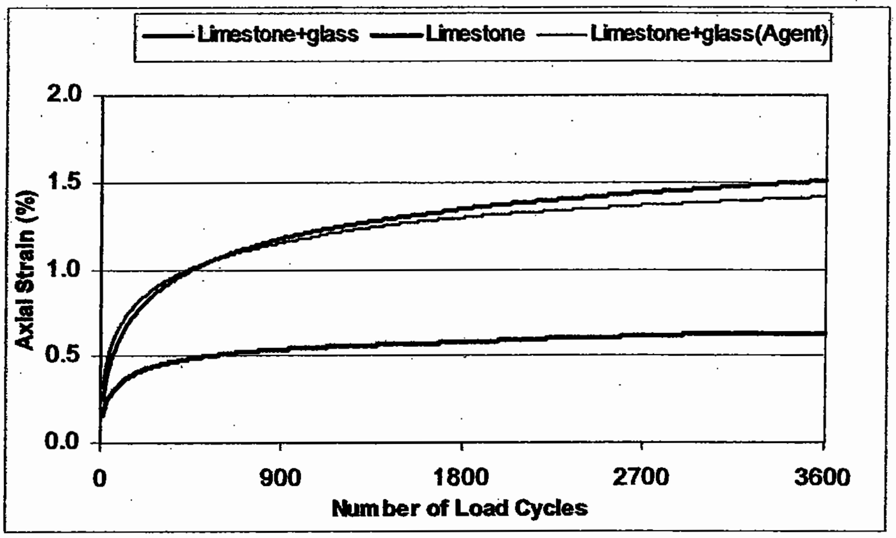


Figure 4-35 CRLAT Results for limestone + glass mixtures

4.2.4 Conclusion

SMA slag mixtures showed poor performance and the DBM slag mixtures showed good performance. From these results, it is deduced that the binder content of a slag mixture affects the result of permanent deformation tests and the optimum binder content of SMA slag mixture can be less than 5.5% with respect to adequate permanent deformation performance.

DBM mixtures incorporating glass aggregate exhibited poorer performance in permanent deformation tests. The reason for this performance is attributed to the smooth surface texture of glass aggregate resulting in less aggregate interlock and surface friction. Even the mixture used anti-stripping agent did not exhibit an improved resistance to rutting performance. Therefore the use of glass aggregate in a bituminous mixture could have the problem of inadequate permanent deformation resistance.

4.3 Fatigue Cracking

4.3.1 Factors affecting Fatigue cracking

Generally, binder content and air void content are the main factors affecting the fatigue property of continuously graded bituminous mixtures. If the binder content of a mixture increases, fatigue life will increase. If the air void content of a mixture decreases, fatigue life will increase. Stiffness of binder (mixture) would influence the fatigue response. In stress-controlled test, fatigue life would be longer if the stiffness is higher. However, the opposite result would be obtained from a strain-controlled test. For the same reason, the influence of temperature would be different in both test methods. Aggregate type seems to have much influence on the fatigue property of mixtures.

4.3.2 Test procedure

In the Indirect Tensile Fatigue Test (ITFT), pulse loads are applied to the specimen repeatedly until the specimen is failed by cracking. The result is expressed as a relationship between the maximum tensile horizontal strain and the number of cycles to failure. The maximum tensile strain ε_{Xmax} is defined as,

$$\varepsilon_{X\max} = \frac{\sigma_{X\max} \times (1+3\nu)}{Sm} \times 1000 \qquad (4.2)$$

σ_{Xmax} = maximum tensile stress at the centre of the specimen (kPa)

$$\sigma_{X\max} = \frac{2 \times P}{\pi \times d \times t} \qquad (4.3)$$

P = vertically applied loading (kN)
d = diameter of the test specimen (mm)
t = thickness of the specimen (mm)

Sm = indirect tensile stiffness modulus at σ_{Xmax} (MPa)
ν = Poisson's ratio

Specimens are tested at various stress levels, and the results are plotted as a linear line on logarithmic scales. This expresses the characteristic of the fatigue strength of the material. The methodology of the ITFT test is in accordance with LINK BITUTEST Project procedure [2]. The test is carried out at a temperature of 20°C. From the specimens used in the ITSM test, 100mm × 40mm specimens were obtained by trimming.

4.3.3 Test Results

14mm SMA

Stress-Fatigue life

Influence of conditioning

Figure 4-36, Figure 4-37 and Figure 4-38 show the fatigue lives obtained from SMA mixtures, which are expressed as a relationship between maximum tensile stress and number of cycles to failure. As can be seen, fatigue lives obtained from aged samples of each of three mixtures are longer than for unconditioned or moisture conditioned samples. Slag results illustrate this clearly. Thus, the fatigue life of an aged slag sample is much longer than that of the other lives. This is because the stiffness modulus of aged slag mixture samples increased significantly. However, the results indicate that the moisture conditioning does not affect the fatigue properties. Even though ITSM test results exhibit some influence of moisture conditioning (decrease in stiffness), especially of the gritstone lower density mixtures, the fatigue properties of moisture conditioned samples were not affected very much. Decrease in stiffness does not necessarily lead to increase in fatigue cracking risk.

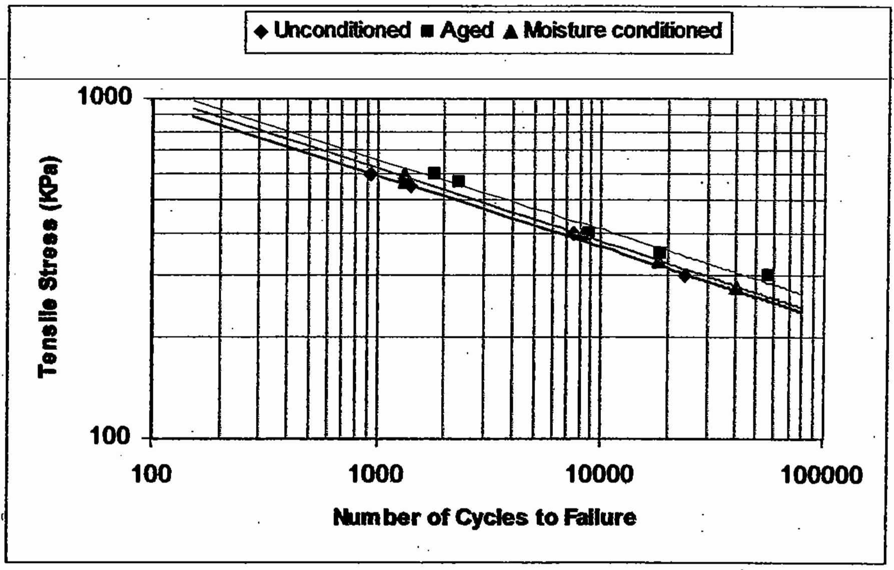


Figure 4-36 Stress-Fatigue Lives (SMA gritstone Vv=1.0%)

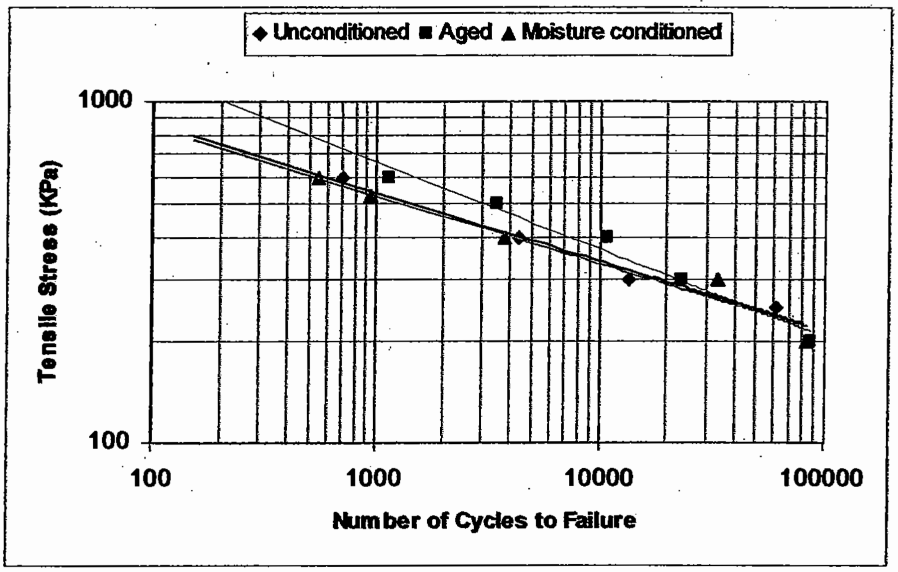


Figure 4-37 Stress-Fatigue Lives (SMA gritstone Vv=2.5%)

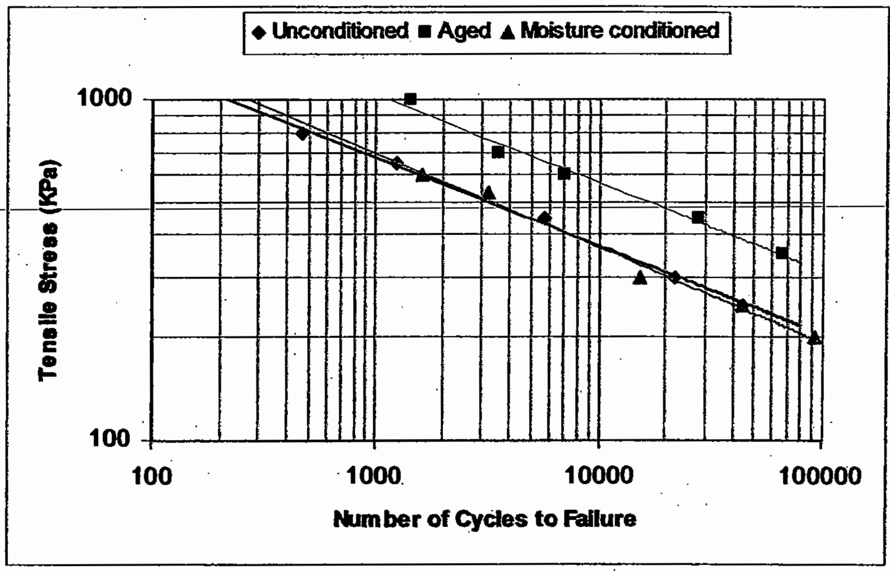


Figure 4-38 Stress-Fatigue Lives (SMA slag mixture)

Influence of Different Aggregate Type

Figure 4-39 shows all the results obtained from fatigue tests carried out on 14mm SMA mixtures. As can be seen, only the aged slag specimens behaved differently from others. A trend line was obtained from all results to express an average stress fatigue life. Furthermore, to understand the advantage / disadvantage of individual mixtures, the residual error was calculated using this trend line and actual data, and was plotted on a graph that is expressed as a relationship between log (predicted value) and log (residual error). Figure 4-40 shows that the residual error of individual results and Figure 4-41 shows average values of residual error for each mixtures. Therefore, this graph shows the advantage of a mixture against the other mixtures. As mentioned above, aged slag samples behaved very differently from the others. To eliminate the influence of these extreme results, the data were rearranged not using the results obtained from the aged samples. Figure 4-42 shows the results obtained from not using aged samples. It can be said that slag mixtures have slightly better fatigue properties than gritstone mixtures, although there is not much difference between these mixtures.

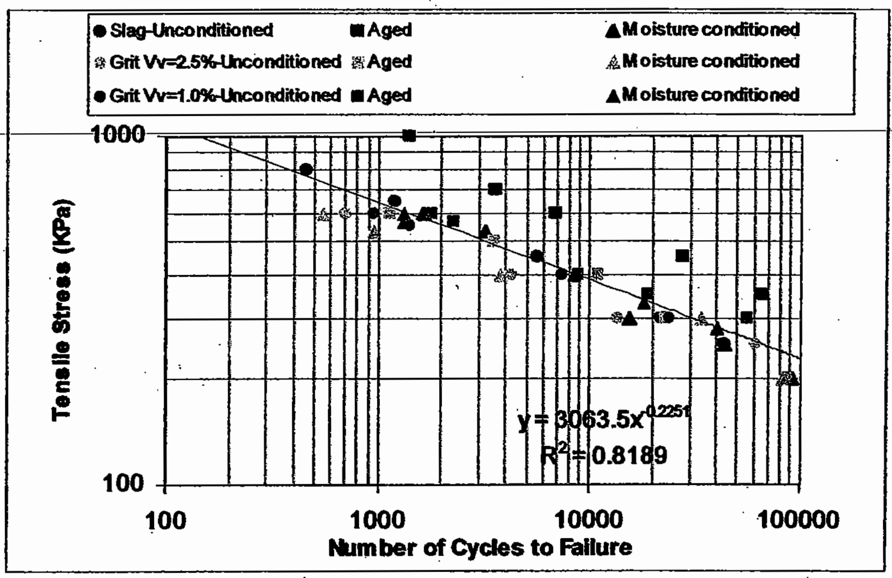


Figure 4-39 ITFT Results (Stress-Fatigue Lives, all data from SMA mixtures)

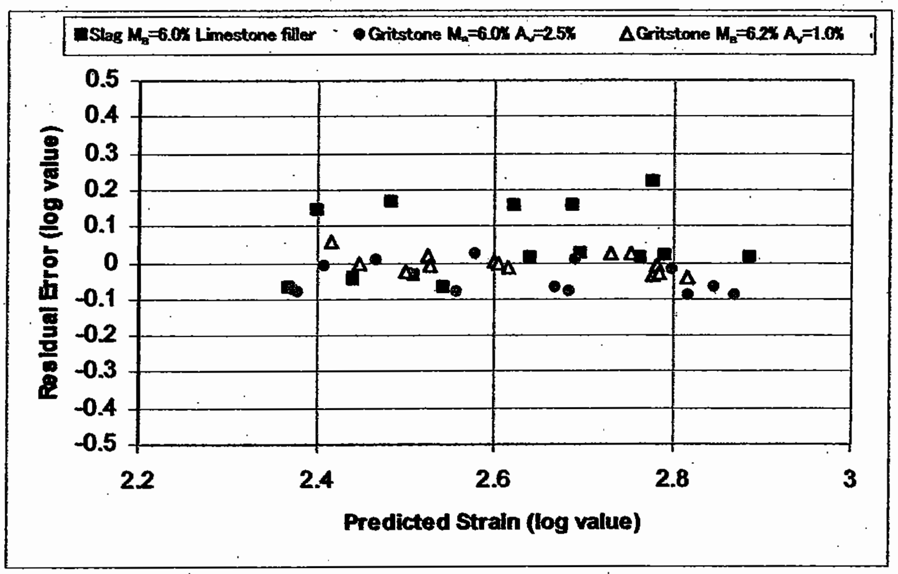


Figure 4-40 Residual Errors on Stress-Fatigue Lives for SMA mixtures

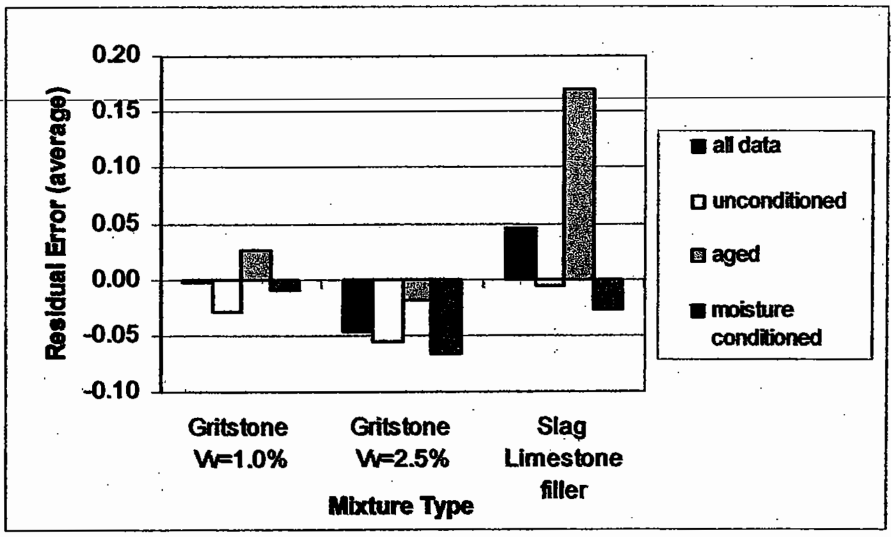


Figure 4-41 Average Residual Errors on Stress-Fatigue Lives for SMA mixtures

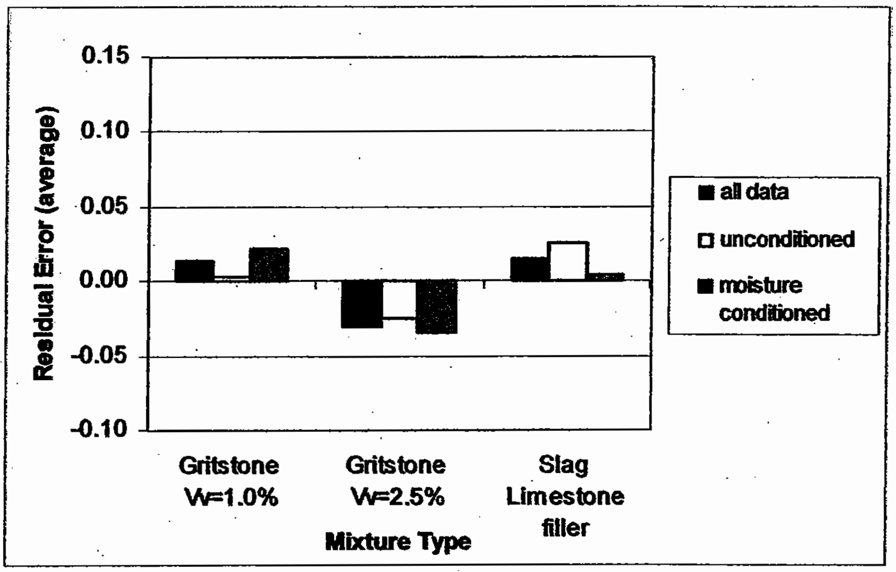


Figure 4-42 Average Residual Errors on Stress-Fatigue Lives for SMA mixtures (without aged samples)

Strain-Fatigue life

Influence of conditioning

Figure 4-43 and Figure 4-45 show the fatigue lives obtained from gritstone higher density mixtures and slag mixtures, respectively, and these are expressed as a relationship between tensile microstrain and number of cycles to failure. From these results, it can be thought that there is not much difference between each. However, results obtained from the gritstone lower density mixtures shown in Figure 4-44 indicate that the moisture conditioned samples would have a longer fatigue life than that of the other conditioned samples. It is known that, normally, the fatigue life of bituminous mixtures approximately complies with the strain criteria. It seems that only the low density gritstone moisture conditioned samples do not comply with the criteria, although the reason for this is not clear.

Influence of Different Aggregate Type

These data were rearranged in the same manner as described previously to understand the advantage and disadvantage of each mixture in terms of strain fatigue life. The results are shown in Figure 4-46, Figure 4-47, and Figure 4-48. Because the moisture conditioned gritstone lower density mixtures behaved different from the others, the data were also rearranged not using all the moisture conditioned samples and this is shown in Figure 4-49. As can be seen, slag mixtures show less resistance to fatigue cracking, which is in contrast with the stress-fatigue life results.

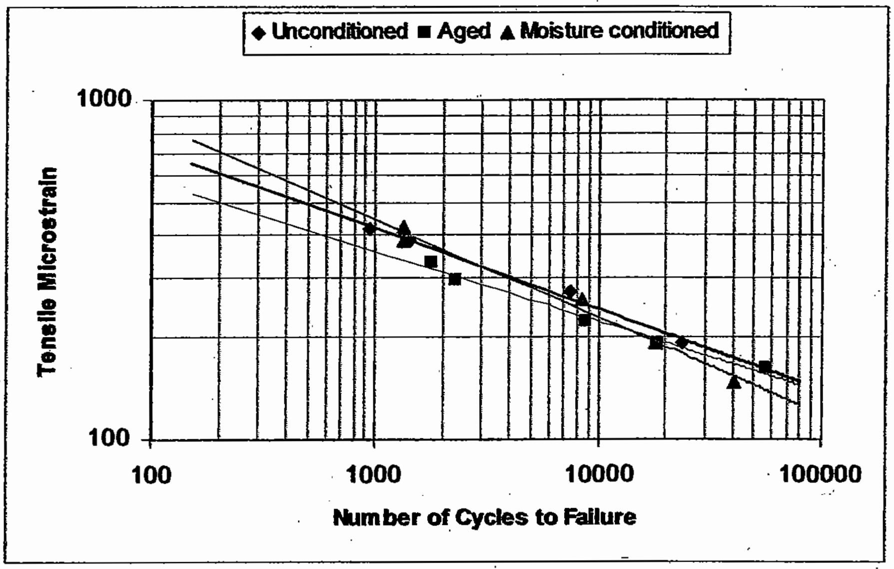


Figure 4-43 Strain-Fatigue Lives (SMA gritstone Vv=1.0%)

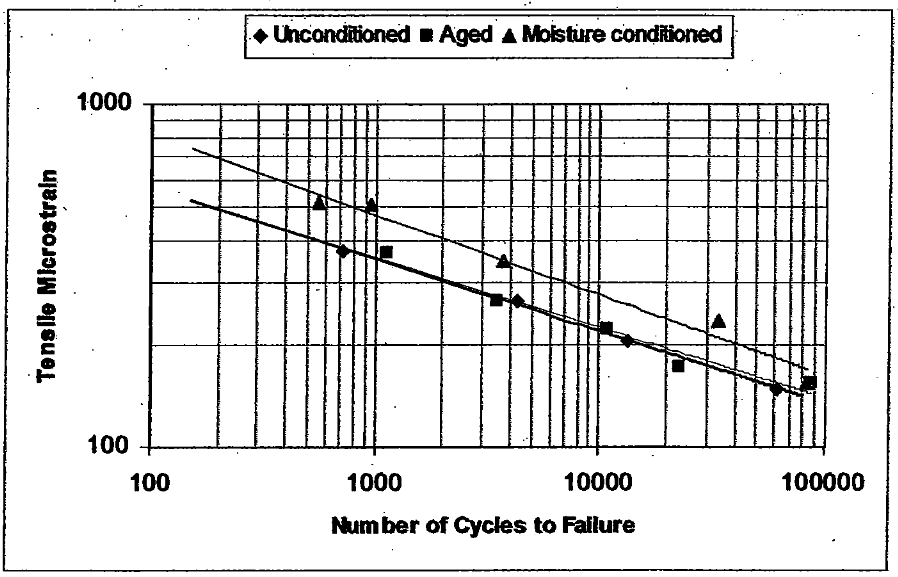


Figure 4-44 Strain-Fatigue Lives (SMA gritstone Vv=2.5%)

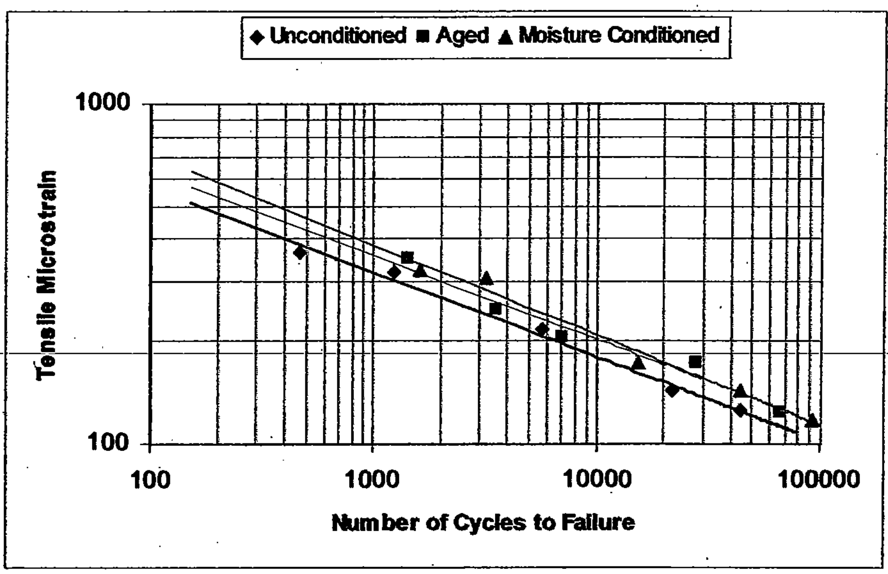


Figure 4-45 Strain-Fatigue Lives (SMA slag mixture)

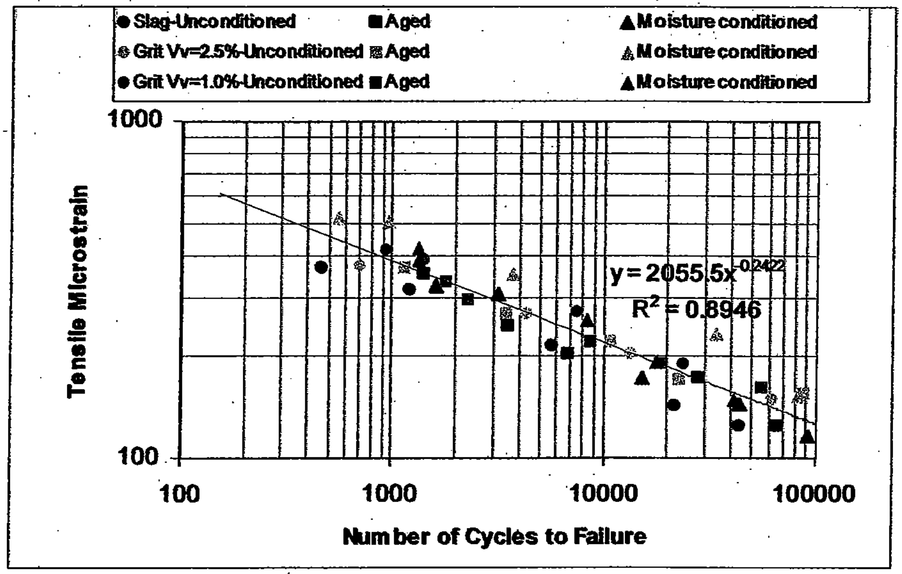


Figure 4-46 ITFT Results (Strain-Fatigue Lives, all data from SMA mixtures)

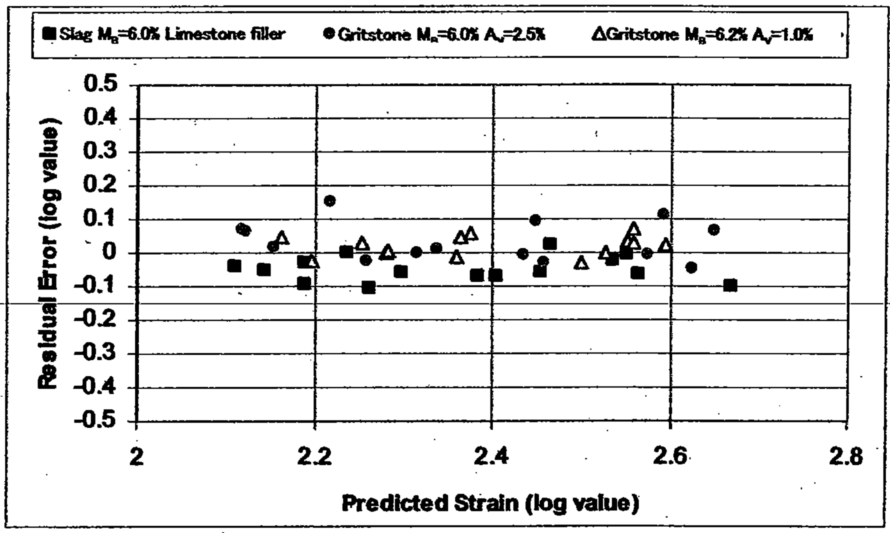


Figure 4-47 Residual Errors on Strain-Fatigue Lives for SMA mixtures

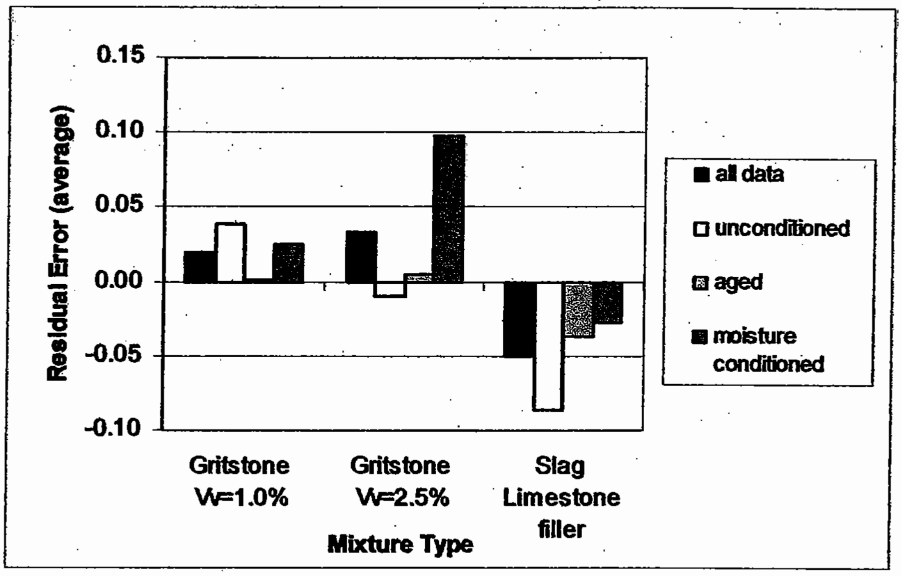


Figure 4-48 Average Residual Errors on Strain-Fatigue Lives for SMA mixtures

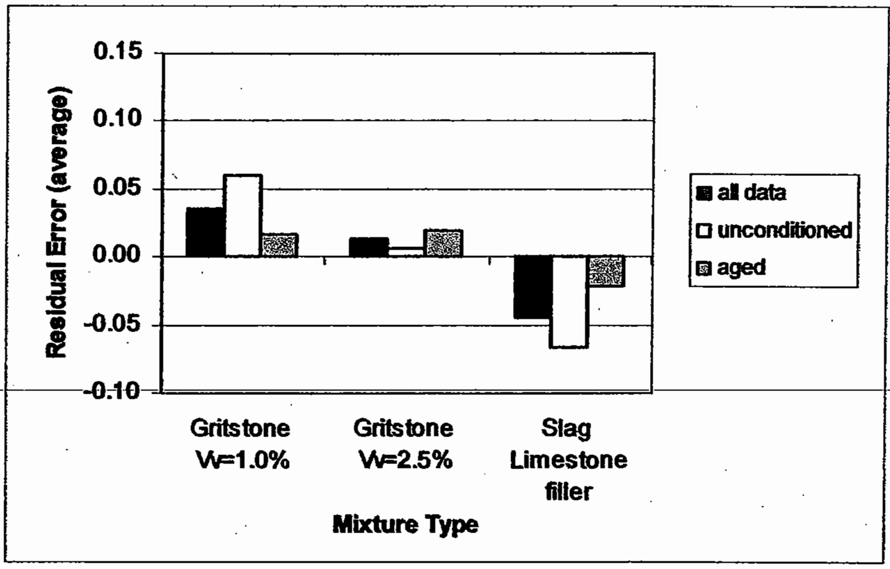


Figure 4-49 Average Residual Errors on Strain-Fatigue Lives for SMA mixtures (without moisture conditioned samples)

28mm DBM

Stress-Fatigue life

Influence of conditioning

Figure 4-50, Figure 4-51, and Figure 4-52 show the ITFT results obtained from DBM mixtures. As can be seen, longer lives were obtained from aged samples in each mixture, although, for the limestone + glass mixture, the aged samples tend to fail as same as the other conditioning samples at a high stress level. For the limestone mixture, the fatigue life of the moisture conditioned sample is better than for the unconditioned samples. Water sensitivity ITSM tests also showed the good performance of the limestone mixture. In contrary, the limestone + glass mixture exhibited poor performance on moisture conditioning samples. This could be related with the stripping problem of glass aggregate, which will be discussed in Chapter 5. For the slag mixture, aged samples exhibited good resistance to fatigue cracking because of high stiffness of aged samples, while moisture conditioned samples behaved similar to unconditioned samples although the water sensitivity ITSM test showed poor performance of the slag mixtures.

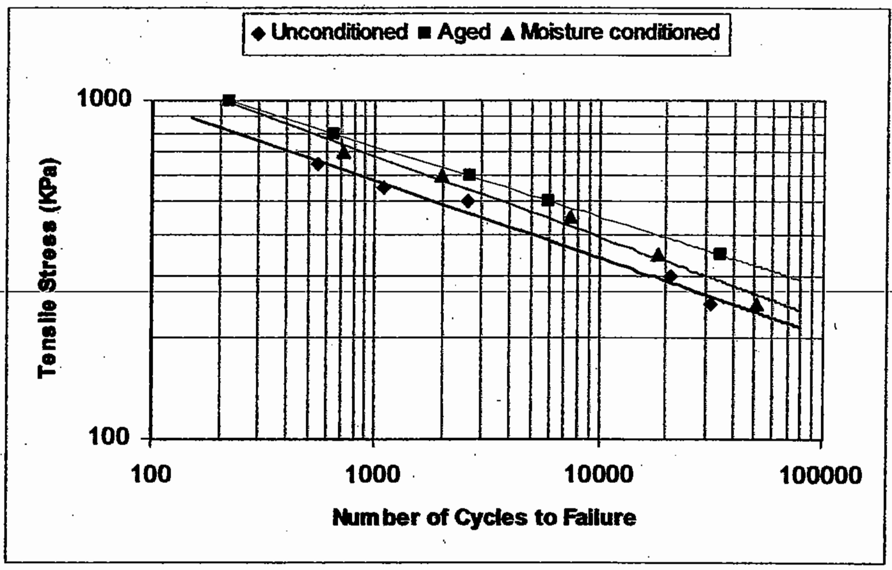


Figure 4-50 Stress-Fatigue Lives (DBM limestone mixture)

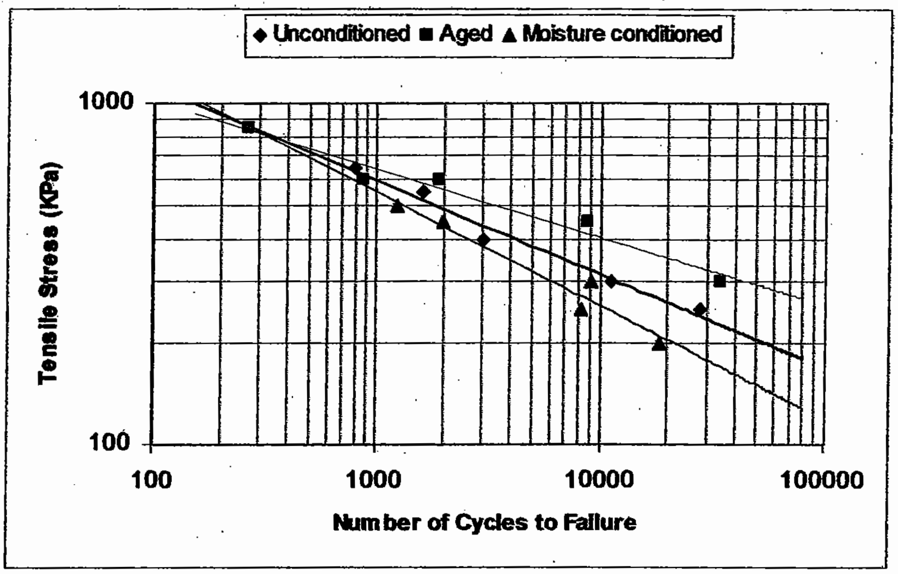


Figure 4-51 Stress-Fatigue Lives (DBM limestone + glass mixture)

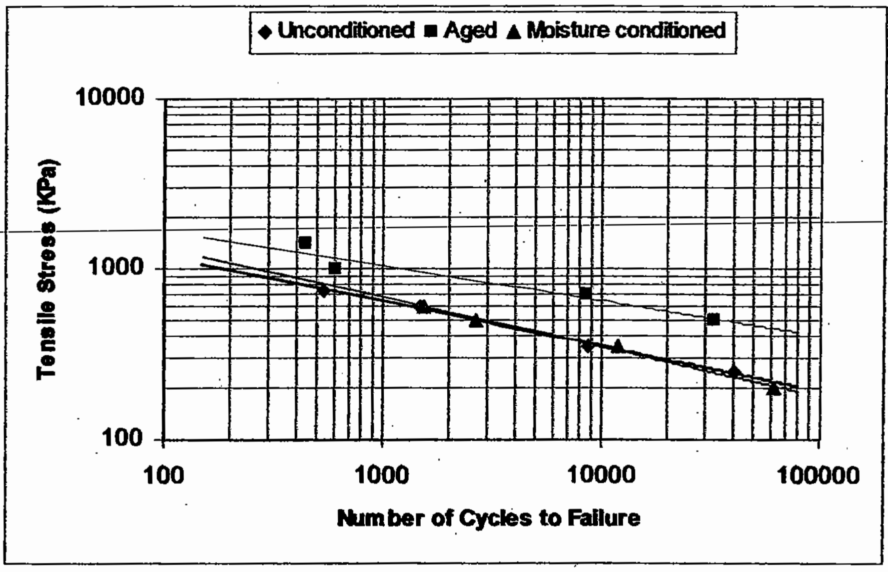


Figure 4-52 Stress-Fatigue Lives (DBM slag mixture)

Influence of Different Aggregate Type

Figure 4-53 shows all the results obtained from fatigue tests carried out on 28mm DBM mixtures. As can be seen, because of its high stiffness, aged slag mixture samples behaved quite different from the others. The data were rearranged in the same manner as described previously to understand the advantage / disadvantage of individual mixtures and the results are shown in Figure 4-54 and Figure 4-55. Data were also rearranged not using the aged samples to eliminate the superiority of aged slag mixtures and this is shown in Figure 4-56. From these results, it was found that the moisture conditioned limestone + glass samples would have poor resistance to fatigue cracking.

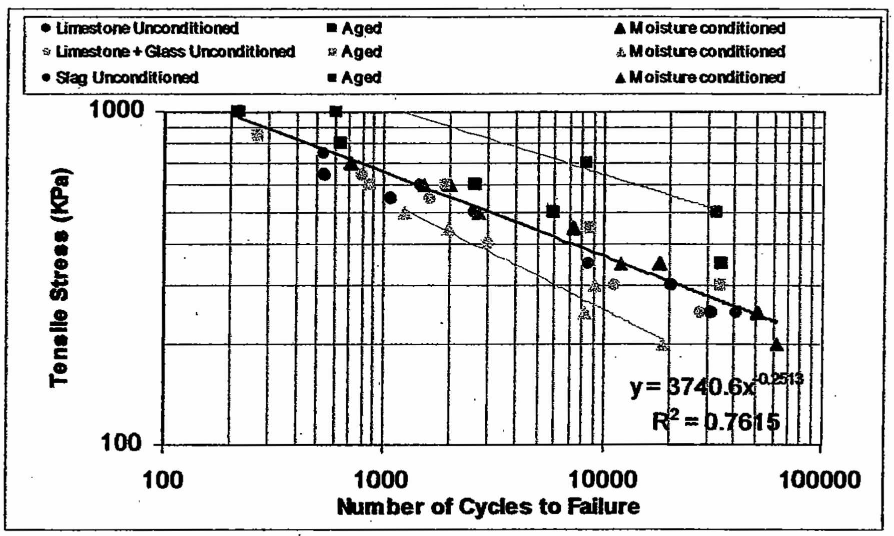


Figure 4-53 ITFT Results (Stress-Fatigue Lives, all data from DBM mixtures)

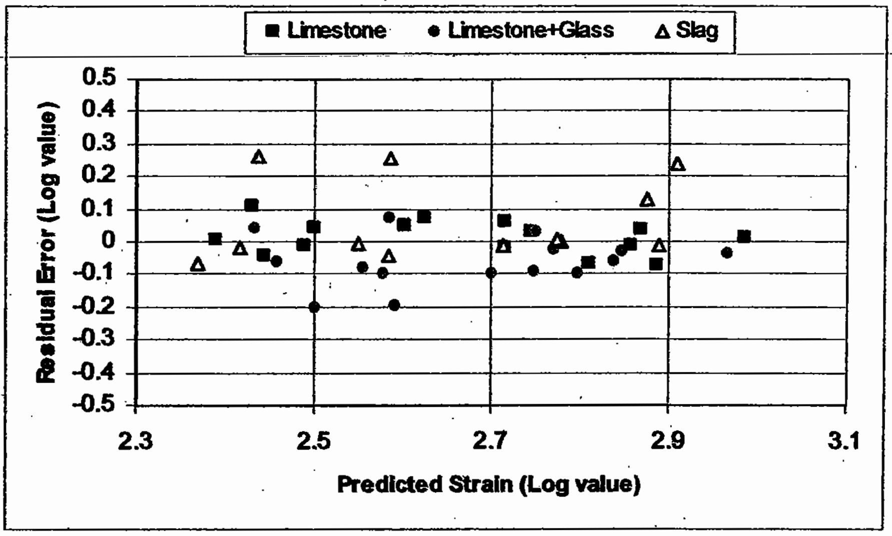


Figure 4-54 Residual Errors on Stress-Fatigue Lives for DBM mixtures

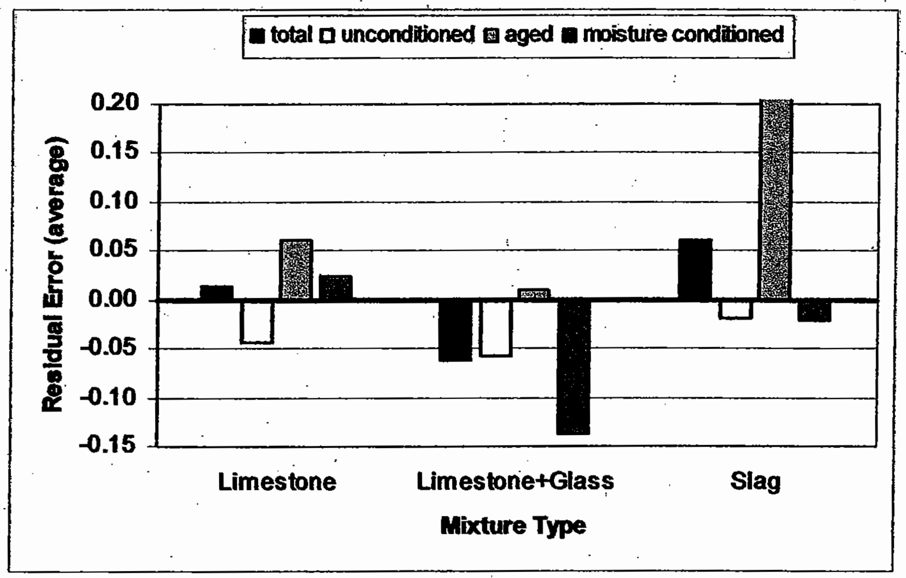


Figure 4-55 Average Residual Errors on Stress-Fatigue Lives for DBM mixtures

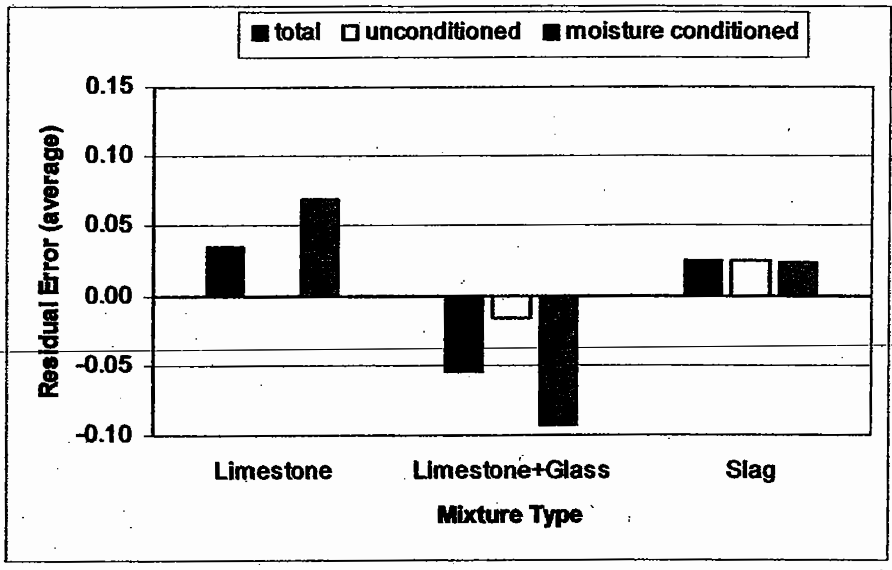


Figure 4-56 Average Residual Errors on Stress-Fatigue Lives for DBM mixtures (without aged samples)

Strain-Fatigue life

Influence of conditioning

Figure 4-57, Figure 4-58, and Figure 4-59 show the ITFT results obtained from DBM mixtures, which are expressed as a relationship between tensile microstrain and number of cycles to failure. The results obtained from both limestone mixtures and slag mixtures show that the moisture conditioned samples resulted in better performance than unconditioned samples. Although the reason for this is not clear, the results show that, together with the results obtained from SMA mixtures, moisture conditioning would give a better resistance to fatigue cracking. However, the results of limestone + glass mixtures did not show this trend. It may be that the stripping of aggregates affected this result.

In the limestone mixtures, the aged samples resulted in a slightly worse performance than that of the unconditioned samples. Both limestone + glass mixtures and slag mixtures indicate that, at a high strain level, aged samples would fail earlier than unconditioned samples.

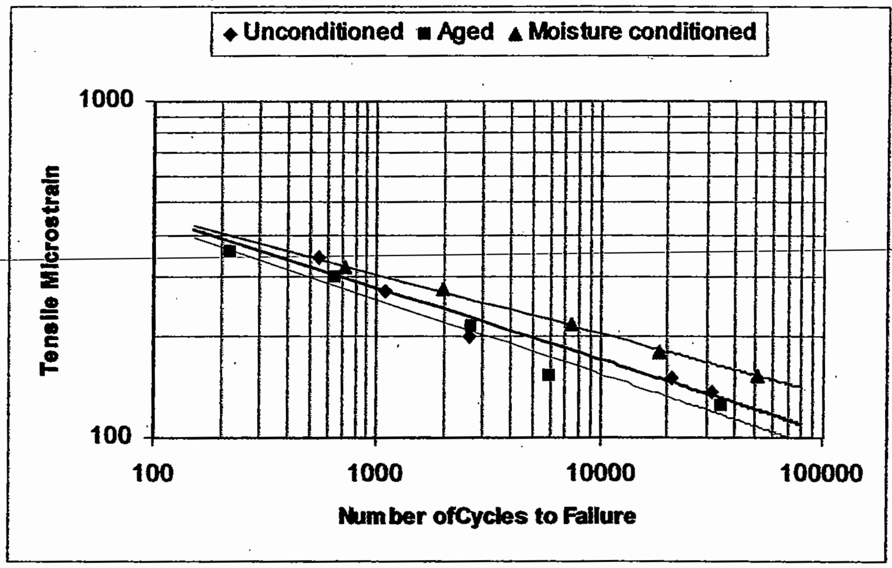


Figure 4-57 Strain-Fatigue Lives (DBM limestone mixture)

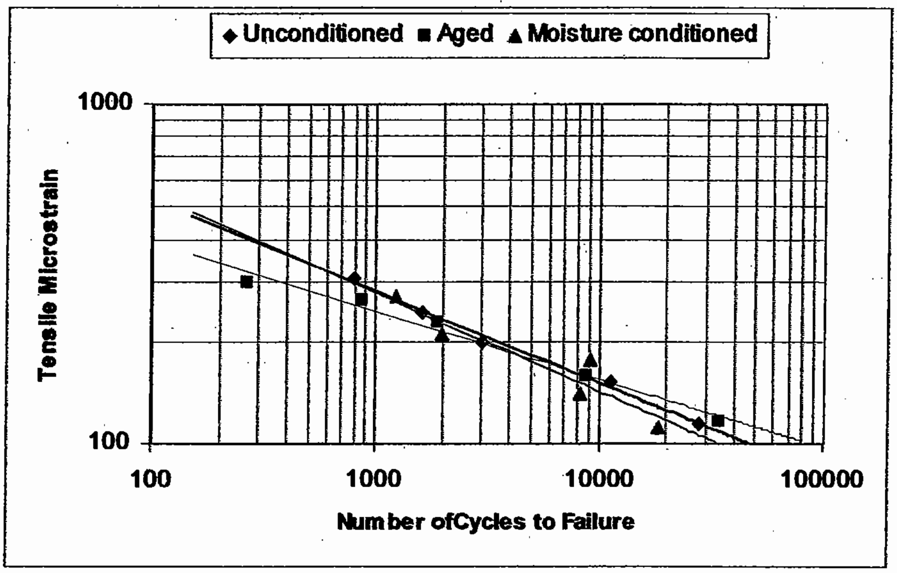


Figure 4-58 Strain-Fatigue Lives (DBM limestone + glass mixture)

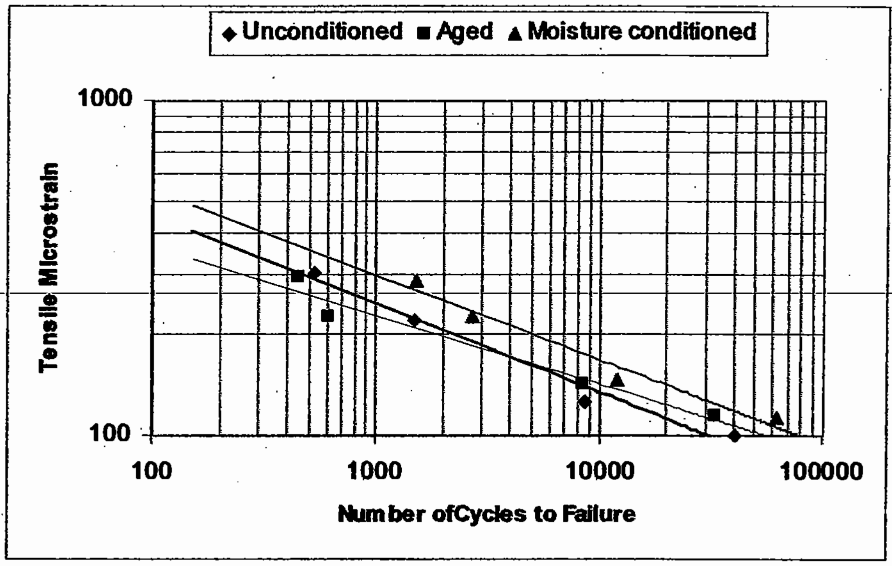


Figure 4-59 Strain-Fatigue Lives (DBM slag mixture)

Influence of Different Aggregate Type

These data were rearranged in the same manner as described previously to understand the advantage and disadvantage of each mixture in terms of strain fatigue life and the results are shown in Figure 4-60, Figure 4-61, and Figure 4-62. Because the moisture conditioned limestone mixtures resulted in much better performance than the others and it seemed that these samples behaved differently from the others, data were also rearranged not using all the moisture conditioned samples and this is shown in Figure 4-63. As can be seen from those results, slag mixtures show less resistance to fatigue cracking, which is in contrast with stress-fatigue life results.

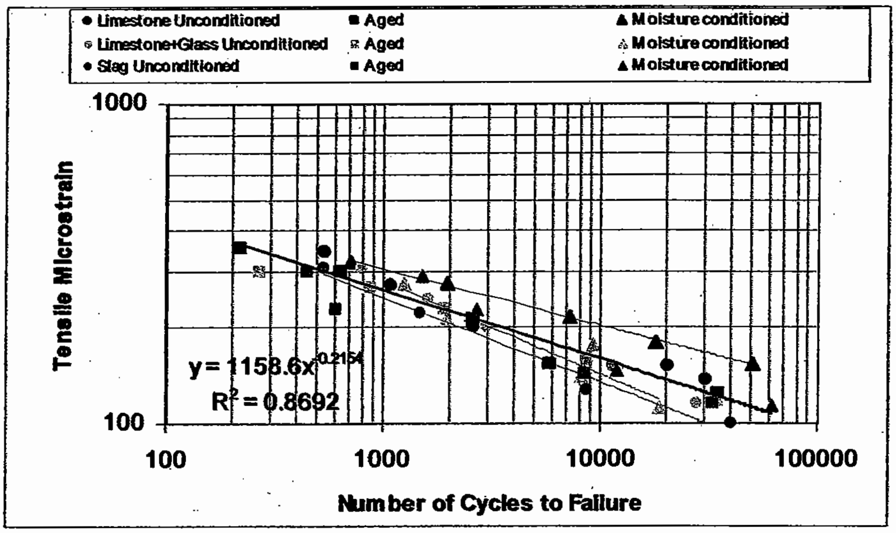


Figure 4-60 ITFT Results (Strain-Fatigue Lives, all data from DBM mixtures)

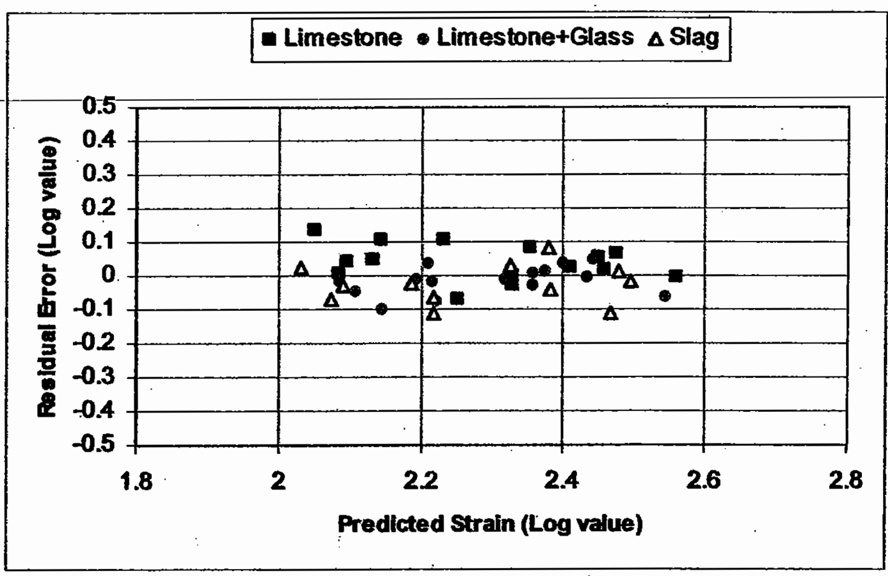


Figure 4-61 Residual Errors on Strain-Fatigue Lives for DBM mixtures

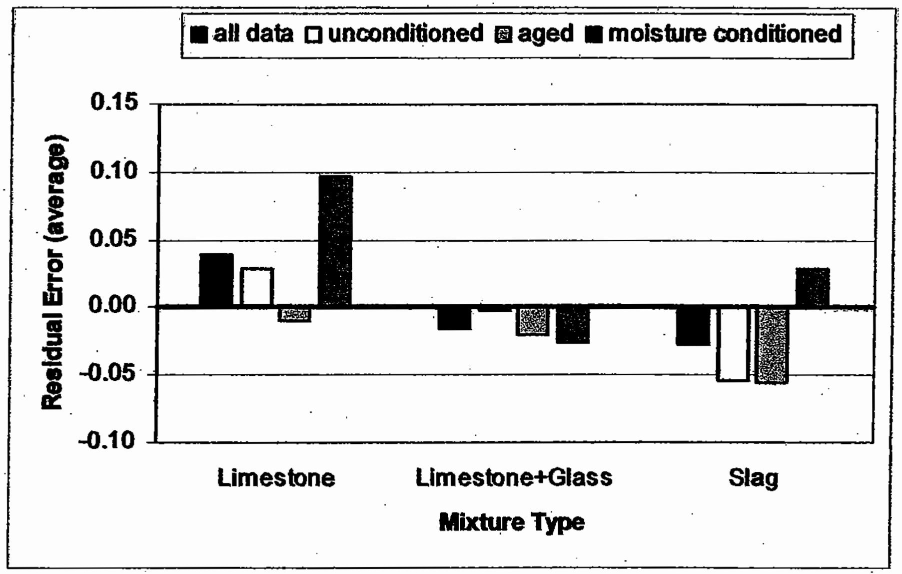


Figure 4-62 Average Residual Errors on Strain-Fatigue Lives for DBM mixtures

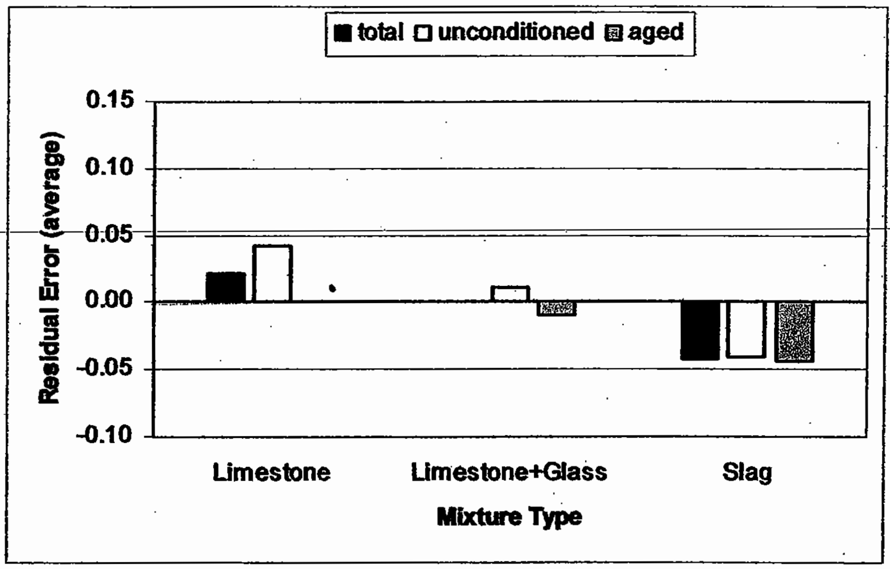


Figure 4-63 Average Residual Errors on Strain-Fatigue Lives for DBM mixtures (without moisture conditioned samples)

Process to failure

Normally, during the ITFT, data are stored as a relationship between vertical deformation of a sample and number of cycles. Figure 4-64 shows the data obtained from lower stress (strain) samples plotted in log-log scale graph. In each mixture, a similarity is found in the slope of the data. Namely, between 100 cycles and 10000cycles the change in vertical deformation of each sample in every mixture is similar, and is not influenced by the different conditioning. Furthermore, the limestone and limestone + glass mixtures have similar slopes to each other, while the slope of slag mixtures is more gentle than those of other mixtures. The point where the gradient of the line changes is regarded as a crack initiation point. Crack propagation occurs from this point to failure. Both limestone mixture and limestone + glass mixture would have reasonable crack propagation time, however, slag mixture might have very short time because the slope of the line is quite steep. This indicates that the slag mixtures became more brittle materials than the other mixtures. If those samples failed at the same number of cycles, slag mixtures would take a more gradual slope than the other mixtures until reaching the crack initiation point, then reach failure point more quickly than the other mixtures.

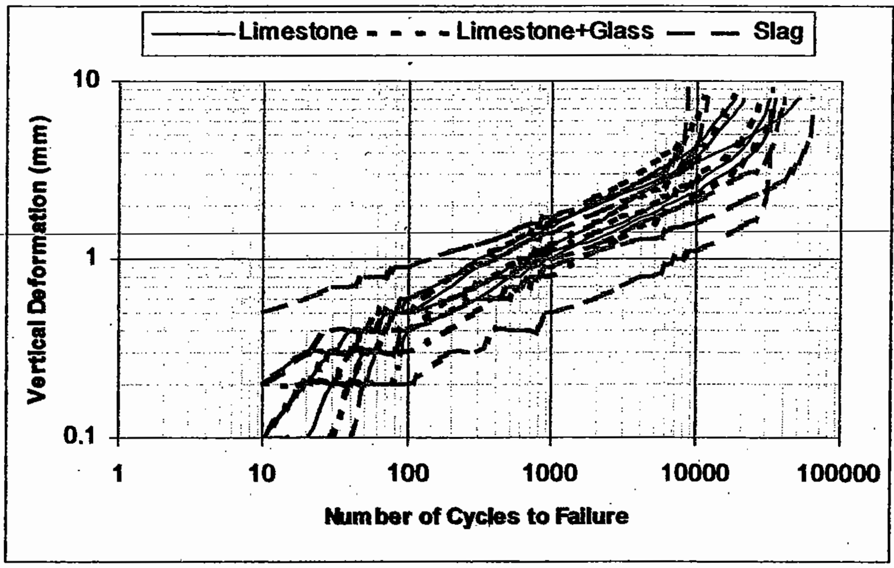


Figure 4-64 Processes to Fatigue Cracking for DBM mixtures

4.3.4 Conclusion

Different behaviour has been found in stress-fatigue/strain-fatigue life. For example, slag mixtures showed good performance in stress-fatigue and, on contrary, slag mixtures showed poor performance in strain-fatigue life. In terms of slag mixtures, it takes a long time to reach the initial fatigue point and thereafter the fatigue crack progresses rapidly. It can be said from these results that the slag mixtures would have no problems when the function of the pavement required is governed by stress, however, the pavement governed by strain, e.g., a pavement on a support which tends to bend easily, could have a fatigue crack problem. This is because the strain occurring in the surface of pavement is not only dependent on the stiffness of the surfacing material itself but also on the whole structure of the pavement.

28 DBM limestone mixtures showed good performance under both stress and strain fatigue. Moisture conditioning might have some effect on limestone mixture behaviour.

The mixtures incorporating glass aggregate exhibited somewhat poor performance in regard to fatigue cracking. This may be due to the smooth surface aggregate texture

4.3 References

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Chapter 5 Stripping of Bituminous Mixtures

5.1 Definition of Stripping

Fatigue cracking and permanent deformation are regarded as the major distresses of a pavement. Another major distress occurring in a pavement, whose cause may be derived from physical or chemical properties of aggregate and bitumen rather than mechanical properties of bituminous mixtures, is stripping. The definition of stripping is found in some literature in different expressions [1]. It seems that stripping used to be defined as the physical separation of asphalt cement (bituminous binder) from aggregate surface due to moisture induced damage causing the lack of adhesion between aggregate and binder. However, recent studies showed [2,3] that the weakening of adhesion and cohesion due to moisture induced damage would occur within binder and / or aggregate. Therefore, stripping would be defined as the physical separation of a part of pavement from its main body (structure) because of the weakening of adhesion and / or cohesion occurring between binder and aggregate surface and / or within a binder / aggregate.

5.2 Mechanism of Stripping

There are 3 possible states that would make stripping phenomenon;

1. loss of adhesion between aggregate surface and binder
2. loss of cohesion within binder
3. bond disruption within aggregate

Loss of adhesion between aggregate surface and binder

The strength of adhesion between aggregate surface and binder would be dependent on the bond energy generated from both aggregate and binder. The stronger the bond energy, the greater the resistance to stripping would be expected. There are three possible theories for the bonding; surface energy concept, mechanical concept and chemical reaction concept [4]. The surface energy concept is explained by the surface tension (cohesivity) and interfacial tension (adhesivity). In terms of the bonding of binder and aggregate, a better bond would result when there is a low surface tension and a high interfacial tension. This is the reason for using amine as an anti-stripping agent because it will reduce the surface tension of bituminous binders. The mechanical concept is explained by the physical properties of aggregate, such as surface texture. A rough surface texture would provide a better bond due to the greater surface area per unit volume of aggregate. The chemical reaction concept is because of the presence of reactive components in both the bituminous binder and the aggregate, bonding would be generated by the results from the reaction of these components. The bond energy would be a combination of these theories. Concerning the chemical reaction concept, one report showed [2] that the presence of cations such as iron, magnesium, calcium and aluminium at the aggregate surface would enhance the bond energy. Some limestone is known to have a high resistance to stripping and this is due to the formation of water insoluble bonds between calcium sites on the aggregate with bitumen constituents. On the other hand, the presence of potassium and sodium would decrease the bond because the reaction between these substance and constituents in bituminous binder would generate water soluble substances.

Loss of cohesion

El Hussein reported [3] that debonding caused by adhesion failure occurred mainly between the asphalt matrix (mixture of bituminous binder and fine materials, such as fine aggregate and filler) and the coated aggregate particles. The coarser fractions of aggregates are covered by a very thin film of bitumen during mixing. This thin bituminous film and the bituminous materials mixed with fine materials would have different characteristics. Moisture could enter the interface between coated aggregate and asphalt matrix and result in failure. (The author insisted that this is adhesion failure because the thin bituminous film covering the coarse aggregate could be regarded as a part of aggregates, while Graf [13], who also reported similar phenomenon concluded this was the cohesive type of failure.)

Disruption within aggregate

Intensive research work has been done on stripping by SHRP [4] and it has revealed that the bond disruption takes place, not mainly at the interface between bitumen and aggregate, but usually within the aggregate. The reason for this is that once the bitumen has wetted the microscopically rough aggregate surface and partially penetrated the porous subsurface, the application of a separating force is more likely to cause failure within the bulk aggregate or bitumen or both rather than at the bitumen aggregate interface. The results of Surface Analysis by Laser Ionization

(SALI) showed [2] that there was substantial amount of inorganic element derived from aggregate at the sub surface monolayers of debonded bitumen. Dissolution of cations, such as sodium, potassium and calcium was greater at the stripped area than unstripped area.

5.3 Test Methods for Evaluating Stripping

Qualitative evaluation

Boiling test

The boiling test has been used for a long time, especially in the U.S.A, because this test can be carried out easily and in a short time and it has been standardised as ASTM-D3625 - 96 [5]. Uncompacted bituminous coated aggregate are placed in boiling water for 10 minutes. After 10 minutes boiling and then cooling down to the room temperature, water is decanted and the sample is placed on a white paper towel. Potential for stripping is evaluated by the visual observation. Because the result would depend on the subjectivity of observer, and correlation between field performance and the test results has not been established, the standard states that this test will be used as an "indicator of the relative susceptibility of bituminous coated aggregate to water".

Aggregate / binder compatibility test

This test method has been developed in Scandinavia and it has been standardised as standard prEN 12697-11 in European [6]. Bitumen coated single sized aggregates (8 / 11mm or 5.6 / 8mm fraction with approximately 3% or 3.4% binder content respectively) are placed in glass bottle with distilled water having a temperature of 5°C. The bottle containing water and sample is placed on a rolling bottle machine providing a rotation speed of 60 r/min or 40 r/min. Visual observations are made after 5 hours, 24hours, 48hours and 72hours rotation. Similar to the boiling test, the result of the observation is expressed as the degree of bitumen coverage.

Quantitative evaluation

Modified Lottman test (Splitting test)

This is the currently most used test method for evaluating the stripping potential of bituminous mixtures. The tensile strength of both unconditioned and moisture conditioned specimens are measured and the judgement whether the material is susceptible to moisture damage or not is determined by the ratio between the unconditioned tensile strength and moisture conditioned tensile strength (TSR). The theory of this test method is based on the splitting test for concrete. A monotonic axial load, at a rate of displacement of 50mm/minute, is applied to a specimen until failure. The indirect tensile strength is designated as below,

$$St = \frac{2 \times Pult}{\pi \times D \times t} \qquad (5.1)$$

Where, St = Indirect tensile strength (MPa)

Pult = Ultimate applied load required to fail specimen (N)

D = Diameter of specimen (mm), and

t = Thickness of specimen (mm)

The indirect tensile strength may be influenced by the rheology of binder, aggregate skeleton structure, density, and binder adhesion.

In the original Lottman test procedure, specimens are subjected to a freeze-thaw cycle and the tensile strength test is carried out at a temperature of 12.8°C. After Lottman, Tanicriffe modified the procedure with the soaking of specimens in a hot water bath (60°C) instead of a freeze-thaw cycle and the tensile strength test is carried out at a temperature of 25°C. This test method has been standardised as AASHTO T 283-89 [7] and according to the standard, the conditioning method should be selected either as a freeze-thaw cycle or as the soaking hot water bath, and the tensile strength test should be carried out at 25°C. A TSR > 70% was suggested by Lottman as an index for determining whether the sample is susceptible to moisture damage or not.

Although the conditioning procedure is designated in ASSHTO-T283, in this study the moisture conditioned tensile strength was determined using the specimens which were conditioned in accordance with the procedure stated in previous chapter.

Immersion wheel tracking test

This test method was originally developed in the U.K. in the 1950's [8]. Since stripping phenomenon can be thought to be derived from the combination of moisture induced damage and traffic load, this test would simulate realistic circumstance. The principle of this test is that three rectangular specimens are mounted on the apparatus and immersed in water and subjected to wheel tracking load. Vertical deformation (rut depth) is measured during the test. Normally the test lasts 7 days or until the time specimens fail. The temperature of the water can be selected in the range 40°C to 60°C. The wheel generates a vertical load of 181N and the wheel moves 25 cycles/minute with a stroke of approximately 280mm.

5.4 Test Results

5.4.1 Splitting

14mm SMA

Figure 5-1 shows the results of tensile strength obtained from the gritstone (M_B=6.0%) mixtures and slag mixtures. As can be seen, the tensile strength of the slag mixture is slightly higher than that of the gritstone mixtures. Increased strength was observed in aged samples in both mixture types. Especially, the slag mixture exhibited much higher tensile strength in aged samples, similar to the aged ITSM results. Moisture conditioned samples exhibited slightly different behaviour. Thus, the gritstone mixture decreased its strength, while the slag mixture increased. Figure 5-2 shows the TSR value of these results. The resistance to moisture induced damage of the slag SMA mixture is better than that of the gritstone SMA mixtures, confirming the results of the water sensitivity ITSM tests presented in previous chapter.

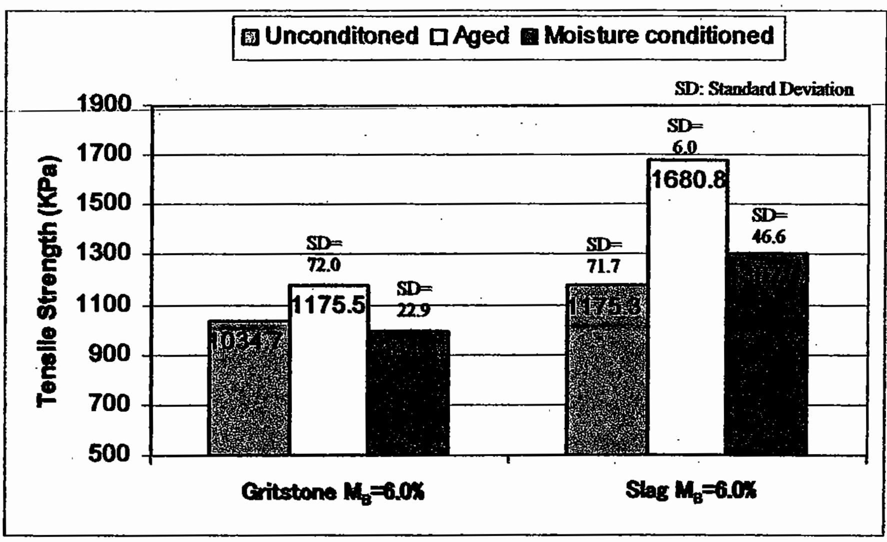

Figure 5-1 Splitting Test Results for SMA mixtures

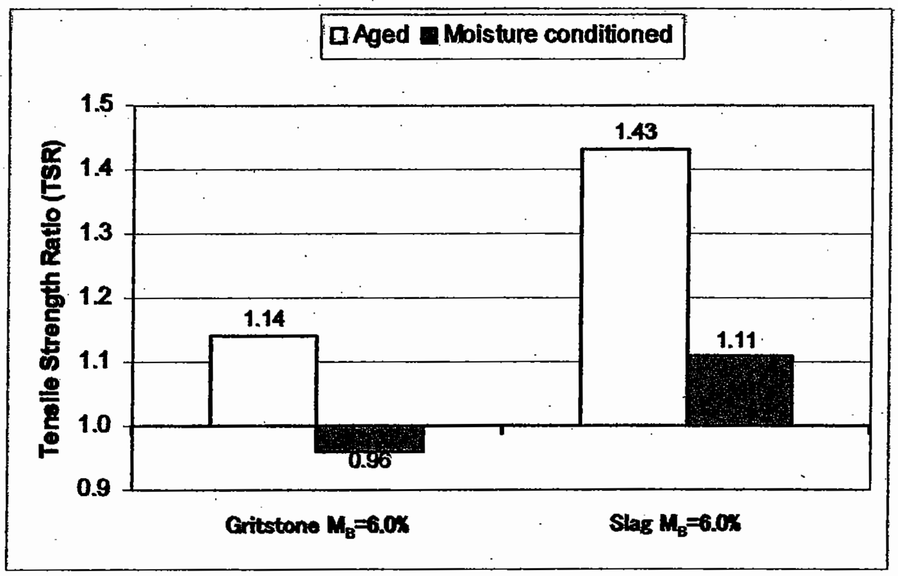

Figure 5-2 TSR Value for SMA mixtures

28mm DBM

Figure 5-3 shows the results obtained from limestone, limestone + glass, and slag (M_B=4%) DBM mixtures. As can be seen, the unconditioned tensile strength of slag (M_B=4%) and of the limestone + glass mixtures showed higher strength than the limestone mixture. Much increase in strength was found in aged slag specimens, which is a similar finding to that of the ITSM tests. In terms of moisture conditioned results, the limestone mixture maintained its tensile strength, while the limestone + glass and slag (M_B=4%) mixtures lost strength significantly. Figure 5-4 shows the tensile strength ratio (TSR) obtained from these results. It is clear that the limestone mixture was not affected by moisture conditioning, while both limestone + glass and slag (M_B=4%) mixtures are susceptible to moisture induced damage significantly.

In line with the test results presented in the previous chapter, the limestone mixture exhibits good resistance to moisture induced damage. It is known that some limestones are resistant to moisture damage, therefore it can be assumed that the limestone employed in this research is not an exception.

As described in Chapter 2, stripping is the one of major problems arising from glass aggregate use in bituminous mixtures. The results showed clearly the potential for the stripping of this mixture. Reduction of tensile strength of limestone + glass mixture occurred only by moisture conditioning.

As mentioned in the previous Chapter, a 4% binder content for the slag mixture seemed to be insufficient to cover the aggregate adequately and this might cause a significant moisture induced damage of the mixture.

In addition to these three mixtures, limestone + glass with anti-stripping agent mixture, and slag (M_B=5%) mixtures were evaluated with respect to unconditioned and moisture conditioned tensile strength. These results are shown in Figure 5-5 and Figure 5-6. As indicated by the results, it seems that the use of anti-stripping agent could improve the resistance to moisture susceptibility of the limestone + glass mixture, although the unconditioned tensile strength of the mixture is slightly lower than that of the non-agent treated mixture. The unconditioned tensile strength of the slag mixtures also decreased as binder content increased, however, the resistance to moisture susceptibility appeared improved.

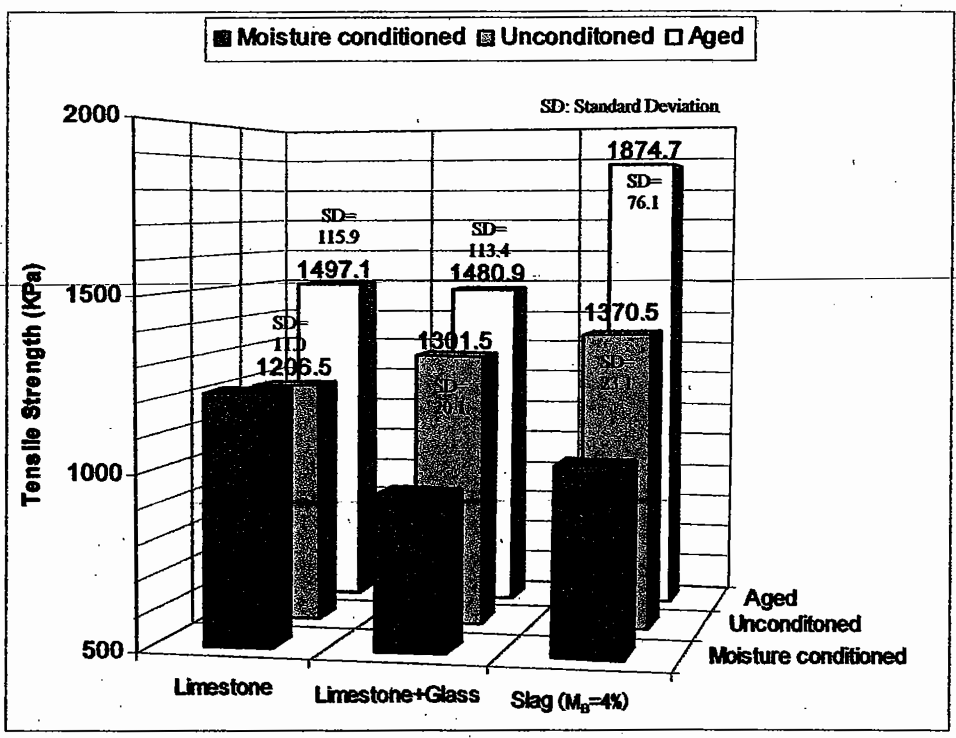

Figure 5-3 Splitting Test Results for DBM mixtures

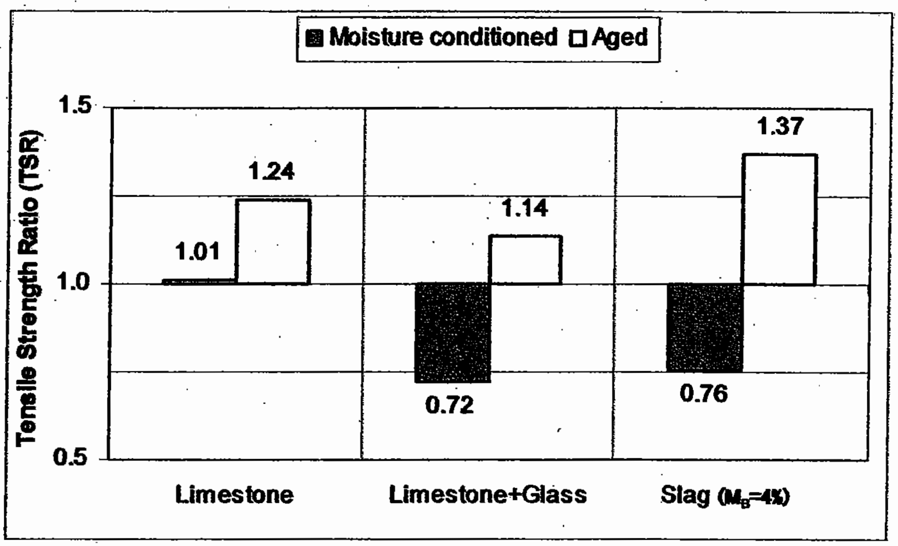

Figure 5-4 TSR Value for DBM mixtures

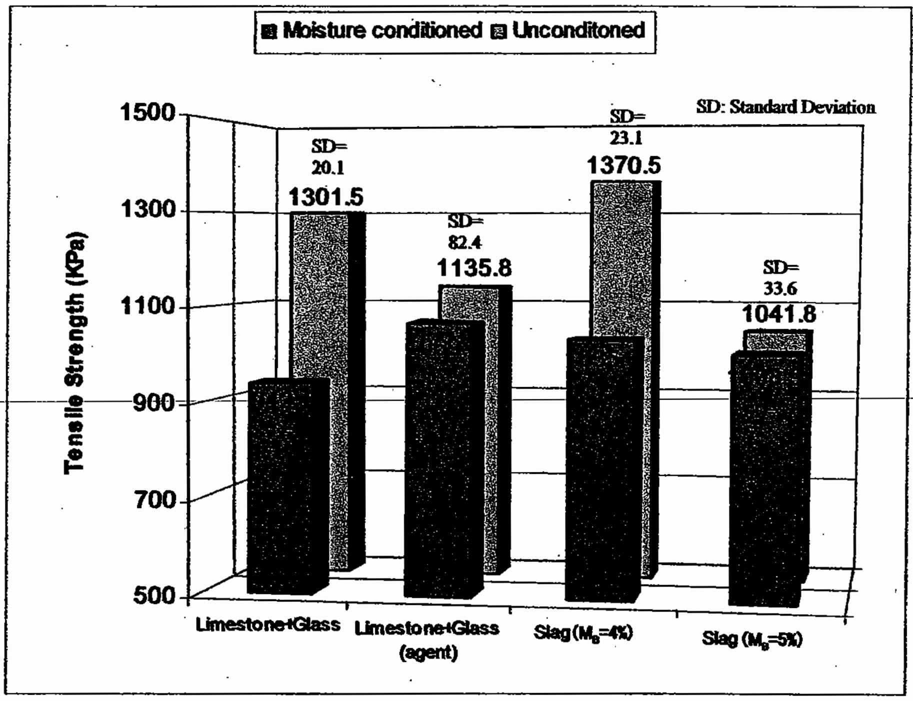

Figure 5-5 Splitting Test Results for DBM Mixtures (2)

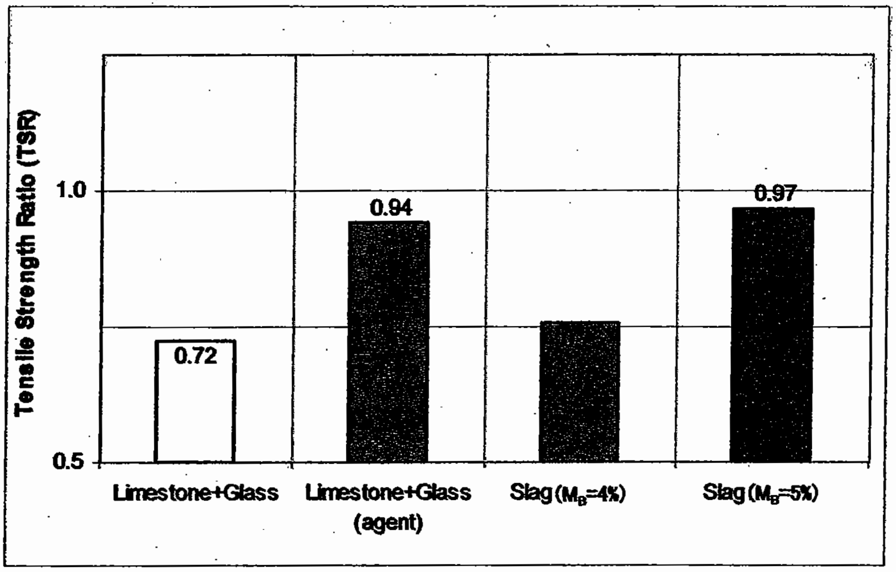

Figure 5-6 TSR Value for DBM Mixtures (2)

5.4.2 Immersion Wheel Tracking Test

14mm SMA

Immersion wheel tracking tests (IWTT) were carried out using gritstone (M_B=6.0%) and slag (M_B=5.5%) mixtures. Specimens for the tests were prepared from cutting slab samples which were fabricated in the same way as used to make core samples. At first, tests were carried out at a temperature of 40°C and for 7 days. After this duration, tests were continued for 5 days at a temperature of 50°C. It was observed that in some aggregates binder was stripped off from the aggregate surface. However, deterioration, such as the ravelling of aggregate, derived from this, was not observed in both mixtures. Figure 5-7 shows the rut depth measured during the tests. The rut resistant properties of these mixtures obtained from the IWTT were similar.

28mm DBM

The procedure of the IWTT was slightly amended because no stripping, nor deterioration derived from stripping, were observed in SMA mixtures. Specimens were mounted in the test machine and immersed in hot water for 16hours (overnight) having a temperature of 50°C which seemed to be a maximum temperature to carry out the test. Tests were carried out at a temperature of 50°C for 5days. Similar to the results of the SMA mixtures, deterioration derived from stripping was not observed in both types of mixtures. Figure 5-8 shows the rut depth measured during the test. As can be seen, the mixture incorporating glass aggregate had slightly greater rut depth than the other mixture.

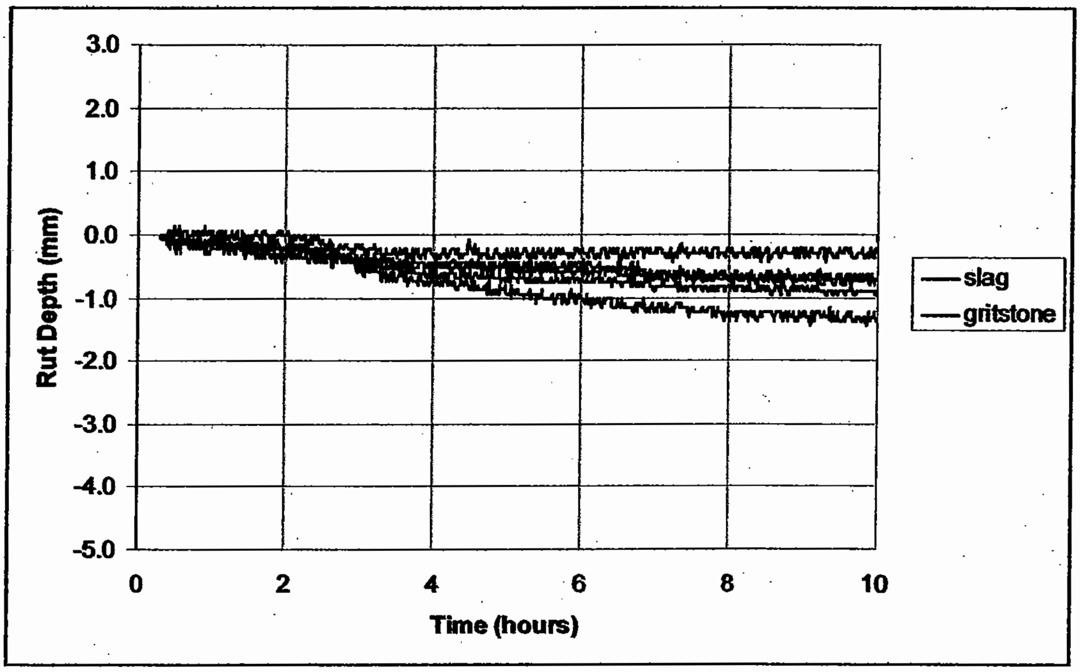

Figure 5-7 IWTT Results for SMA Mixtures

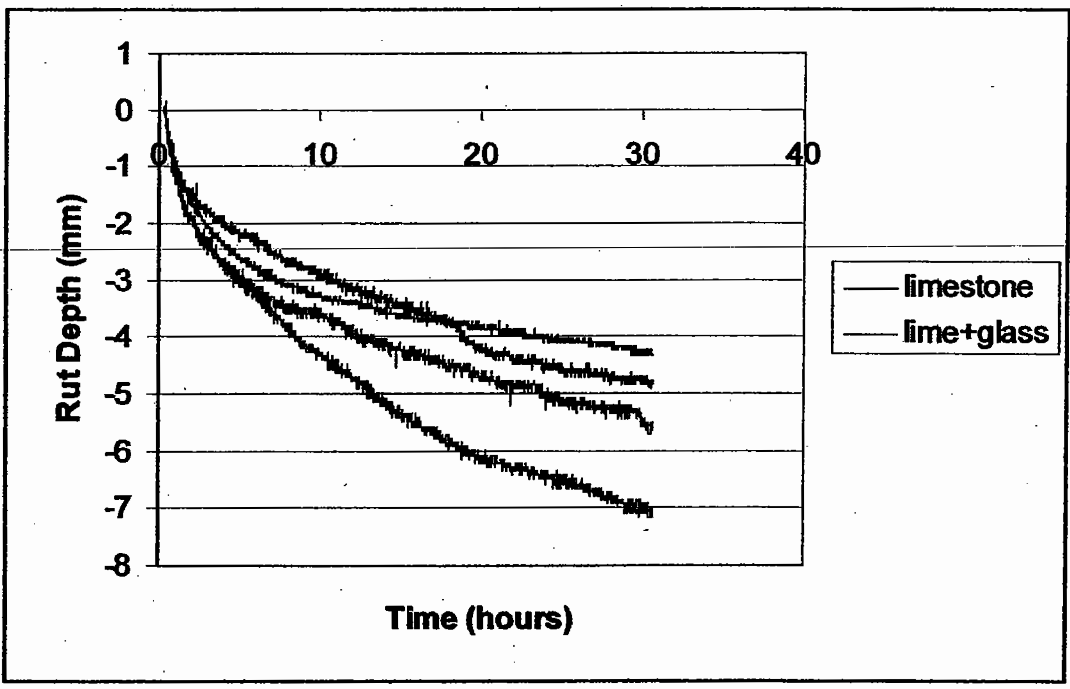

Figure 5-8 IWTT Results for DBM mixtures

5.5 Conclusion

It was found that the SMA mixtures retained tensile strength after moisture conditioning or ageing. Even the SMA mixture containing slag exhibited better performance than the gritstone SMA mixture. The slag DBM mixture reduced the tensile strength after moisture conditioning, in contrast to the result of SMA mixture. Furthermore, the relationship between the retained tensile strength of the slag mixture and the binder content (film thickness) was verified using increased binder content mixture. As the binder content increase, the tensile strength can be retained, even though the initial tensile strength decreased.

Excellent performance was obtained from the limestone DBM mixture. Good performance was also obtained from the moisture conditioned ITSM tests for the limestone DBM mixture. In line with these results, the limestone aggregate should have some good effect on moisture conditioning.

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Chapter 6 Conclusion

Three secondary aggregate combinations have been assessed in this laboratory study. These combinations have consisted of coarse primary aggregate + fine glass cullet with and without an anti-stripping agent, steel slag coarse aggregate + blast furnace slag fine aggregate with either BFS filler or limestone filler and steel slag coarse aggregate + fine glass cullet. The performance of these secondary aggregate mixtures has been compared to that of conventional, primary aggregate mixtures using both a base material (28 mm DBM) and a surfacing material (14 mm SMA). All the mixtures have been designed to have similar volumetric proportions within each mixture type and the mechanical properties of stiffness modulus, resistance to permanent deformation and resistance to fatigue cracking have been determined in the material's unaged, aged and moisture conditioned states.

Mixtures that incorporate slag

The results obtained from the ITSM tests show that the unconditioned ITSM of bituminous mixtures containing slag and/or glass aggregates were satisfactory. The higher stiffness of the slag mixture is likely due to the different volumetric characteristics (effective binder content) caused by the vesicular surface texture of BFS aggregates. Ageing ITSM tests suggest that the binder hardening in slag mixtures would be accelerated by vesicular surface texture of BFS aggregates and chemical composition of steel slag aggregates. As a result of hardening of binder, the mixture would become a more brittle material. From water sensitivity test results of slag mixture, it was confirmed that whether or not the aggregates are covered by binder sufficiently is the important condition for performance in the water sensitivity test. The SMA slag and DBM slag mixtures indicate contradictory results with respect to the water sensitivity test. The slag mixture showed good performance while the DBM mixture showed poor performance. The reason could be that the binder content of SMA mixture is very high while that of DBM mixture is low, and also the BFS aggregate content of the SMA mixture is lower than that of the DBM mixture. Therefore, there could be adequate binder to cover the aggregate sufficiently in the SMA mixture, while there might not be in the DBM mixture. This could lead to the poor performance in the water sensitivity test of the slag DBM mixture. The slag

DBM mixture of which binder content was increased by 5% was used for the water sensitivity test and an improvement of resistance to moisture induced damage as binder content increases was found, although the initial stiffness modulus decreases. Therefore, it can be recommended that the determination of binder content shall to be carried out depending on the required performance. This can be concluded from the results of the permanent deformation tests. Thus, SMA slag mixtures showed poor performance and the DBM slag mixtures showed good performance. From these results, it is seen that the binder content of the slag mixture affects the result of the permanent deformation test and that the optimum binder content of SMA slag mixture can be less than 5.5% with respect to adequate permanent deformation response.

From the RLAT results, it could be thought that the susceptibility to permanent deformation of SMA slag mixtures is a problem, however, the Immersion Wheel Tracking Test results did not show a difference between slag and gritstone SMA mixtures. Because the total strain of the SMA slag mixture in the RLAT did not exceed 2%, rutting will not be a problem in practice.

In terms of fatigue cracking, slag mixtures showed good performance in terms of stress-fatigue and, in contrast, slag mixtures showed poor performance in terms of strain-fatigue life. Slag mixtures take a long time to reach the initial fatigue point and thereafter the crack progresses rapidly. It can be said from these results that the slag mixtures would have no problems when the function of pavement required is governed by stress, however, the pavement governed by strain, e.g. a pavement on a support which tends to bend easily, could have a fatigue cracking problem, because the strain occurring in the surface of the pavement is not only dependent on the stiffness of the surfacing material itself, but also on the whole structure of the pavement.

Mixtures that incorporate glass

Although the moisture susceptibility of the glass aggregate mixtures was greater than the control mixture, probably due to the smooth surface texture of the glass, nevertheless, in the light of the excellent performance of limestone mixtures, the limestone + glass mixture exhibited a rather good performance for moisture susceptibility in terms of stiffness modulus. The results from the mixture incorporating anti-stripping agent show that it slightly improves the resistance to moisture susceptibility.

On the other hand, the glass mixtures exhibited a poor performance in the permanent deformation test. The reason, it is thought, that the smooth surface texture of the glass aggregate resulted in less aggregate interlock and surface friction. Even the mixture using anti-stripping agent did not have an improved resistance to rutting. Although the total strains were still below the acceptable limit, the use of glass aggregate in bituminous mixtures would have a problem with regard to the permanent deformation property, because the results obtained from the IWTT showed that the rutting performance of the glass mixture was inferior to that of the control mixture.
The fatigue performance of the limestone + glass aggregate mixture was found to be comparable to that of the control mixture.

Fatigue Cracking
Different behaviour has been found in regard to stress-fatigue relative to strain-fatigue life.
Similar strain-fatigue life behaviour was observed from different conditioned samples. However, 28 DBM limestone mixtures showed good performance for both stress and strain fatigue life and it seems that the moisture conditioning makes limestone mixtures give excellent performance against fatigue cracking.

Design
Test performance was evaluated using volumetrically designed mixtures. To achieve the objective of this project, volumetric design procedure needs to be applied because of different specific gravity of secondary aggregates. When using aggregates having very different specific gravity from conventional aggregates, the volumetric design procedure should be applied in practice otherwise the mixture might become a different type of mixture.