Current and Future Research topics for Europe identified by the COST 337 Action

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ABSTRACT: Until recently, unbound granular materials used for road pavements have received less research interest than other pavement materials. In many countries road pavement research has concentrated on materials for the most heavily trafficked roads and research on pavement materials - including granular materials - for other road categories, was often given priority. In addition, technical difficulties posed by laboratory testing of materials with large particle sizes, sometimes in loose state, encouraged researchers to concentrate past studies on the constituent particles rather than on the material as a whole. Such research was less fruitful than that based on performance tests carried out on the whole material. However, during the last 25 years the situation has changed and a significant research effort in Europe has been undertaken towards the characterisation of granular materials for road pavements.

During the COST Action 337, much active research on granular materials for road construction in Europe was underway; the Action therefore identified current and recently completed research studies, and synthesised the results to give guidelines for future research in which the priority research areas are specified. This was achieved by an EU-sponsored study contract, and from a combination of general questionnaires, interviewing of research leaders, literature review and discussions with industry experts, six specific topics were selected for the review as those with the most promise of producing valuable findings.

One important result that emerged from the work presented in this paper is a comprehensive ranked list of the most promising subjects for research on unbound materials for road pavements, at a pan-European level, nationally and to provide recommendations for the organisation of European research. Promising research subjects are considered to be those with the potential to generate more information or to improve the usefulness of existing information for the technical community. Through questionnaires, twenty-nine proposals were proposed and ranked.

The paper concludes by listing what the Action considered to be the most important proposals for research on the use of unbound granular materials in road pavements. The paper concludes by recommending that maximum priority at National level and particularly at European level, should be given the most promising ranked research topics, as most of them involve the analysis of different climates and road conditions and are so broad that it is necessary to co-ordinate pan-European efforts.

1 INTRODUCTION

Until recently, unbound granular material for road pavements has received less research interest than other pavement materials. This can be partly explained because unbound granular materials lies between the fields of pavement and geotechnical engineering and has in the past been overshadowed by both. Because of its low cost compared with bound materials, granular material has not received the same privately sponsored research funding as concrete or bituminous materials, and most interest in the field has been promoted by government funded research initiatives. In many countries road pavement research was concentrated on materials for the most heavily trafficked roads and research on pavement materials - including granular materials - for other road categories, was often given priority.

In addition, technical difficulties posed by laboratory testing of materials with large particle sizes, sometimes in loose state, encouraged researchers to concentrate past studies on the constituent particles rather than on the material as a whole. Such research was less fruitful than that based on performance tests carried out on the whole material.

However, during the last 25 years the situation has changed and a significant research effort in Europe has been undertaken towards the characterisation of granular materials for road
pavements. Three significant markers of this were the series of Unbound Aggregates in Roads symposia (UNBAR), which started in 1981, and which most recently was held in 2000, at the University of Nottingham, England [Dawson, 2000], the International Symposium on Soils under Cyclic and Transient Loading held at Swansea in 1980, and the Symposium EUROFLEX [Gomes Correia, A. (ed.), 1996], held in 1993, which provided the basis for much subsequent work on the stress-dependent modelling of the resilient response of granular materials to repeated loading. On an international level, the rôle played in this field by the International Conference on the Bearing Capacity of Roads and Airfields, which has been running every fourth year since 1982, must also be highlighted.

A large proportion of this research has been based on the use of the cyclic load triaxial testing (CLTT) equipment to determine the resilient behaviour of granular material and to measure the permanent deformation during the test procedure. At the same time, research on the use of simple, particle-based assessments of granular materials was being carried out. Some research has also addressed the hydraulic properties of granular materials in road pavement layers and the influence of water on the bearing capacity of these layers, and, in the last decade, there has been increasing research in the use of alternative materials as replacements for conventional aggregates.

At the time of COST Action 337, there was much active research on granular materials for road construction in Europe and it was considered of great interest to identify current and recently completed research studies, to synthesise the results and to give guidelines for future research in which the priority research areas are specified. All of this should contribute to co-ordinate National Test Programmes and to increase the efficiency of European research.

2 CURRENT RESEARCH ACTIVITIES

2.1 Work performed

The current research within European countries was identified in order to:

- Determine a large number of active and current projects on the topic of unbound granular materials
- Distribute this list widely and make it available to any Internet user
- Identify the key topics of research at the present time
- Summarise this information.

The initial activity was to collect a list of recent and current research and development projects in the participating countries. By this means, a total of 71 projects (listed by title, a brief description and a contact person) were identified in 9 countries. The list was posted on a web page that can be found at: (www.nottingham.ac.uk/~evzard/cost4-2.html) so that it was accessible by all interested parties both within and outside of the Action. The main topics in these research projects are summarised in Table 1.

The second activity in this field was to send a brief questionnaire to those persons identified in the first stage of the investigation as being responsible for those projects. In addition it was sent to many of those active in the COST 337 Action. The questionnaire asked questions on six topics judged to be of most relevance, given their assessment of the major issues concerning the development of granular material usage and understanding.

The third element of the work was to obtain more detailed information from some project leaders, and from other sources. This was achieved by amplified written response to some of the questionnaires just mentioned, by interviewing interested parties and by literature review. The interviewing of researchers was achieved by an EU-sponsored study contract, for which the Task Group 4 final report contains full details. A large number of references were also read and together these allowed a study contract to deliver its observations and conclusions on the state-of-the-art on those topics (Hill & Dawson, 1998). Some of the costs of the visits were covered under an EU short-term scientific mission budget.

Table 1 - Listing of Projects Reported by Topic

<table>
<thead>
<tr>
<th>Topic</th>
<th>List number of current or recent National research projects in the participating countries (71 identified in total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compaction</td>
<td>6, 49</td>
</tr>
<tr>
<td>Contamination</td>
<td>16, 41</td>
</tr>
<tr>
<td>Crushing</td>
<td>2, 55</td>
</tr>
<tr>
<td>Design / Guide</td>
<td>44, 53, 60</td>
</tr>
<tr>
<td>Evenness</td>
<td>7</td>
</tr>
<tr>
<td>Frost Effects</td>
<td>32, 34</td>
</tr>
<tr>
<td>Functional Requirements</td>
<td>9, 52</td>
</tr>
<tr>
<td>Granulometry</td>
<td>3</td>
</tr>
<tr>
<td>In situ Testing</td>
<td>5, 6, 10, 18, 21, 22, 24, 27, 35, 37, 42, 44, 45, 50, 61, 63</td>
</tr>
<tr>
<td>Layer Thickness</td>
<td>3, 39</td>
</tr>
<tr>
<td>Low Quality Aggregates</td>
<td>23</td>
</tr>
<tr>
<td>Mechanical Laboratory Testing</td>
<td>4, 8, 11, 22, 28, 32, 33, 38, 46, 51, 54, 56, 62</td>
</tr>
<tr>
<td>Mechanical Understanding</td>
<td>11, 12, 15, 19, 28, 51, 56, 57</td>
</tr>
<tr>
<td>Modelling</td>
<td>56, 57, 58</td>
</tr>
<tr>
<td>Moisture</td>
<td>27, 63</td>
</tr>
<tr>
<td>Permeability</td>
<td>16, 43</td>
</tr>
<tr>
<td>Petrography</td>
<td>36</td>
</tr>
<tr>
<td>Production</td>
<td>55</td>
</tr>
<tr>
<td>Recycling / Waste / By-products</td>
<td>4, 5, 22, 25, 29, 30, 31, 40, 41, 46, 47, 50, 59</td>
</tr>
<tr>
<td>Sampling</td>
<td>1</td>
</tr>
<tr>
<td>Specification / Standards</td>
<td>9, 20, 42</td>
</tr>
<tr>
<td>Trial Sections</td>
<td>2, 3, 5, 37, 40, 43, 47, 48, 50, 58, 59, 61, 63</td>
</tr>
</tbody>
</table>
2.2 Current European activities

At the time of this report three European Union RTD research projects on granular materials for pavements have been completed. Two of them were waiting for the publication of the final report (COURAGE and ALT-MAT, see Annexes 12 and 13).

An important European research project entitled “An European Approach to Road Pavement Design”, commenced in 1989 and was reported at the EUROFLEX symposium held in Lisbon, Portugal, in 1993 [Gomes Correia, A. (ed.), 1996]. The main work achieved in the project was: firstly to evaluate the ability of models to describe the behaviour of UGM, by comparison with the results of cyclic load triaxial testing (CLTT); and secondly to implement the models in a pavement analysis program and to compare the results obtained with these models with experimental data from full-scale accelerated load testing (ALT) of pavement test sections.

COURAGE commenced in 1998 and finished in 1999. The project examined the mechanical properties of a number of commonly used aggregate sources across Europe by means of comprehensive materials testing and analysis program. In particular, the issues of non-linearity of granular material resilient response and the sensitivity of the material to moisture content was noted, not only in laboratory testing, but also in situ. Six different aggregates were tested and the results were compared with their performance. The resilient behaviour was then modelled using the Boyce and Dresden models and the models were implemented a finite element code. This code was used to model pavements that were being monitored. The project also included the monitoring of moisture and temperature changes within a number of trial pavements in several countries and the results demonstrated that these characteristics can have an important effect on pavement performance and need to be incorporated into modern design and assessment analyses. Finally, two full-scale experiments on instrumented pavements were carried out, one in Portugal and the other in the Nantes (France) accelerated load testing facility. The results from the testing of these sections highlighted again the importance of characterising the granular material properties upon which pavement modelling can be based.

ALT-MAT also commenced in 1998 and lasted for two years. The project was intended to encourage the wider use of alternative materials in road construction. The objective was to define methods by which the suitability of alternative materials for use in road construction can be evaluated. Specifically, municipal solid waste incinerator bottom ash, crushed concrete, demolition rubble, steel slag, air-cooled blast furnace slag, glasslike slag and recycled glass were tested, along with natural materials used as a point reference. The methods covered the mechanical properties (both in situ and in the laboratory), functional requirements, leaching potential (lysimeter, climate chambers and laboratory tests), hydrodynamic tests and long-term stability of the materials and concentrated on unbound granular materials. Inspection and monitoring of existing roads were carried out in four countries, giving a wide range of geological and climatic conditions. The results obtained in the project show that alternative materials appear to give better performance in situ than would be expected from the results of standard laboratory tests. The response of alternative materials to Los Angeles or Micro-Deval tests indicates that their behaviour is significantly different from that of natural aggregates. It was recommended that a new leaching test be developed which would be applicable to granular materials under unsaturated conditions with no or extremely slow moisture movements. A model was proposed for predicting the impact of leaching from materials in road construction on the quality of groundwater. Also, a new test was developed for measuring the water content of municipal incinerator bottom ash, with its high electrical conductivity.

Other current research work was disseminated during the international workshop on Unbound Granular Materials in Lisbon, Portugal (Gomes Correia, A., 1999; published as: Unbound Granular Materials; Laboratory testing, in situ testing and modelling. Balkema, Rotterdam).

2.3 Research summary on selected topics

It can be seen in the preceding Table 1 that the subject matter of referenced research projects is very wide, ranging from equipment for measuring frost depth, to seasonal influences on the properties of crushed rock aggregates and gravels to performance-based specifications and the micro-mechanics of granular materials. The magnitude of this topic field necessitated some pre-selection, if the intended review was not to be superficial and of little value. From a combination of general questionnaires, interviewing of research leaders, literature review and discussions with industry experts, six specific topics were selected for the review as those with the most promise of producing valuable findings.

The six topics selected were:

1. Simplified laboratory mechanical assessment methods for routine purposes
2. Permanent deformation
3. Resilient modulus in situ
4. Moisture in situ
5. Variability and quality control needs and strategies for alternative materials
6. Design approach for pavement layers incorporating alternative materials.

On these topics, a state-of-the-art review was produced (Hill, A.R. & Dawson A.R., 1998) and the main conclusions obtained are included in the following paragraphs in this Section.

General

1 As many researchers appear to be working on similar aspects of research. Collaboration between institutes would seem to be beneficial. It is recommended that a continuing mechanism be developed to assist inter-laboratory collaboration. The PAFOG meeting and associated mailing list is one such means and this should be encouraged.

Triaxial Testing

2 For laboratory assessment of resilient modulus characteristics, the cyclic load triaxial testing (CLTT) apparatus is pre-eminent, and is likely to remain so for the foreseeable future. It is now accepted and becoming more widely employed to test granular materials. A draft CEN standard has been prepared and, when accepted by CEN, is likely to encourage further development (CEN WI 00 227 413 of CEN TC 227 / WG4 / TG2).

3 Many institutes are performing cyclic load triaxial tests (CLTT) on a variety of materials, the chief intention being to characterise the material. This results in the generation of substantial quantities of data. Individuals are working on producing models to predict the laboratory performance of materials and to collate this with simpler tests. The volumes of data required to complete and verify this type of work is enormous and far beyond the scope of many individual research projects.

4 The relative complexity (equipment, specimen preparation and test procedure) of the cyclic load triaxial test (CLTT) - which leads to expense - partially hinders its routine application. Recent work relating simple material characteristics to resilient modulus data and observing patterns of behaviour, seems likely to permit a hybrid testing approach (in which some carefully obtained triaxial test results of resilient modulus are extended to a wider range of materials and conditions by simple laboratory characterisation) as a viable means of determining the resilient modulus of materials in the laboratory. This needs confirming, but is a promising development.

5 The laboratory study of permanent deformation is less advanced than for resilient deformations. Several test procedures exist; however, they are relatively complex and laborious procedures. Some further development on methods of assessing permanent deformations is required to ensure that laboratory determined deformations are comparable with field values. As with the resilient behaviour, correlation to simpler tests is also required.

6 A possible alternative test to the cyclic load triaxial test is the K-mould (developed by CSIR, South Africa), but considerable developmental work would be required before this would be suitable for routine application. However, it has the potential to assess strength and permanent deformation behaviour as well as resilient modulus characteristics, and sample preparation may be simpler.

In situ Material Assessment

7 An increasing number of sophisticated and robust in situ test equipment are becoming available, many at reasonable cost.

8 The in situ measurement of resilient modulus is an important problem to be addressed. Although many test methods exist and are well established, precision and accuracy are generally poor. There is only limited correlation between the data obtained from different test methods (often as a consequence of the different techniques measuring different, and only loosely related, quantities). Several methods are often required before the data can be understood (or thought to be understood). Thus, there continues to be a need to develop a better understanding of the fundamental influences upon the results obtained; otherwise, the end result becomes little better than the empirical index that it attempts to replace (i.e., the California Bearing Ratio test, CBR).

9 The obvious difficulty with in situ assessment procedures is the huge number of unknown variables that can influence the results. In particular, the influence of overlying and underlying layers (and the varying influence of temperature and climate) are not yet adequately allowed for.

10 The larger, two-sensor, dynamic plate test apparatuses show the most potential for routine application and now require further research on their routine application.

11 Ground Penetrating Radar (GPR) seems likely to develop further and may provide a useful tool, both for investigating in situ moisture conditions, and to assist in the interpolation of mechanical assessments made at discrete points using other techniques.

Permanent Deformation

12 Rutting, while a major mode of failure of unbound pavement layers, has received very little research attention. A number of observational studies have been completed or are in progress, but little work has been done in trying to understand the causes and control of the rutting. The permanent deformation test carried out in the laboratory can be very useful for ranking material behaviour, thus
permitting the preferential selection of one candidate material over another. However, researchers have either not attempted, or have been unable to produce, a quantitative relationship with pavement rutting. This is due to the difficulty of producing a sufficiently simulative test in the laboratory, the difficulty of knowing (or reproducing) the stress state and stress history that exists in the field and the almost complete absence of analytical work in this area.

13 The “shakedown” conceptual approach is attractive, but requires considerable further work before it can be useful as a practical modelling tool. In the short-term, ensuring that unbound granular materials provide resistance to permanent deformation seems likely to rely on meeting an array of index measures (such as angular shape and shear strength).

**In situ Moisture**

14 Many countries are currently monitoring moisture conditions within test road sections. It is hoped that in a few years time this will lead to more data being available in this area.

15 Problems may occur due to the inaccuracy of the measuring devices used. Many problems have been noted with the use of Time Domain Reflectometers (TDRs).

16 There is still inadequate understanding of in situ moisture values and their variability with climate, locality, pavement type, geology, etc.

17 The issue of moisture is often only loosely addressed in the design code and may be treated in a rather pessimistic fashion due to the uncertainty concerning realistic values. This reinforces the research needed to learn the likely value, variation and influences upon in situ moisture regimes. As with cyclic load triaxial testing, there is a need to look at existing data with a view to drawing out an overall pattern that can be used in design.

18 Maintenance of drainage systems is often not satisfactory and can lead to serious problems at a later stage in the road pavement’s lifecycle.

**Alternative Materials**

19 The mechanical properties of alternative granular materials can be very good, or can be very poor. Often, high quality derives from self-binding characteristics.

20 Other materials are of poor mechanical performance and strategies now exist for improving performance at moderate effort and cost. There remains concerns about long-term life and durability.

21 The variability of granular materials is a concern when using both primary and alternative aggregates. In practice, variability is often assessed simply by visual inspection of a material. Many alternative materials, especially slags and ashes from individual plants, have a high degree of consistency. Some other materials, such as demolition wastes, are usually controlled by restricting the amount of degradable material allowed in individual samples. There is currently no satisfactory way of assessing variability, either in the laboratory or in situ.

22 It is apparent that some countries are still reluctant to use alternative aggregates. If good quality control regimes could be employed in these countries, then further use could be encouraged. The European CEN groups are beginning to pull together the information available in Europe and to put some of the ideas into practice. This would appear to be a logical approach to this problem and should be encouraged.

**Pavement Design**

23 The design of roads varies in individual countries. Many countries rely primarily on empirical data and experience. In situ methods are being increasingly used to monitor the pavement and materials during construction. Problems with this type of testing however, may result in these tests being of limited practical use at present.

24 Pavement design procedures and design criteria are at a point of flux. With the rapidly increasing power of computing being experienced, it seems possible that finite element-based techniques could soon become routine. However, such techniques need significant work to make them useful for routine purposes and to validate them to measured in situ performance, particularly with those incorporating high quality internal stress and strain measurements that these new computational techniques aim to predict. They also allow different design criteria to be proposed, for which little experience is available. The analytical design of pavements is still in its infancy as regards the granular layers.

25 There still appears to be a very large gap between assessment of material in the laboratory and the application of this data to the field and design situation. The laboratory tests are used primarily to produce a numerical result that is then compared to limitations given in relevant specifications. The actual meaning of such numbers in terms of real field performance is not known.

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1 “Shakedown is the concept by which a repeated stress application less than a critical value (the shakedown limit) will cause incremental plastic strains which decrease from cycle to cycle, eventually ceasing. Stresses applied repeatedly above this limit cause non-stabilising plastic strains leading, eventually, to failure.”
3 GUIDELINES FOR FUTURE RESEARCH

3.1 Work performed

The main objective of this COST 337 activity is to develop a comprehensive ranking list of the most promising subjects for research on unbound materials for road pavements, on a European level. Promising research subjects are considered to be those with the potential to generate more information or to improve the usefulness of existing information for the technical community. This list should help to establish priorities for research in Europe.

A second objective is to obtain a similar ranking list at the national level in order to detect gaps between both levels and identify the main needs in technology transfer and in local or regional research.

Finally, it was decided to include some recommendations from COST 337 for the organisation of European research.

The working method was based on the development and analysis of surveys of the COST 337 members. First a questionnaire directed to the Task Group leaders of COST 337 was set up, asking for the main research needs emerging from their work. The answers were collected and some gaps were detected that were covered by new research proposals developed by the Task Group. Subsequently, the proposed research subjects were sent to the Management Committee Members (MCM) for rating and comment, asking for new proposals, and to detect whether there still was any gap in the proposed future research coverage. They were also asked for their opinions on how to organise the research at the European level. The rating of the subjects was done at European as well as at the National level of the respondent. A classification from 0 to 5 was assigned for both levels to each subject according to the following criteria:

5 Maximum priority
4 High priority
3 Medium priority
2 Low priority
1 Not necessary

Twenty-nine proposals were proposed and ranked. The number of respondents was 22 for the first round of voting (the first 23 proposals) and 12 for the remaining additional proposals (6 last proposals from the MCM). Replies to the questionnaire were received from AT, BE, CH, DE (2), DK, ES, FI (3), FR, GR (2), HU, HR, IE, GB (2), NO (2), PT (2) and SI (ISO country codes). Thirteen respondents come from National Research Centres, six from National Universities, two from National / European Associations and one from a National Road Administration.

3.2 Outcome of the survey

Each of the research proposals that were submitted included a Topic number, a description of the research topic, main guidelines on the research and its organisation, benefits and output to be obtained, as well as a time schedule for developing the research. Some of the research addresses similar or supplementary subjects that could be combined into a single European research subject (topic).

The main lines of the proposed research are showed in Table 2. This Table presents a matrix where the numbered proposals are classified by the main objective of the research (rows / records) and the main activity(ies) in the research (columns / fields). Table 2 lists the titles and rankings of the different proposals. The proposals cover all the general aspects related to granular materials: Performance (10 subjects), Factors (12), Design (2) and General Methods (5). In general, proposals that rely on more than one of the main objectives are included. The different activities included in the proposals are Laboratory testing (14), In situ testing (15), Accelerated load testing (5), Modelling (13) and Design (5). Proposals are referred to by their proposal number. The following paragraphs present a short account of the priorities highlighted in the proposals.

Performance / Resilient modulus

Over the past years, characterisation of the non-linear behaviour of unbound granular materials has been one of the main focuses of research on unbound layers. As a consequence, this is the area with the largest number of proposals: eight, plus three others included in general methods. Most of them are a continuation of research already active. In the following Sections, the numbers given in brackets are the Topic numbers of the research proposals listed in Table 2. The main research objectives included are:

- Comparison (and improvement if necessary) of the different in situ testing devices and methods regarding their capabilities to characterise the stiffnesses of granular materials (Topic 5). It is necessary to have in situ tests, which are reliable when determining the stiffness of granular materials. Dynamic plate methods offer advantages for the control of granular layers during construction, but their results should be correlated to the static plate load tests. Furthermore, wider experience is needed with the Falling Weight Deflectometer (FWD). Roller Integrated Continuous Compaction Control (RICCC) is the only method allowing a continuous control of the stiffness of the layer, but it also needs to be correlated with the standard plate load test. The influence of overlying and underlying layers (and their
varying influence with temperature and climate) on those tests requires further study, as does the depth of influence of the different equipment. Specific procedures should be developed to characterise the non-linear behaviour of unbound granular layers. Existing methods should be harmonised, analysed, improved if necessary and standardised.

- **Validation of fundamental laboratory tests** (cyclic load triaxial tests, RLTT) and models through instrumented sections on roads or test tracks and in situ testing of pavements (Topic 4, 8 and 15). There is a strong need for good in situ performance data in order to provide the raw material for validation of the new approaches currently being developed. A preceding step should be the validation of the different sensors on which some of the data relies.

- **Introduction of non-linearity in current practice.** This can be done by implementing non-linear models in current design methods (Topic 19), but also by simplification of the Boyce model (Topic 16 and 26) and / or any other non-linear elastic models presently accepted and used by pavement engineers. Furthermore, the cyclic load triaxial test should be standardised. This should be complemented with the definition of the performance requirements for unbound layers and also by the simplification (K-mould) of the cyclic load triaxial testing procedure (Topic 7 and 21) in such a way as to facilitate its use in the current testing. Data should also be collected on the influence of grading, moisture contents, etc., in order to establish reliable estimations of the resilient behaviour to be used in pavement design methods and in the selection and manufacture of unbound granular materials.

- **Development and validation of advanced models** to approach the response of unbound granular materials. The two most promising advanced models are those based on the hyperelasticity (Topic 6) and the micromechanics (Topic 25) theories. The first one is mainly in need of validation with field results. The second one, based on the micromechanics of heterogeneous media, should be developed for application in unbound granular materials for roads, which involves the use of appropriate methodology for numerical analysis at several micro-levels and the transfer to global structural analysis at the macro-level (pavement). Development of micromechanics for granular layers should allow a better understanding of the macroscopic mechanical behaviour of granular layers.

- **It is necessary to establish the relationship between rapid laboratory assessments and long-term changes in in situ behaviour,** if an incremental design procedure, such as that proposed by COST Action 333, “Development of New Bituminous Design Method” is going to be implemented in European pavement design practice.

### Performance / permanent deformation

The research on permanent deformation in unbound granular materials has been less successful than that on resilient behaviour, due in part to the practical difficulties involved in carrying out the mechanical tests in the laboratory. Current research attempts are at a lower level of research than in the case of resilient behaviour, despite the fact that rutting originating in granular layers (unbound granular materials or subgrade soil), is one of the most important causes of degradation on lightly trafficked roads.

There are two proposals in this field (Topic 1 and 24), and three others included in the general area (Topic 4, 21 and 25) are related to it. One of the proposals was ranked in first place in the final list (Topic 4), indicating the strong need of research on permanent deformations. The main objectives included in these proposals are:

- **Development of a fundamental test** (e.g., the cyclic load triaxial test) procedure through comparison with more simulative tests or full-scale loading tests (Topic 1 and 4). For the moment, research in this field is based mainly on cyclic load triaxial testing, though it is not yet standardised. The results of this test should be validated by comparison with simulation tests, such as the wheeltracking method (laboratory) and by using some form of Heavy Vehicle Simulator, HVS (for in situ accelerated load testing of existing pavement sections). This is a first step before standardising the test and carrying out the necessary research on the influence of the different factors for particular unbound granular materials in given situations.

- **Development of a simplified alternative test** (Topic 21) overcoming the practical problems of the cyclic load triaxial tests. This should be a new laboratory / in situ method where the operator is able to achieve a reasonable number of “cycles or load repetitions” with a load corresponding to the actual loads in the pavement. Some promising tests are the gyratory compaction device and the DCC (Dynamic Compaction Control) method, the latter to be used either in the field or in the laboratory with a small-scale apparatus.

- **Modelling the permanent deformation with both empirical (Topic 1) and fundamental micro (Topic 25) or macro models (Topic 1 and 24).** Even supposing that a sufficiently robust, economical and representative test can be found, there is a shortage of reliable and reasonable models for measured response and, furthermore,
a shortage of well tried and validated analytical frameworks that can use adequate models to predict pavement performance. In a first stage, empirical approaches may be adequate, but there is an important gap to fill in the area of fully analytical approaches.

Factors / materials

Three main lines of research are proposed:

Natural materials

One important aspect concerning conventional materials is to establish the relationship between general empirical specifications and performance. Proposals 12 and 14 address this subject (shape, quality and quantity of fines). It would be of great interest to compile the national experiences regarding different granular materials, as proposed by Topic 17 in order to have a broad basis to set the requirements for granular materials.

Alternative materials

There is a growing interest in the use of reclaimed and secondary aggregates. This action would reduce the amount of primary aggregate extraction and also reduce stockpiles of discarded materials. Regarding alternative materials, the priorities are to:

- Characterise the fundamental properties of alternative materials (Topic 3). ALT-MAT has pointed out that conventional tests are not adequate for alternative materials and fundamental tests for these materials should be developed and related to performance.
- Identify the self-binding properties of some alternative materials (Topic 10). Some alternative materials (and also some natural materials) have self-cementing properties. Hydration processes and chemical reactions create stiff pavement layers of these materials when used in road construction. This very important strength property can have a very favourable impact on both the mechanical properties of the material itself and the environment, therefore making it worthy of investigation.
- Develop strategies to cope with the variability of alternative materials (Topic 20). Some alternative materials are variable in their characteristics. Currently, in many European countries, alternative materials have to perform to the same set of standards as traditional aggregates. At the moment, there are no reliable and reproducible methods to test material variability, either for the laboratory, or for in situ conditions.
- Analyse individual alternative materials. Although the application of many alternative materials on roads has been analysed and defined, there is a continuous line of research in this field for new materials, or for new applications of current alternative materials.

Geosynthetics

Some recent research and practical applications have shown benefits in the combined use of geosynthetics and granular layers. These materials open new possibilities that should be systematically analysed and evaluated (Topic 22 and 27). The proper characterisation, both in situ and in the laboratory, of the effects using geosynthetics in unbound granular materials, along with rationalisation of the design using these materials, are important priorities in this field.

Factors / climatic effects

Knowledge of moisture conditions in unbound pavement layers and subgrade soils is essential to:

- predict the seasonal mechanical behaviour of these materials in pavements
- improve the design of pavements and of their drainage systems
- understand possible leaching of pollutants when using alternative materials.

It is widely recognised that in situ moisture conditions affect the responses of unbound granular materials to traffic loading, and that the sensitivity of the responses can be relatively high for some materials. Water or moisture and the effect of freeze-thaw cycles are still the most important and unsolved parameters related to the deterioration of roads.

Three proposals (Topic 2, 9 and 13) were presented on the effect of water and one was presented (Topic 28) on freeze-thaw in pavements containing granular layers. The main objectives in these proposals are:

- Measuring moisture conditions in the field under different conditions to gather data for selecting the proper water content for the characterisation of granular materials (Topic 2 and 9). The COURAGE program, the Mn/Road trial in the USA and Nordic HVS research investigations by VTT and VTI, have taken some measurements of the moisture (or pore pressure) in the subgrade or lower layers of road constructions, but in general there is a shortage of in situ moisture content data, which are necessary for a better appreciation of the effect of moisture variability to be incorporated into the design process and to provide the basis for engineering techniques in order to modify the moisture regime. The technology associated with the TDR sensors and the interpretative framework for its results should be improved. This measure would also help to understand the main origin of the infiltration of water in the studied pavements.
of freezing and thawing processes in order to the development of rational methods for analyses its basic variables, the gathering of field data and for testing and analysing frost susceptibility and should focus on improving laboratory methods granular materials (Topic 28). This research Analysing the effects of freeze-thaw on unbound or light traffic. that drainage, especially for roads with medium required, or on the best method for providing overall agreement on the degree of drainage (Topic 13). An important issue in a design code is how it handles the question of draining the (Topic 2 and 9). This would allow the variation with material, climate, rainfall, topography, construction, etc., to be more reliably assessed. It would be useful to be able to predict the seasonal change in the moisture and therefore to be able to design the pavement applying the correct parameters. An accurate research project identifying those factors related to moisture that are most critical for the long-term performance of a road would create a better background for more relevant, innovative and efficient engineering solutions for road construction in the future. Ideally, a broad database of moisture values is required that incorporates both short-term sampling and long-term monitoring over several months / years.

Evaluating the different drainage systems on the performance of pavements with unbound layers (Topic 13). An important issue in a design code is how it handles the question of draining the pavement structure. At present there seems little overall agreement on the degree of drainage required, or on the best method for providing that drainage, especially for roads with medium or light traffic.

Analysing the effects of freeze-thaw on unbound granular materials (Topic 28). This research should focus on improving laboratory methods for testing and analysing frost susceptibility and its basic variables, the gathering of field data and the development of rational methods for analyses of freezing and thawing processes in order to minimise or eliminate detrimental frost action when designing pavements.

Project
As our understanding of the mechanical behaviour of granular materials increases, this understanding must be incorporated into pavement design and evaluation procedures in order that actual benefits are achieved. This should be carried out by implementing both response models and performance models in the current analytical procedures. There is a research proposal in this field (Topic 29), which proposes the first step to deal with this. There is also another included in a general issue (Topic 11) on the life cycle (whole life costing) approach in design of road pavements. The response models should include the non-linear behaviour of the unbound granular materials in the pavement layers, especially for the design of pavements with a very thin cover of asphaltic materials or unsurfaced pavements. When the asphalt thickness is greater than approximately 120 mm then non-linearity is no longer very important, and linear mechanistic design or evaluation approaches may be adopted, but for thicknesses lower than that, the effect of non-linearity is important, though it is not yet clear how detailed the modelling of this should be.

In the future, some other aspects should also be incorporated. At the present time, consideration of anisotropy in design and evaluation is probably not very important (especially as this must be viewed against uncertainty in other variables). However, initial and developing in situ residual stresses are very uncertain, and these have a great effect on performance. They will affect stiffness values because of non-linearity - especially at low stress levels (i.e., nearly unconfined). Moreover, locked-in stresses probably have a large effect on resisting rutting. It will be necessary to develop tools to consider these factors in the current design, though as yet they are largely unmeasured, unconsidered, or occasionally assessed by indirect means.

The use of the subgrade strain criterion as a performance model, often adopted in mechanistic pavement design methods, is recognised as being (ultimately) inappropriate and unhelpful. While it may have pragmatic value, it does not help an understanding of how permanent deformation occurs, or of how it may be controlled. The limited understanding of the behaviour of granular materials and soils regarding permanent deformation suggests that a stress criterion is more appropriate, perhaps applied separately to each unbound layer at risk of undergoing rutting. However, in unbound granular materials a stress criterion is not as easy to develop as in soils (subgrade materials), even though such a
criterion seems desirable. There is no easy way to define a yield criterion, as behaviour under dynamic loading is not simply related to a Mohr-Coulomb failure envelope (or similar). Taking these arguments into account, along with the issue of sensitivity of design approach to pavement type (e.g. non-linearity being unimportant under thick asphaltic layers), may suggest that the type of design criterion will change with pavement cross-section and depth in (and thickness of) the pavement.

The change of stiffness (and of susceptibility to permanent deformation) with time, cyclic loading, water content equilibration, and deterioration due to water and particle self-cementation effects is, as yet, unknown. For some natural and many alternative materials these effects may be very important if maximum reliable performance is to be obtained from a particular material. These influences have not yet been incorporated into pavement design and should be analysed under a systematic approach, either in experimental road test sections or full-scale test tracks (Topic 11) on a long-term basis.

General methods

Six proposals (Topic 4, 11, 17, 18, 21 and 25) have been presented that can be classified as general, because they apply to more than one of the fields already exposed. Most of them have already been described in the specific paragraphs: Topic 4 on full-scale accelerated load testing, Topic 11 on application of the life cycle (whole life cost) approach for alternative materials, Topic 17 on the development of a database, Topic 21 on simplified testing and Topic 25 on a micromechanics approach for modelling unbound granular materials in road pavement layers.

Proposal 18 refers to the development of a laboratory compaction method to reproduce initial conditions. Packing conditions influence the results of every behaviour parameter of granular layers, but especially the response to permanent deformations, which has shown a great dependency on the initial state and on the history of stresses in the layer. The existing methods should be assessed and compared to the levels of compaction measured in the field.

3.3 Most promising subjects for future European research

Table 2 presents the complete list of the subjects, including a proposal number for each one, the title of the research subject, the mean score obtained in the voting and the resulting ranking at EU level.

<table>
<thead>
<tr>
<th>Topic No.</th>
<th>Title of Proposal</th>
<th>Mean score</th>
<th>EU level Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Determination of the permanent deformation properties of unbound granular materials</td>
<td>4.41</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Measurement and prediction of water movements in unbound granular materials and subgrade soils</td>
<td>4.14</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Mechanical properties of alternative unbound granular materials</td>
<td>3.77</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Full-scale accelerated load testing of flexible pavements with granular bases</td>
<td>3.77</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Evaluation of in situ test methods for unbound granular materials</td>
<td>3.91</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Non-linear resilient behaviour of unbound granular materials</td>
<td>3.57</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>Simplified cyclic (cyclic load) triaxial testing procedures to obtain isotropic and anisotropic Boyce parameters</td>
<td>3.40</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>Stress-strain in situ measurements</td>
<td>3.75</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>Water movements and moisture contents in road constructions</td>
<td>3.82</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>Creation, identification and utilisation of the self-binding properties of some alternative materials in road construction</td>
<td>3.73</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>Life cycle approach for design, construction, implementation and monitoring of test tracks constructed with various natural materials (aggregates) and alternative materials</td>
<td>2.82</td>
<td>25</td>
</tr>
<tr>
<td>12</td>
<td>Evaluation of the performance of unbound granular materials with different quantity and quality of fines</td>
<td>2.77</td>
<td>26</td>
</tr>
<tr>
<td>13</td>
<td>Evaluation of different types of drainage systems on the performance of unbound granular materials</td>
<td>3.45</td>
<td>17</td>
</tr>
<tr>
<td>14</td>
<td>Evaluation of the performance of unbound granular materials with different shape characteristics</td>
<td>3.32</td>
<td>22</td>
</tr>
<tr>
<td>15</td>
<td>Validation of the Hyperelastic model in several materials, both in laboratory tests and at selected road sites</td>
<td>2.67</td>
<td>27</td>
</tr>
<tr>
<td>16</td>
<td>Use of a simple approach to reproduce the results of Boyce’s model for normal pavement design</td>
<td>3.33</td>
<td>20</td>
</tr>
</tbody>
</table>
17 Development of a public database of material test results and index properties 3.57 13
18 Development of a laboratory compaction method to reproduce the initial field conditions of a road pavement 3.57 13′
19 Comparison of computer packages to reproduce the non-linear behaviour of unbound granular materials 3.29 23

Table 2 Priorities for future research (continued) European level

<table>
<thead>
<tr>
<th>Topic No.</th>
<th>Title of Proposal</th>
<th>Mean score</th>
<th>EU level Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Variability and quality control needs and strategies for use of alternative materials in road construction 3.73 9′</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Simplified laboratory mechanical assessment methods for routine purposes 3.64 11</td>
<td></td>
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<tr>
<td>22</td>
<td>Evaluation of geosynthetics between pavement layers as a means of possible increase of their performance, to eliminate the effects of groundwater and to reduce the total thickness of road pavements 2.91 24</td>
<td></td>
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<tr>
<td>23</td>
<td>Addition of fly ash as a filler additive in unbound granular materials used for the construction of sub-bases and bases 2.50 29</td>
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<tr>
<td>24</td>
<td>Advanced modelling of permanent deformation in unbound granular materials with emphasis on principal stress rotation effects and hydromechanical coupling 3.58 12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Micromechanics of unbound granular materials 2.67 27′</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Development of a simplified model to reproduce the non-linear behaviour of unbound granular materials 3.33 20′</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Efficiency and performance of geosynthetics in road construction 3.42 18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Movements and effects of water by freezing and thawing in pavements layers and subgrade soils. 3.50 16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Granular Pavement Design (i.e., a manual / code of practice for the design and use of unbound granular materials in road pavements). 4.00 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

On a rating from 1 (lower priority) to 5 (highest priority), two proposals collected overall average scores equal to or higher than 4, and 15 proposals had scores above 3.5. The 10 highest score results concern research on permanent deformation, water movements and effects (2 proposals), granular pavement design, in situ test methods, alternative materials (3 proposals) and stress-strain in situ measurement (2 proposals). The five research subjects with the highest ranking are described in the following ranked topics.

1) Determination of permanent deformation properties of unbound granular materials (mean rating = 4.40)

**Objective of the proposed research**

The aim of the proposed research is to develop a reliable test procedure for determining and modelling the permanent deformation properties of unbound granular materials using the cyclic load triaxial test (CLTT) procedure for determining the permanent deformation properties of UGM, and a response model to be implemented in road pavement design.

**Main guidelines**

The proposed research has two main parts:

The first part of the research deals with the development of the test, selecting several cyclic load triaxial test (CLTT) procedures, and comparing their results with more “simulative” tests, like wheel tracking tests, or full-scale accelerated loading tests and the results from full-scale road test section experiments. The research should be carried out on several different materials. An important problem in this study is the initial state of the specimens (method of compaction, preloading), which largely influences the development of permanent strains. Studies should be made to characterise the initial state of the materials in situ (by some in situ tests, or by taking samples in situ).

The second part of the research deals with the modelling of permanent strains. Once the test procedure is selected, tests will be carried out on several materials, for different stress levels, to study the variation of permanent strains with the stress level and the number of load cycles. In this way it will be possible to define a model for the prediction of permanent strains, which can be implemented in
pavement design. Two types of models can be considered: empirical models, where the permanent deformations are related directly to the number of load cycles, or more fundamental elastoplastic models capable of describing cyclic behaviour.

**Main output**
Test method for evaluation of permanent deformation properties of unbound granular materials.
Model for prediction of rutting of unbound granular pavement layers.

**Comments**
This research could be broadened to include other methods other than the cyclic load triaxial test: Hollow cylinder apparatus, large shear box, laboratory scale wheel tracking, and laboratory plate loading test or K-mould.

(2) Measurement and prediction of water movements in unbound pavement layers and subgrade soils (mean rating = 4.13)
Also proposed in this field: Water movement and moisture content in road construction (Mean rating = 3.81).

**Objective of the research**
The aim of the proposed research is the measurement of moisture conditions in unbound pavement layers and subgrade soils, for several types of pavements and climatic conditions, associated with laboratory studies of the hydraulic properties of the materials, and the prediction of moisture conditions in road pavements by modelling.

**Main guidelines**
The proposed research has two main parts:

1. Undertake computational analyses of various pavements with different materials under different conditions.
2. Develop failure criteria on the basis of a review of failure modes.
3. Develop a design procedure to link the two.
4. Assess against pavement performance and accelerated load testing.
5. Incorporate environmental (especially suction) effects.
6. Calibrate and validate the design procedure.

**Main output**
Models for prediction of water movements in pavements.
Better prediction of moisture conditions beneath pavements.
Improvement in the design of pavements (especially flexible, low traffic pavements) and drainage systems.
Guidelines for choice of water contents for mechanical testing of unbound granular materials and subgrade soils.

**Comments**
This research can also be combined with studies of the influence of moisture contents on the mechanical behaviour of unbound granular materials and subgrade soils, or also on the leaching of pollutants from alternative materials.

(3) Granular Pavement Design (mean rating = 4.00)

**Objective of the research**
To develop a design procedure for pavements with granular layers, which are unsurfaced or with thin asphalt surfacings.

**Main guidelines**
1. Undertake computational analyses of various pavements with different materials under different conditions.
2. Develop failure criteria on the basis of a review of failure modes.
3. Develop a design procedure to link the two.
4. Assess against pavement performance and accelerated load testing.
5. Incorporate environmental (especially suction) effects.
6. Calibrate and validate the design procedure.

**Organisation.**
Research may be best realised by one research centre provided with strong European level leadership from a steering panel, and research collaboration from subcontractors at other centres who will work on subtasks and critical testing of the outputs.

**Main output**
Design guide and associated software.
Evaluation of in situ test methods for unbound granular layers (mean rating = 3.90)

Objective of the research
The objective of this research is to evaluate various test methods for the in situ measurement of the stiffness of unbound granular materials in road pavement layers.

Main guidelines
First, several in situ test methods (SASW, Static Plate Bearing Test, Dynamic Plate Bearing Tests, FWD, Benkelman beam,...) for the measurement of the stiffness of granular bases or sub-bases (the granular layer directly over the subgrade soil) should be selected, evaluated and compared, and if necessary, the test procedures should be improved and standardised.

The experimental conditions should include several levels of modulus of the subgrade soil, and several types of materials and thicknesses for the unbound granular materials.

It is also proposed to test the materials in the laboratory, using cyclic load triaxial tests and to compare the performance obtained in the laboratory and in situ.

Main output
More reliable determination of in situ stiffness of granular layers. Improvement of quality of unbound pavement layers.

Test procedures and recommendations for in situ measurement of stiffness of unbound granular layers.

5. Mechanical properties of alternative unbound granular materials (mean rating = 3.77)

Objective of the research
Study of the mechanical properties of various alternative materials using cyclic load triaxial tests. The materials of interest are industrial by-products, and recycled materials, such as crushed concrete, demolition waste, waste incineration slag, and aggregates taken from soft rocks, etc.

Main guidelines
It is proposed in this study to characterise, using cyclic load triaxial tests, various types of alternative materials that are being used as unbound granular materials in pavements, in order to:
Verify the applicability of the present test procedures used for these materials, and if necessary adapt them.

Determine the mechanical properties of these materials and the main parameters influencing these properties.
Propose models describing their behaviour that can be used in pavement analysis and design.

Main output
Test procedures for cyclic load triaxial testing of alternative unbound granular materials.

Data on the mechanical performance of alternative unbound granular materials and recommendations for their use.

Approaches for taking into account alternative unbound granular materials in pavement design. Improved use of alternative unbound granular materials in pavements, and consequently more economical solutions for road construction.

Comments
This research could be combined with in situ tests on the same materials, and studies of the environmental risks associated with these materials.

4 CONCLUSIONS
In the opinion of the COST 337 Action and other experts, the most important proposals for research on the use unbound granular materials in road pavements are:
1. Determination of permanent deformation properties of unbound granular materials.
3. Development of an European Method of Granular Pavement Design (i.e., a manual / code of practice for the design and use of unbound granular materials in road pavements).
5. Mechanical properties of alternative unbound granular materials.

The development of these research topics will not only help to raise practical knowledge on unbound granular materials, but also road engineering technology as a whole. These subjects should be given maximum priority at National level and particularly at European level, as most of the subjects involve the analysis of different climates and road conditions and are so broad that it is necessary to co-ordinate pan-European efforts.