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1. **Background**

In recent years the increasing traffic volumes on the world’s highways have indicated shortcomings in the existing empirical procedures that are used to assess road building materials. As a result, new fundamental performance based test procedures have been developed that are currently being considered for acceptance in defining material specification codes of practise. In Ireland, to date, it has only been possible to observe and monitor these developments. The procedures will shortly be introduced by the Central European Standards Organisation (CEN) and will affect Irish material suppliers, design engineers in local authorities and consulting engineers.

To promote national awareness of these developments and the consequences of pending legislation, a workshop on Performance Related Test Procedures for Bituminous Mixtures was held over two days (6-7 November 1997) at University College Dublin. The four main themes that underlay mechanical tests on bituminous mixtures are compaction, permanent deformation, fatigue and stiffness, and the effects of ageing. Leading international experts from America, Holland, France, Austria and Britain were invited to set the scope of the most recent developments in these fields. The implementation of these particular issues into American and European standards was discussed by J. Don Brock of ASTEC Industries Inc. (US) and Jos van der Heide of VBW Asfalt (Holland). A limited audience of some 50
engineers participated in the lively discussion sessions that followed the presentations. This article summarises the presentations and discussions that took place at the workshop.

2. **Compaction**

2.1 **Introduction**

Compaction forms a very critical part in the construction of an asphalt layer. During the compaction process air voids are reduced, aggregates are packed together and binder is bonded to the aggregates. The basic structure of the mix after compaction is determined by the particle distribution and by the shape and texture of the aggregates with cohesion being provided by the bitumen. Ideally, the aggregate, binder and air voids should be uniformly distributed throughout a layer or test specimen.

During the session on compaction, Derek Fordyce discussed a theory, developed at Heriot-Watt University (UK), that describes the process of compaction and mixture formation. Jacques Bonnot of LCPC (France) concentrated on the usage of laboratory compaction equipment to determine reference densities and compactibility, and to prepare specimens for performance testing.

2.2 **The compaction process**

Studies at Heriot-Watt University have attempted to develop a fundamental understanding of the process of compaction. A constant strain rate compactor has been developed in which a test specimen is subjected to repeated axial loading applied at a constant strain rate, with rest periods to accommodate relaxation. Figure 1 shows a typical time based series of load-relaxation profiles. Compactibility is defined as the time (s) to the cut-off load on the first loading cycle. A shorter loading time indicates less change in density with input energy and thus better mixture compactibility.
Figure 1: Compaction profiles of load-relaxation with time

Figure 2 shows a typical compaction-resistance profile depicting the different phases of the compaction process. During the mixing process agglomerates of aggregate and binder are bonded together. The size of the agglomerates and the probability of air voids being present within the agglomerates depends on the aggregate grading and the binder content. During the initial stages of compaction these agglomerates are deformed and squeezed together, as indicated by the flat portion on the resistance-deformation profile. The shearing action between agglomerates reduces the air voids between them and promotes the effective packing of the aggregates. Once a continuous aggregate structure is formed, the second stage occurs (curvilinear portion of the graph). Under the kneading action of compaction, the aggregate particles will orientate themselves towards a more effective packing, dividing and displacing the air voids. The rheology of the binder will influence the movement of the aggregates and the length of time taken to form the aggregate structure. In the third and final stage the elastic response of the mixture is observed.

In reality, however, large volumes of material are compacted which results in lower internal stresses being generated. Laboratory specimen that are compacted under total mould confinement experience intense internal pressures so that a uniform internal structure is more likely. Nevertheless, the internal structure of a mixture can be examined to determine the suitability of different laboratory compactors for different mixtures. For example, continuously graded mixtures with a relatively large maximum aggregate size require a
kneading action, like that of the gyratory compactor, to ensure the effective packing of the finer fractions into the coarser fractions.

Figure 2: Typical compaction resistance-deformation profile

2.3 Reference density and compactibility

Reference density is defined as the density that is used to calculate the void content of a mixture. It is also called the target density for compaction control on site. Refusal density is a type of reference density and is achieved at a very high compaction energy. The compaction degree is the ratio of the bulk (or maximum) density to the reference density.

The gyratory compactor is preferred for calculating reference densities because it simulates the kneading action as opposed to impact compactors. There are currently seven different gyratory compactors commercially available. Due to basic differences in manufacturing technologies, different results are obtained in compacting specimen using the standard setting of 0.6 MPa at 1° angle. A calibration exercise was carried out at the LCPC and a nominal angle setting was determined for each compactor to achieve comparable compaction results.

A draft European standard has been prepared to characterise the compactibility of bituminous mixtures. This standard will help contractors to assess the mixtures’ resistance to compaction
so that the appropriate equipment can be selected. Three compaction methods can be used; impact (Marshall), gyratory compactor and vibratory hammer. The principle of the test is to determine the relationship between the compaction energy applied to the mixture and the resulting change in density or void content. A typical curve is shown in Figure 3. Generally, more compactible mixes have a higher initial density and achieve their maximum density at a lower compaction effort. The CEN draft standard acknowledges the fact that compaction efficiency is dependant on layer thickness. It also eliminates excessively workable mixtures by specifying a minimum void content at a given compaction energy.

![Figure 3: Typical compactibility curves](image)

2.4 Compaction for performance testing

Compaction affects the properties of a mixture in so far that it controls the void content. If the void content is too small, the mixture will be prone to rutting, while a large void content will increase the mixture’s susceptibility to fatigue cracking. Laboratory prepared specimens for performance testing are required to have a homogeneous composition (density) with the same properties as the mixture compacted using site plant. A number of laboratory compaction methods are available and several studies have been devoted to comparing them.
• The static compression method, such as the Duriez test, applies a very high pressure (+/- 20 times the pressure under a pneumatic tyre compactor) to achieve the reference density. This high pressure crushes the aggregate, squeezes the binder films and ultimately changes the mixture properties.

• Impact compaction methods, such as the Marshall, are criticised because; aggregate degradation can occur, reproducibility is relatively poor and the compaction action does not simulate the kneading action under plant compactor rollers.

• The gyratory compactor has limitations as specimens are not always homogeneous, especially when the height to diameter ratio of the specimen becomes large.

• The rolling wheel compactor is strongly recommended and CEN has produced draft specifications for 3 different types of rolling wheel compactors. These are the laboratory pneumatic tyred compactor, smooth steel wheel (pedestrian or segmented wheel type) and a roller running on vertical sliding plates.

3. **Permanent deformation**

3.1 **Introduction**

In the session dealing with permanent deformation Enrico Eustacchio of Technical University Graz (Austria) developed a theoretical spring-dashpot model, which could describe the long and short term response of viscoelastic materials such as bituminous paving mixtures. Keith Cooper of Cooper Research Technology (UK) subsequently discussed the different variables that influence the development of permanent deformation and elaborated on test methods available to assess resistance to permanent deformation.

3.2 **Modelling of permanent deformation**

Viscoelastic materials can be distinguished from other material systems (elastic, plastic) by the time dependancy of their response to loading and deformation. Viscoelastic material are profoundly influenced by the rate of loading (eg. strain is larger if stress increase more slowly
to its final value). Viscoelastic materials also display creep effects (an increasing deformation under sustained load) and relaxation effects (time dependant recovery after unloading). Bituminous roadbuilding materials have a similar behaviour and can be treated as viscoelastic.

The behaviour of viscoelastic materials under uniaxial stress closely resembles that of mechanical models built from discrete elastic (spring) and viscous (dashpot) elements. Using springs and dashpots in series, models of fluids are build. The Maxwell fluid is the most elementary and is shown in Figure 4. The graphs show the output of a creep-relaxation test, where, in the first stage, the strain increases under constant stress and then, in the second stage after time $t_1$, the stress decreases under constant strain.

![Figure 4: Standard Maxwell fluid](image)

Using springs and dashpots in parallel, solid models are build. Figure 5 shows a standard Kelvin solid. In this case the strain grows gradually to a limit, which is proportional to the stress value. When the strain is fixed, the stress immediately relaxes and remains at this value.
Following from these, three and four parameter models can be built, such as the one shown in Figure 6. Governing equations for these models could be quantified for particular asphalt mixtures by means of standard tests consisting of a creep and a stress relaxation phase. With the use of superposition, these linear models can be expanded to consider the action of successive loadings. Additionally, components can be added to the model to account for vibrations and unrecoverable deformation.

3.3 Factors affecting the development of permanent deformation
Permanent deformation can be considered to develop in two stages namely, densification and shear flow. Densification is essentially a continuation of the compaction process while shear flow occurs when the mix, usually rich in fine material and binder with no voids, is pushed outwards from the wheelpath.

Generally, aggregates with a rough surface texture and angular shape promote good aggregate interlock and inhibit the development of permanent deformation. This applies equally to coarse and fine aggregate. The aggregate grading influences the interlock and thus the rut development. The more particles that are introduced to a given volume, the more contact points will exist between the particles, increasing the strength of the aggregate skeleton and the resistance to deformation. The amount of voids in mineral aggregate (VMA) gives an indication of how well aggregate actually interlock. A low VMA value indicates a closely packed aggregate structure. From Figure 7 it is clear why continuously graded mixtures show better aggregate interlock and higher resistance to permanent deformation.

![Figure 7: Relation of VMA to percentage coarse aggregate in mix](image)

Figure 7 illustrates how the void content and VMA varies as the binder content of a mixture is increased. In theory, the optimum binder content for maximum resistance to rutting exists when the VMA is a minimum. As the binder content is increased further, the mix becomes binder rich, voids are filled with bitumen and aggregates start to float apart making the mix
unstable. Ideally, the mix should veer to the slightly coarser side of minimum VMA to ensure adequate coating of the aggregates by the binder.

Compaction also influences rut development since a poorly compacted mix will have the potential to densificate under traffic loading.

3.4 Tests to assess permanent deformation resistance

Ideal performance tests should simulate in situ conditions and test specimens should be representative of the material in the road. Various test methods exist to determine permanent deformation resistance and these are generally effective in ranking mixture performance.

The most widely used method is the Marshall test. Limitations to this test are its unrepresentative application of the load and the small sample size in relation to aggregate size.

Wheeltracking is a popular method because of its simple and intuitatively representative nature. Drawbacks are that the wheel passes to and fro over the same point with no lateral distribution, its comparatively slow wheel speeds, lateral mould restraints on the specimen and the heating of the specimen due to wheel friction.
The uniaxial test has the advantage of being very simple and able to indicate small variations in mixture composition. The main problem with the test is the absence of radial constraint, especially when testing gap-graded mixtures such as Stone Mastic and Porous Asphalt.

The triaxial test seems to be the most simulative but its complexity and cost restricts its use to laboratory research. A uniaxial indentation test has been developed to provide a simple test with a form of confinement, but the stress conditions generated within the specimen are difficult to analyse.

4. **Stiffness and fatigue**

4.1 **Introduction**

Papers were presented by Mike Nunn of the Transport Research Laboratory (TRL), (UK) and John Read of Croda Bitumen (UK) and these focused on predicting the stiffness and fatigue response of bituminous mixtures with the aim of implementing this method as a compliance test during road building contracts. The indirect tensile method seemed very attractive as it is a simple and relatively inexpensive test method that can be performed on equipment such as the Nottingham Asphalt Tester. The method uses cylindrical specimens that are easily cored from a pavement. British Standards exist for both the Indirect Tensile Stiffness Modulus (ITSM) and Fatigue Test (ITFT). An Indirect Stiffness Modulus test has been included in the Draft European Standard.

4.2 **Indirect Tensile Stiffness Modulus**

Stiffness is important to the pavement structure as it governs how much the road bends under traffic loading. In general, the higher the stiffness, the less strain develops in the layer or else the less layer thickness is required. Traditionally bending beam tests were used to assess mixture stiffness and although these tests are regarded as more fundamental, they require expensive sophisticated equipment which makes them impractical for compliance testing.

In the development of the Indirect Tensile Stiffness Modulus (ITSM) test numerous validation studies were carried out. At Nottingham University and the TRL the ITSM has
been compared to three point bending and trapezoidal cantilever tests. Correlation coefficients in the order of 99% were obtained.

SHRP researchers compared the Indirect Stiffness Modulus method with axial and flexural methods and found that the ITSM ranked the four mixtures that had been investigated in the same order as the other test methods. In a more recent study conducted by RILEM a range of test methods were compared. Results indicated a good agreement between the Indirect Tensile Stiffness and the stiffness determined from bending tests.

Precision validation was done through inter laboratory tests. The first trials indicated inadequate specification of test variables as well as a lack of operator training and instruction standards. Under the guidance of a British Standards Specialist Panel improvements were made which included the introduction of a material dependent load waveform factor. Another precision trial was carried out where nine laboratories and 3 different mixtures were involved. The result was an improvement of the precision by a factor of two.

ITSM values were also compared to stiffness values backcalculated from Falling Weight Deflectometer (FWD) measurements. The correlation shown in Figure 9 indicates that the ITSM is a good measure of the load spreading capabilities of the asphalt layers.

![Figure 9: Correlation between ITSM and FWD measurements](image)

4.3 Indirect Tensile Fatigue Test
Fatigue has been defined as material failure or fracture under repeated loading having a maximum value less than the strength of the material. Fatigue cracking is a process consisting of two phases, crack initiation and crack propagation. During crack initiation micro-cracks coalescent to form a macro crack. The presence of a macro crack marks the start of the crack propagation phase where the crack grows further through the material under repeated load applications.

The Indirect Tensile Fatigue Test (ITFT) offers significant potential for ranking mixtures’ susceptibility to fatigue crack initiation provided that the criterion is based on maximum tensile strain. The test can be performed in a very short time (4 hours) using very high stresses and a low number of cycles.

ITFT validation studies carried out at Nottingham University include correlation with the trapezoidal cantilever fatigue setup and the uniaxial tension compression apparatus. Using the initial tensile strain to characterise the fatigue curve, high correlation coefficients (in the order of 99%) were determined. To validate the repeatability of the test method 3 mixtures were tested in duplicate and the results compared. Small variations were calculated for the Hot Rolled Asphalt and Dense Base Course Macadam mixtures. Variations in the crumb rubber results were attributed to segregation problems and to the smaller amount of samples used to determine the regression lines. A series of inter laboratory reproducibility tests were carried out. Six laboratories contributed and three different mixtures were evaluated. Statistical analysis of the results indicates that the different data sets were statistically comparable.

Current research at Nottingham University is focused on the analysis of fatigue crack propagation. Two generic methods have been adopted, namely a theoretical approach using fracture mechanics and an experimental approach. Simulative crack propagation testing was carried out on beam samples. Actual crack lengths, as opposed to crack depths, were monitored with the use of image analysis software. As expected, polymer modified mixtures exhibited far greater resistance to crack propagation than conventional mixtures. A weak interface that influenced the direction of crack propagation was identified between the aggregate and the binder. Work being done by the authors at University College Dublin on fatigue crack propagation verifies the existence of this weak interface as indicated in Figure 10.
Using a modified indirect tensile test and the principles of fracture mechanics, crack propagation can be modelled. By drilling a hole through the centre of a 150mm diameter specimen that is diametrically loaded, crack length can be monitored by measuring vertical displacements and relating it to crack length through a compliance relationship. Linear elastic fracture mechanics is then applied to model fatigue crack propagation.

5. **Ageing of asphalt mixtures**

5.1 **Introduction**

The term ageing is used to describe the oxidation of asphaltic mixtures over time that results in the stiffening of the mixture and the reduction of the pavement’s flexibility, which may lead to the formation of cracks. Hussain Khalid of Liverpool University (UK), gave an account of the mechanisms of ageing and the techniques available to evaluate the ageing process. He elaborated on current research at Liverpool University on the ageing of porous asphalt mixtures. Chris Bell of Oregan State University (US), presented the results of research under the Strategic Highway Research Program (SHRP) which lead to the adoption of the short and long term oven ageing procedures by the Federal Highways Administration (FHWA).
5.2 Mechanisms of ageing

Asphalt technologists have identified the following factors that influence the ageing of bituminous mixtures:

- oxidation of the bitumen (rate depends on binder characteristics and temperature)
- evaporation of lighter bitumen constituents (function of temperature)
- polymerisation of bitumen molecules
- thixotropic hardening due to the formation of a structure within the binder
- syneresis or the exudation of the oily liquids from the bitumen
- separation where oily constituents are absorbed from the binder by porous aggregates in the mixture
- water and light effects
- micro-biological deterioration of the binder

All these reactions eventually lead to the embrittlement of the binder and the loss of durability properties of the asphalt mixture.

5.3 Ageing simulation and evaluation methods

Two distinct ageing processes underlay the service life of a bituminous mixture. Firstly, during construction, the mix is subjected to high temperatures and a high degree of air exposure (short-term ageing). Then it is subjected to the environment at relatively mild temperatures for a long duration (long-term ageing).

In general, short term ageing methods are either by oven heating or extended mixing. Long term ageing techniques include extended heating, pressure oxidation and infrared/ultraviolet treatment.

Ageing evaluation test methods are required to identify performance differences in the aged specimen. Ideally these methods should not only be cost effective and simple but also non-destructive in nature. Accordingly, preference has been given to modulus measurements such as the Indirect Tensile Stiffness Modulus (UK), Resilient Modulus (US) and the Dynamic Modulus.
Evaluation methods applied to aged binders include the following: Ring and Ball softening point, Black Diagrams and Master Curves Form Rheology, Fourier Transform Infrared Spectroscopy (FTIS) and Gel Permeation Chromatology (GPC).

5.4 Ageing of porous asphalt

Major concerns exist in connection with the long-term durability of porous asphalt due to its open nature which allows the ingress of water and air. The constant exposure of the binder film speeds up physical hardening and oxidation.

Current research at Liverpool University is focussed on the long-term durability of 20mm Porous Asphalt using four different binders (100pen, 200pen + 5% SBS, 100pen + 5% EVA and a polymer modified proprietary binder). An ageing apparatus, passing 3 liters/minute of 60°C air through a Marshall compacted sample has been developed. Ageing is periodically evaluated by measuring the ITSM of the mixture and the rheology, viscosity and Fourier Transform Infrared Spectroscopy of the binder. Analysis indicated that the 100pen mixture is the most susceptible to ageing effects and that the SBS and EVA mixtures are the most resistant to ageing.

5.5 Development of SHRP short and long term ageing procedures

Two substantial testing programmes were conducted at Oregon State University between 1989 and 1994 under SHRP to develop and evaluate ageing procedures. The first programme considered a wide range of laboratory test methods to age a variety of mixtures. The second part of the study was a field validation of the developed test methods.

The various types of ageing procedures that were examined include; low-pressure oxidation (LPO) at 60 and 85°C, and long term oven ageing (LTOA) at 85°C for 5 days and 100°C for 2 days. Triaxial testing and the measurement of the Resilient Modulus were used to evaluated the ageing process. From the analysis of results the following were concluded:

- Mixture ageing is influenced by both binder and aggregate (certain bitumens performed better with certain aggregate and vice versa).
• Two ageing tests were identified which offered the best compromise of ability to predict ageing, time and available equipment. The methods were:
  ♦ for short term ageing (0 – 2 years): Short term oven ageing (STOA) where the uncompacted mixture is placed in a 135°C forced air circulating oven for four hours,
  ♦ for long term ageing (+/- 5 years): Long term oven ageing (LTOA) where the compacted mixture is placed in a 85°C forced air circulating oven for 2 days.

6. **Conclusion**

It is anticipated that the introduction of these new performance related test methods will lead to improved mix designs that will perform better under high traffic. In addition to this, it will also lead to smoother construction, fewer delays and higher quality performance of pavements in Ireland.

7. **Acknowledgements**

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8. **Reference**

A general reference is made to the workshop proceedings, “Performance Related Test Procedures for Bituminous Mixtures”, edited by the authors. Copies of this volume (ISBN 1 85748 5955) can be obtained by contacting Michael Gilchrist directly.