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Accelerated Laboratory Curing of Bitumen-Emulsion and Foamed Bitumen Treated Specimens: Review of Current Practice

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Abstract: The objective of this project was to identify the most appropriate laboratory curing method(s) for bitumen-emulsion and foamed bitumen treated materials to ensure that laboratory testing should reliably characterise field properties. The findings from the literature study and overview provided a clear insight into the problems of characterising these types of material, and various contributing factors have been identified that appear not to be addressed consistently in the process of trying to relate laboratory testing to field conditions. Consequently, this project has ventured considerably beyond the original brief and main conclusions arising from this extended study include:

- no conformity either nationally or internationally on laboratory curing practices
- realistic characterisation for these materials demands that laboratory processes must closely reflect field conditions, especially regarding timing of mixing processes, compaction of specimens, and laboratory curing.
- field properties for any given mix will vary due to differences in environmental/climatic factors which influence the development of binder matrix.
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No standard laboratory curing method, in which time period, temperature and/or humidity are prescribed, will give consistent correlation with key early field properties. It is therefore recommended that ambient curing be adopted for most reliable comparison of laboratory and field properties.

The main findings represent key components that must be addressed in determining the suitability, application and probable field performance of bitumen-emulsion or foamed bitumen treatment. In this respect they are therefore viewed as providing a framework from which pragmatic development ought to ensure that some of the current technical confusion in making meaningful evaluations of these materials is minimised.

Keywords:
Laboratory curing, curing, bitumen-emulsion, foamed bitumen, laboratory testing, materials characterisation, roads

Proposals for implementation: Recommendations on best practice for laboratory curing, laboratory evaluation and materials characterisation of bitumen-emulsion and foamed bitumen treated materials are given. This report should be reviewed by key practitioners and researchers, and then the recommendations disseminated for adoption by industry in order to accelerate rational development of mix and pavement design methods for these materials.

Related documents:

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EXECUTIVE SUMMARY

The objective of this project was to identify the most appropriate laboratory curing method(s) for bitumen-emulsion and foamed bitumen treated materials to ensure that laboratory testing should reliably characterise field properties.

The findings from the literature study and overview provided a clear insight into the problems of characterising these types of material, and various contributing factors have been identified that appear not to be addressed consistently in the process of trying to relate laboratory testing to field conditions. Consequently, this project has ventured considerably beyond the original brief since it is considered neither reasonable nor constructive to confine the study to the initial objective when it is clear that laboratory curing cannot be viewed in isolation from these other contributing factors.

Main conclusions arising from this extended study are:

- There is no conformity either nationally or internationally on laboratory curing practices to ensure laboratory testing will reliably characterise field properties.
- Realistic characterisation of field properties by laboratory testing for these materials having time- and environment-dependent properties demands that laboratory processes must closely reflect field conditions, especially regarding timing of mixing processes, compaction of specimens, and laboratory curing.
- Field properties for any given mix will vary due to differences in environmental/climatic factors which influence the development of binder matrix.
- No standard laboratory curing method, in which time period, temperature and/or humidity are prescribed, will give consistent correlation with key early field properties.
- Realistic characterisation of these materials demands that the process must identify <u>when</u> acceptable properties are attained that meet practical time considerations.
- Primary characterisation of field properties by laboratory testing for these materials must be based on a reliable, robust and fundamental indicator that is inherently consistent, and can allow direct comparison of field and laboratory results. Material stiffness is viewed as best meeting these requirements.
- Predictions of field performance from Accelerated Pavement Tests for these materials having time- and environment-dependent properties are likely to be conservative due to the longer-term enhancement of engineering properties which benefit performance,

and to an extent that will be influenced by timing of such tests but which cannot be presently predicted.

- Practical guidance for practitioners on pavement design for these materials should draw on the established performance of "comparable" untreated materials, in which material stiffness provides a key point of comparison.
- The bitumen-emulsion treated materials that have provided the long-term track record for these materials in South Africa invariably used a low percentage of ordinary Portland Cement to aid in breaking of the anionic emulsion. This practice has spilled over into the more recent adoption of foamed bitumen treatment.
- Anecdotal evidence and more formal studies indicate that the inclusion of a small amount of cement with bitumen-emulsion, with sufficient moisture to promote the reaction, leads to the development of a complex bitumen-cement matrix. Such a complex matrix would undoubtedly be the source of the long-term and beneficial improvement in engineering properties that does not take place with bitumen or at the same protracted rate with cement.

The main findings from this study as summarised in the foregoing are considered to represent the key components that must be addressed in any rational method for determining the suitability, application and probable field performance of bitumen-emulsion or foamed bitumen treatment.

In this respect they are therefore viewed as providing a framework from which pragmatic development ought to ensure that some of the current technical confusion in making meaningful evaluations of these materials is minimised.

The scope for further work is regarded as considerable, particularly in terms of defining and refining criteria for future performance prediction, and developing the pavement design method to accommodate the broad scope of treated materials that could potentially be used.

The primary recommendation in respect of the original project objective is that ambient laboratory curing be adopted. This is the only practical method by which some reasonable similitude with field conditions can be expected, and which should therefore provide most realistic comparison of key early field and laboratory properties for these materials in which engineering properties are time- and environment-dependent.

Other primary recommendations given in this report include the need for a preliminary laboratory test programme to assess the feasibility of the proposed approach, and the need for a national test programme involving accelerated pavement testing, long-term pavement performance monitoring, and comprehensive laboratory programme.

It is also proposed that the inclusion of 1% cement (as a starting point), in line with the earliest applications of bitumen-emulsion treatment that have provided the track record for these materials, should be specified for both bitumen-emulsion and foamed bitumen applications. The mix design process will then be primarily used to identify the bitumen content necessary to yield a target material stiffness within an acceptable period under the environmental conditions pertinent to the application.

Adoption of this recommendation will draw on past successful experience, accept the ostensible importance of cement addition in development of the binder matrix for these materials, and provide a sounder basis on which to further develop the knowledge base.

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1. INTRODUCTION

Although accelerated laboratory curing of bitumen-emulsion and foamed bitumen treated materials is undertaken widely, there does not appear to be an accepted standard procedure.

A major contributing factor to this situation is undoubtedly the complex composition of these materials, which can include both active and inactive fillers such as lime, cement, fly ash, etc., as well as the bituminous binder and parent material. The complexity of the various chemical reactions and interactions that will occur during the treatment process is poorly understood at best.

While the laboratory curing regime must be benign (in that it should not alter these fundamental processes from those that would occur in field conditions), given the variations in composition of these treated materials in terms of specific composition and quantities, there is concern that the influence of accelerated curing is not known. Consequently there is a significant possibility that laboratory cured specimens have strength or other characteristics that are dissimilar to the field materials that they supposedly represent.

This is clearly undesirable as it means that decisions on the treatment of road materials, based on the results obtained from laboratory specimens could therefore be incorrect.

The original objective of this project has therefore been to identify the most appropriate laboratory curing method for these types of treated materials to ensure that laboratory testing should reliably characterise field properties.

This has been undertaken through a review of practices reported internationally, interviews and discussions with local practitioners and experts, and an overview of the fundamental mechanisms and reactions that could govern the curing needs. The original approved project proposal is given as Appendix A.

In the event, the findings arising from the overview of fundamental mechanisms, and both local and international practices and studies have highlighted the need to look beyond curing regime *per se*. This is due to the overriding link between material curing and meaningful evaluation of the engineering properties of the treated materials.

Consequently this study has gone far beyond the original proposed project scope. In particular it has reviewed all the factors considered most significant in influencing the properties of these bituminous cold mixes. This review has then presented a basis for what is seen as a rational method for practical evaluation of these types of material, which should ensure best correlation of laboratory tests with field condition.

2. CURING OF BITUMINOUS COLD MIX ROAD CONSTRUCTION MATERIALS

2.1. The curing process

This is usually understood to represent the process for treated road construction materials during which the new binding matrix is formed, and in cold bituminous mixes is directly associated with changes attributable to water. It is further implicit that the practical period of curing would be that taken in the field for the new matrix to develop to an extent commensurate with satisfactory early performance[Note1], and will normally be the period after which subsequent layer construction or opening to traffic is permitted.

A practical curing period can therefore be considered in the order of a few days to two weeks or so, regardless of the fact that strength/stiffness gains may continue over months and years.

Most applications for road construction necessitate that the treatment enhances the parent material properties. Significant changes and improved engineering properties, compared with the untreated parent material, would normally be expected in no more than a few days during the field curing process even if these are not yet sufficient to allow trafficking.

The rate of field curing will be influenced by the in situ conditions which, inevitably, will involve cyclical diurnal/nocturnal temperature and humidity changes. Temperature will almost certainly have the most dominant influence on curing for a given bituminous cold mix, since it affects directly both the rate of moisture change (evaporation) and the rate of any chemical reaction. Temperature is thus the primary factor considered in developing accelerated curing methods for laboratory tests.

In this respect it must be noted that prevailing temperature conditions in South Africa will generally be conducive to more rapid changes than those in northern

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[1] Acknowledging that microscopic changes to the matrix will continue to occur under normal service conditions, these generally being regarded as beneficial and leading to improved engineering properties (essentially increased stiffness and/or strength).

Europe and the United States, for example, which must be borne in mind when reviewing practice elsewhere.

Other factors that have been found to affect field curing rate include:

- mix moisture content after compaction;
- specific surface area and void content after compaction (grading);
- type of aggregate (specifically mineralogy and porosity);
- type and quantity of bituminous material;
- type and quantity of active filler if used (usually cement and/or lime);
- compaction method;
- layer sealing and sub-surface drainage conditions.

It will be readily appreciated that these are the factors that will influence the development of the binder matrix: proximity of active matrix ingredients, attraction to and coating of parent material, inherent speed of reaction, and constraints to moisture movement. It will further be noted that each of these will be uniquely project specific.

The difficulties in identifying the best approach to laboratory curing of cold bituminous mixes can, perhaps, be best placed in perspective by reference to the Optel project (Optimisation of slow-setting cationic bituminous emulsions for the construction and maintenance of roads)(1).

This objective of this major European research project (involving seven industrial and academic partners, and entailing 300 man-months effort over a three and a half year period) was to deepen knowledge on the manufacture of emulsions and cold bituminous mixes so as to use it in a rational way within improved design methods. The approach adopted, drawing on the specialist knowledge of the consortium partners, was to study first the individual components of cold mixes (bitumen, aggregates, emulsifiers), then their combined effects in bitumen-emulsions, and finally their combined effects in cold mixtures.

While the findings on curing from the Optel project are discussed in section 4, no specific hard recommendations on this aspect were made and it was left open to the need for further work. Significantly, this was concluded without any consideration of the additional complexities of incorporating active filler as is commonly the case in South Africa.

In contrast this study (approximately one man-month) of necessity seeks a pragmatic approach, while trying to avoid the overly esoteric and possible uncertainty that this can give rise to.

This section therefore provides a limited overview of the mechanisms and reactions that tend to govern the behaviour of the more common stabilising agents. The principal aim is to provide some insight into the conditions required in each case to promote most effective action/reaction of the stabilising agent, how the response is likely to take place under field conditions, and the likely influence of primary accelerated curing parameters (temperature and moisture content/rate of moisture change).

The overview is necessarily cursory within the context of this project, and errs on the side of the engineering impact rather than the fundamental behaviour in terms of chemical and microscopic binder interactions.

2.2. Laboratory processing

The sole objective in producing laboratory specimens of both treated and untreated road materials is to enable a reliable prediction of the field properties of a particular material combination, and therefore determine whether or not it should be satisfactory for the proposed application.

Disparity between laboratory and field conditions in processing road building materials has always been a concern, specifically in whether laboratory specimens are representative of the field. Assessing the extent of this potential problem is exacerbated by the evaluation test method since it is usually difficult to perform exactly the same test in the field or on recovered undisturbed samples.

In terms of laboratory samples, it is self-evident that these should approximate a realistic match to the probable field condition to ensure the most reliable and meaningful evaluation. Essentially standard preparation and test methods developed over years for conventional road construction materials, and for which good correlation of laboratory and field performance has been established, have been for untreated and stabilised materials.

While shortcomings in most standard preparation and test methods have been identified during the years, particularly with respect to the fundamental requirement of emulating field condition, it is clear that such shortcomings are not critical for those material types because consistent reliable results are obtained and the correlation with performance has been well established.

In the case of typical cold bituminous mixes used in South Africa, in which active additive content is relatively low (i.e. treatment rather than stabilisation), it should be firstly recognised that such low application rates will tend to lead to greater variability in treated material properties on a micro- to small-scale due to inhomogeneity arising from mixing. Field observations show, however, that despite this inherent problem, such materials both appear and behave as if homogenous (uniform) for practical engineering purposes.

This implies that any laboratory testing should be undertaken on specimens that are sufficiently large to ensure that such small-scale variability does not lead to high (and unrepresentative) variability in the test result.

Much more important, and directly related to the factors affecting field curing/ strength gain, is the intuitive recognition that the development of the binder matrix will differ according to degree of compaction achieved since this will directly influence the intimacy and effectiveness of the reagents. Because each cold mix application will differ in many fundamental ways, many of which will affect the compactibility of the mix, it must firstly be accepted that standard test preparations that rely on standard compactive[Note2] efforts will almost certainly yield different relative degrees of compaction for any given cold bituminous mix.

Firstly, this is unlikely to reflect field conditions where heavy vibratory rollers can normally achieve higher compactive effort than standard laboratory test methods, and densities that will approach refusal for the applied compactive effort.

Secondly, and most critical, the laboratory sample will be effectively a different treated material: the binder matrix skeleton is highly unlikely to be comparable. Consequently it is highly probable that the engineering properties determined

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[2] Generally a prescribed number of blows per layer from a drop-weight compacting hammer of specified mass, footprint, and drop height.

from the laboratory test will differ from those in the field and, even more crucial, the rate of change and absolute changes in the properties during curing are unlikely to be similar.

Given the most common applications of this type of treatment, which seeks to enhance the properties of parent material that normally cannot be used untreated (i.e. not usually the best graded or best quality material[Note3]), it should therefore be readily appreciated that standard methods for sample compaction can therefore lead to relative under- or over-compaction, and are unlikely to match field conditions.

This factor alone (correspondence or otherwise of laboratory specimens with field) is therefore viewed as critically important because its effect for these types of material is likely to transcend and subjugate any concerns regarding laboratory curing.

The following sections review the influence of curing (particularly temperature and moisture changes) on component materials, and current laboratory curing practices.

The recommendations arising, however, will take account of this most significant of factors which is viewed as a potentially significant factor contributing to confusion regarding best practice for accelerated laboratory curing for these types of materials.

2.3. Factors influencing curing of component materials

2.3.1 Parent material

Where parent material is untreated road aggregate of acceptable durability and without inherent defect, it can be assumed that no fundamental change in structure will take place in a curing process.

Problems can, however, arise with materials that are mineralogically unsound especially with respect to clay mineral inclusions. This is a concern, particularly when marginal materials are used, since various instances of unsatisfactory field performance not identified from standard laboratory tests periodically occur. For

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[3] Material that is often prone to further mechanical breakdown under applied compaction effort

such materials Atterberg testing does not identify the materials as especially plastic or potentially problematic, and the effects of the expansive reactions with moisture are normally only recognised during construction and service.

In such cases it is very clear that testing the engineering properties of laboratory specimens that have been subject to accelerated curing, thus rapidly drying out and removing the moisture, will undoubtedly mask this problem. While this is fortunately still a relatively rare materials problem, and independent of the laboratory curing process, it is simply flagged here to highlight the need to establish mineralogical soundness prior to any other testing.

For recycled sound and durable parent material that includes old bituminous or cementitious layer materials, it is probably realistic to assume that accelerated laboratory curing (with temperatures up to, say, 60° or 70° Celsius) should have no practical effect in causing any fundamental change to the broken down bound material.

This is on the assumption that these layer materials are likely to be at least a few years old (say, three), during which time the original matrix (albeit bituminous or cementitious) is likely to have become inert for practical purposes under the combined cyclical effects of normal temperature[Note4] and moisture variations.

The effects of curing on the fresh constituent bituminous and cementitious materials are reviewed in the following sections.

2.3.2 Bituminous binder

Bitumen is essentially a visco-elastic material in practical road applications (subjected to small strains and relatively rapid loading) for which the viscosity is highly temperature sensitive. In hot-mix applications, it is normally heated to more than 140℃ to enable mixing with aggregate since it is totally unworkable (too viscous) at ambient temperatures. The parent bitumen used in cold-mix applications, whether emulsion or foamed, is fundamentally the same although

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[4] In South Africa it is normal for road surface temperatures to exceed 50℃, and commonly 60℃, in direct sun during the hottest periods of the day in summer for which nominal ambient shade temperature is typically mid 30℃. In "hot" areas ambient temperatures will be typically 10℃ higher, and road surface temperatures can be significantly higher accordingly.

usually a higher penetration grade is used (say 80/100 or more) rather than the stiffer 40/50 or 60/70 pen bitumen commonly used for hot-mix applications[Note5].

In emulsions, it is applied in the form of bitumen droplets with diameters typically in the range of 1 to 20 micron (.001 to .020 mm) dispersed in water and normally kept stable by ionised emulsifier molecules.

South Africa seems unique in that anionic[Note6] emulsions are most widely used in road construction applications, whereas it appears that cationic emulsions are predominantly used elsewhere (viz, North America, Europe, South East Asia, Australasia). It should be noted, however, that the major application in these other regions is for road surfacings rather than road base construction.

The cationic emulsions are later developments (from the 1950s, rather than early 1900s with significant development from the 1920s for anionic emulsion), and are considered to give better adhesion in both road and industrial applications. In contrast anionic emulsions are regarded as generally providing poor adhesion, especially to siliceous (acidic) aggregates and to metallic or stone substrates.

Both types are produced in various stability grades, nominally termed rapid, medium and slow setting (or stable grade), of which only the medium and slow setting could be regarded as having practical application in road base courses since the rapid setting breaks too quickly. The fundamental developments in bitumen-emulsion technology have all been geared to the additives (such as emulsifiers, surfactants, adhesion agents) necessary to ensure a practical and usable product for the envisaged application. The aim has always been simply to temporarily liquefy bitumen, by means other than heat, in the most cost-effective environmental- and user-friendly manner.

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[5] Apart from penetration, the parent bitumen is also normally checked for softening point ("ring and ball" test). Because this is designated by temperature, which will usually be in the range 40°C to 50°C (for the conditions in this standard test), concerns are periodically voiced that higher temperatures will lead to bitumen flow in the treated material. Such concerns are considered largely due to misinterpretation of the standard test result in relation to the application, and are regarded as moot in this review of curing of bituminous cold mixes.

[6] Anionic emulsion particles carry a negative charge and are therefore attracted to a positive electrode (anion). Cationic emulsion particles are positively charged and are attracted to a negative electrode (cation)

Breaking of the emulsion is the process during which the bitumen reverts to its original (high viscosity) state[Note7], and during which it becomes a binding agent and bonds with the parent aggregate. This should begin during the mixing process and occur slowly enough that the material can be placed and compacted before it becomes "unworkable", which would be the case if the bitumen has fully reverted to its original form.

The significant difference between cationic and anionic emulsions noted during breaking is that the former are electrostatically drawn to the (negatively charged) aggregate, which initiates breaking through a physico-chemical reaction, whereas the anionic emulsion does not normally break chemically but relies simply on water evaporation. In either case, the process requires that the microscopic individual emulsified bitumen particles coarsen into larger agglomerations (simplistically, passing through flocculation and coalescence phases), which adhere to the parent aggregate forming the bituminous binder. Even after breaking is complete, the water must still be completely separated for the residual bitumen to achieve full strength(2).

In terms of accelerated laboratory curing it seems realistic, from this review, to conclude that higher temperature applied to compacted bitumen-emulsion treated material will, for practical purposes (say to 60° or 70°C at least), not have any significant effect on the engineering properties and efficacy of the residual bitumen binder.

In the case of foamed bitumen, in which the bitumen is already heated as a fundamental part of the process, it can again be concluded that the effect of temperature on the binder alone in a compacted foamed bitumen treated material will not alter the engineering properties and efficacy of the residual bitumen binder.

Any significant difference between foam treatment and emulsion treatment of road construction aggregates (that do not include other active ingredients that modify the behaviour) can therefore be primarily attributed to differences in the dispersion

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[7] It may not be exactly the same as the original bitumen if viewed from a micro-chemical stance, but from an engineering perspective it will be effectively the same.

of the binder and coating of the parent material, if other key parameters are similar[Note8].

While this may be generally taken as a broad reality, it should be seen as much more fundamental in that consistent poorer performance of one treatment type or the other implies less efficacy for the specific application, and therefore scope for improvement in the treatment process. Identifying such differences and analysing them in the binder matrix at a microscopic level ought to enable such development.

2.3.3 Active fillers

The two main additional additives commonly used in foam- and emulsion-treated materials in South Africa are lime and cement. They are both active in that they promote reaction and undergo chemical change within a relatively short time and during the construction process. Each has been adopted for different purposes, and they are discussed below. The ensuing discussion is based on the assumption that these active fillers will not react in any significant manner with the bituminous binder.

2.3.3.1. Lime

Lime will only tend to be used when the parent material is plastic (normally a Plasticity Index significantly more than 6). In conventional construction it would normally be applied several hours ahead of any bituminous treatment to reduce the plasticity, while during in-place recycling it would be applied simultaneously. Lime treatment has been used for this purpose for decades in “modern” layered road pavement construction. Application rates will normally be low and, for practical treatment of materials to be foam- or emulsion-treated, will tend to be 2% by mass or less.

In the case that the parent material has been previously lime- (or cement-) treated, as noted earlier, it is probably realistic to assume that the original matrix is unlikely to have any significant additional effect on subsequent cold bituminous treatment regardless of earlier application rate.

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[8] Key parameters are the parent material, compaction (density), residual binder content, temperature and moisture content, on the implicit assumption that the binder has reverted to its original bitumen grade, and that this is the same in each case

Lime is traditionally produced from heating limestone[Note9], is normally applied in a powder form, and reacts with the plastic (clayey) material in two ways. First, it agglomerates the fine clay particles into coarse friable particles, through a phenomenon called base exchange. This base exchange involves calcium ions displacing sodium and hydrogen cations. Secondly it produces a cementing or hardening action in which the lime reacts with the available silica and some alumina in the clay soil forming hydrated calcium silicates and aluminates (pozzolanic).

This pozzolanic process is relatively slow and can therefore allow rework (even over several days if necessary) without detrimental effects. Gradual improvement in engineering properties attributable to lime (basically strength and stiffness gains) can continue over months and years. While the reaction process only occurs in the presence of moisture (water), removal of the moisture will cause a slowdown and practical halt if completely dry, which will be recommenced with addition of moisture.

In the context of accelerated laboratory curing it seems realistic to assume that when lime has been used, provided the initial reaction to reduce plasticity has been effected (which will normally be a prerequisite for further cold bituminous treatment), a temporary slowdown or halt in any very slow longer-term engineering property enhancement due to moisture removal is perfectly acceptable. Thus any laboratory testing should still provide a very good indication of the construction-critical short-term properties, while possibly erring on the conservative side.

2.3.3.2. Cement

The addition of cement to these types of mixes was originally applied simply to initiate breaking of the anionic emulsion, and cement application rates of 1% by mass are still commonly used in South Africa during emulsion treatment. This is normally considered to represent the lowest practical application rate at which a reasonable degree of uniform mixing could be achieved.

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[9] Forming calcium oxide, CaO (quicklime) which is very reactive with water, and commonly used in the less reactive hydrated form calcium hydroxide, $Ca(OH)_2$, or slaked lime.

Whether or not this level of application rate on typical materials used for cold bituminous mixes really adds any degree of improved material stiffness (which could be expected from normal cement stabilisation in which higher additive application rates are used) still seems uncertain. Given the application rate, likely construction application and process, it seems unlikely that any significant enhancement would be achieved in the short-term at least unless a direct, and as yet unquantified, reaction with the bituminous binder takes place.

While cement addition would have been simply ordinary Portland cement (OPC) in the past, the change in South African specification classes and requirements for cements(3) may cause some confusion since there are now five main types defined (CEM-I, -II, -III, -IV, and CEM-V), with various sub-types and strength classes. The wholesale adoption of the European standard in 1996 does not, however, mean that all types are available in South Africa.

For practical purposes, the cements of classes CEM-I and CEM-II (classified as Portland cement (PC), and other Portland cement, respectively) with the lowest strength classification and normal hardening/strength gain (designated 32,5N) are likely to be most used in these applications. The closest to the previous OPC designation is ostensibly CEM-I 32,5N. The main difference between these two classes is the introduction of extenders or fillers in CEM-II (typically in the range 6 to 35% by mass) such as ground blast furnace slag, fly ash and limestone filler.

These extenders, when active (undertaking some form of pozzolanic or cementation reaction), will invariably be less reactive than the parent Portland cement and are normally used for specific longer term benefits in normal concrete applications (such as reduced heat; improved strength gain after 28 days; improved impermeability).

In this discussion, the inclusion or not of these relatively passive extenders should not have a marked significance regarding the influence of accelerated laboratory curing. The primary reactive agent is the PC, and this is predominantly composed of dicalcium and tricalcium silicates (simplified nomenclatures, C_2S and C_3S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) [Note10].

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[10] The nomenclature follows standard cement chemistry shorthand. The corresponding (nominal) chemical composites are as follows: C=CaO; S=SiO_2; A=Al_2O_3; F=Fe_2O_3.

The actual components will often be complex chemical crystalline and amorphous compounds, in which the specific composition will be influenced by the manufacturing process and factors such as kiln temperature and oxygen availability. Typical composition of PC is approximately 50% C_3S, 25% C_2S, and about 10% each for C_3A and C_4AF, plus added gypsum used to modify setting characteristics. The relative proportions of the calcium silicates can vary considerably, but the combined total is reasonably consistent and typically comprises 70 to 75%.

Early hydration is controlled by the C_3A which reacts very rapidly, causing setting and early strength gain in a matter of hours in conventional concrete. The long-term hardening and strength gain is, however, dependent on the calcium silicates. The C_3S is the more reactive and influences early bonding characteristics, and is mainly responsible for initial strength gain during the first few days, while longer term continued strength and stiffness gain is attributable to the slower reacting C_2S. Reactions are exothermic (heat generating), and temperature will influence reaction rate. About 20% lime is produced during the hydration reaction of cement.

The main reaction product from the hydration of these components, calcium silicate hydrate, is the binder matrix controlling engineering properties in conventional concrete (setting and hardening, strength and dimensional stability).

As for lime, the cementing reaction will occur with the presence of moisture and cease when moisture is unavailable, but recommence with addition of more moisture. In conventional concreting it is therefore normal practice to limit moisture loss by application of curing compound or water ponding at least during the first few days to facilitate the reaction and ensure early strength gain to acceptable levels. The water-cement ratio (by mass) of completely hydrated cement is about 0.22 to 0.25.

Water-cement ratio is the key factor influencing development of an impermeable binder matrix and strength of conventional concrete. In normal concreting applications (which will typically have a cement content of some 12 to 15% by mass), the target range for water-cement ratio is typically less than 0.5, being primarily governed by achieving sufficient workability. Higher water-cement ratios lead to an exponential increase in permeability of the matrix, reduction in matrix strength, and associated loss in durability and strength of the concrete.

In the context of application in bitumen-emulsion treatment for road materials, this is therefore about 0.5% free[Note11] moisture content (assuming 1% cement content by mass). However, the nominal water-cement ratio is actually likely to be far higher if it can be assumed that most bitumen-emulsion applications will commonly have a free moisture content of 5% or more. In these applications the moisture content is primarily governed by the compactibility needs of the parent material.

Apart from the actual construction process, which is generally likely to work against developing an undisturbed cementitious matrix, the fact that the nominal water-cement ratio will be abnormally high would ensure a minimal contribution towards any strength or stiffness enhancement based solely on a cement matrix. However the possibility that some other action, such as a more complex reaction with the bitumen binder, cannot be discounted.

In terms of laboratory curing procedures, increased temperature will promote more rapid hydration reaction of the cement (provided that moisture is available for the hydration process). If it is assumed that no reaction with the bituminous binder takes place, then the cementitious reaction should be relatively ineffective, and higher temperature should have little practical influence on the physical cement matrix formation process (if any).

It would seem judicious, however, to avoid too high a temperature (say 80º C or more) which would possibly remove moisture too rapidly and may curtail any reaction within the curing period, thus rendering it dissimilar to field conditions where moisture (both as water and water vapour) would be available within the nominal field curing period.

If, on the other hand, there is in fact a much more complex interaction occurring then it would be imprudent to assume that the basic responses might not be modified to an extent that they do not follow the same behaviour. This should not

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[11] Water that is not held within aggregate particles or otherwise constrained from being available for the hydration reaction

be discounted, simply given the basis for this study, which stems from the manifest difficulty over the years of reliably characterising the treated material particularly in terms of relating field and laboratory responses.

The addition of similar nominal quantities of cement to foamed bitumen treated materials would appear largely superfluous, since it is clearly not required to aid the bitumen foaming process, and seems largely a "genetic" carryover from the established bitumen-emulsion approach in South Africa. In some cases its use could be merited (as for lime) to address a specific need, but overall it appears to be viewed as an "insurance".

However, while it is difficult to envisage any tangible benefit based on the foregoing discussion of fundamental cementitious reaction, this cannot be ruled out especially given the possibility of more complex interaction with the bituminous binder component. Thus the comments on the bitumen-emulsion treated materials can be considered similarly applicable.

2.3.3.3. Other active fillers

At this stage, there does not appear to be any other commonly used additional active filler in these types of treated materials. Main candidates would, in any case, be most likely to be substances such as pulverised fly ash (which is only active when mixed with lime) or blast furnace slag. These types of filler were briefly discussed in the context of additives to certain class Cem-II cements. It was concluded, in effect, that it is unlikely that any significant differences in the engineering properties of the bituminous cold mix could be identified between the field material and laboratory cured specimens that might emanate from these materials. This is on the implicit assumption that application rates would be relatively low, and that any reactions will be slow and of small effect within the practical curing period.

3. LOCAL RESEARCH AND PRACTICE

3.1. Previous experience

The Sabita-sponsored project that commenced in 1996 and led to the publication in 1999 of a manual on the design and use of emulsion treated bases, ETBs, is the current reference document in South Africa for these materials(4). While an updated version is currently being finalised, Sabita Manual 21 therefore remains the *de facto* national yardstick.

The recommended laboratory curing regime, derived after a review of then current practice, is curing in the moulds for 24 hours at ambient temperature, followed by 48 hours curing at 40℃ (if optimum moisture content is less than 8 per cent), or 45 hours at 60℃ (if the optimum moisture content is greater than 8 per cent). It also alternatively proposes that specimens can be cured for 7 days at ambient temperature (when cement has been added) or 28 days at ambient temperature (when no cement has been added).

As an indication of its general application, it should be noted that this approach is currently recommended by the Construction Industry Development Board in their best practice guideline for labour-based construction of emulsion treated gravel published in April 2004(5).

In deriving the Sabita Manual 21 recommendations for bitumen-emulsion treated materials, comprehensive review of contemporary research and practice was undertaken. Marais and Tait's paper at the 5th CAPSA conference in 1989 probably provided the best overview of ETB practice at the time(6). This identified the need for curing to simulate field conditions just after compaction for mix design, and separately curing to the "final" cured state for pavement structural design. In the latter case periods of 6 months to 2 years were nominally suggested as the probable time for ETBs to reach this final state under South African conditions.

A very limited laboratory comparison of curing approaches for a single parent material was reported. This entailed adopting two laboratory post-compaction curing methods to "most accurately simulate site conditions with regard to in situ moisture content and strength development with time". These were 20 hours oven drying at 40°C, and 4 days air drying at 23°C followed by placing in a 100 mm Hg (mercury) vacuum at the same temperature for 3 days, respectively. In each case the specimen material was cured prior to compaction either by standing in air for 24 hours at 23°C, or one hour oven curing at 60°C. It was concluded, on the basis of consistency of results, that there was nothing to choose between the pre-compaction methods while the post-compaction oven drying gave less variability in results.

About the same time, and drawing on mix design procedures proposed by Marais and Tait, another Sabita-sponsored project on curing procedures was reported on by Laatz & van der Merwe(7). Curing variations consisted of oven heating specimens at 40°C or 50°C for periods varying between 5 hours and 30 hours, plus two procedures used in the USA: the Asphalt Institute method (3 days air curing in moulds at 23°C, and then 4 days vacuum drying) and the University of Illinois method (3 days air curing in moulds at 23°C). No clear conclusions regarding most appropriate curing method were drawn from this study.

A later study used as a basis for the mix design aspects of Manual 21 was reported in 1997(8). This gave an overview of various laboratory curing methods used both in South Africa and overseas. An indication of the diversity of curing approaches variously used is summarised as follows:

- 24 hours @ 60°C (with cement)
- 24 hours @ room temperature in mould, then 24 hours @ 38°C after extrusion
- 24 hours @ ambient temperature in mould, 48 hours @ 60/70°C in plastic bag after extrusion, then 4 hours soaking prior to test
- 45 hours @ 60°C in mould
- 48 hours @ 60°C (with lime)
- 72 hours @ 23°C and vacuum saturated in mould
- 72 hours @ room temperature, 96 hours vacuum saturation

Without delving too deep it is readily apparent that there is the strongest probability that each method would give a different result for any given mix and, more specifically, it suggests that either the target field condition to be simulated is different (very likely) or the target field condition is not well defined (also very likely).

In the case of foamed bitumen, Jenkins provides a comprehensive overview of past curing methods adopted by various researchers between 1970 and 1994(9). Again, an indication of the various approaches is listed below, together with the nominal field cure period considered to be represented if defined:

• 24 hours @ ambient in mould	for short term simulation
• 24 hours @ ambient in mould, 24 hours @ 40°C	7 – 14 days
• 24 hours @ ambient in mould, 72 hours @ 40°C	30 days
• 24 hours @ 38°C	7 days
• 72 hours @ 23°C	
• 72 hours @ 60°C	construction period + early life
• 72 hours @ 60°C	23 to 200 days
• 72 hours @ 60°C	1 year simulation
• 72 hours @ 60°C, 72 hours @ 24°C	
• 240 hours (10 days) ambient, 50 hours @ 60°C	

While it appears that more effort has been made to relate the laboratory curing regime to field condition in these cases, it is still readily apparent (particularly from the 72 hour/60°C regimes), and of great significance, that the actual field curing conditions (providing the field target) must differ.

3.2. Current practice

As noted above, Sabita Manual 21 provides the current national yardstick for curing of bitumen-emulsion treated materials, and this is certainly the base method used by Bondietti *et al* as reported at the recent CAPSA'04(10). This work also included a comparison with ambient curing, from which it was found that UCS results from the accelerated curing regime differed from those from ambient curing.

Other local studies reported at the same conference, however, did not follow the Manual 21 recommendations for laboratory curing, confirming possibly similar concerns regarding conformity of accelerated curing with field, and demonstrating that there is currently no consensus.

Thus Hodginson & Visser(11) cured for 24 hours in the mould at ambient temperature, followed by 72 hours at 60°C, in their study of the role of fillers in both bitumen-emulsion and foamed bitumen treated materials. Jenkins *et al* (12), on the other hand, adopted curing of 72 hours at 40℃ in sealed plastic bags in determining which of these treatment types would be most appropriate for cold recycling of a section of the N7.

Houston & Long(13), in a study into ITS and UCS test protocols for foamed bitumen treated materials, adopted various curing regimes, including 72 hours in the mould at 40℃, and 24 hours at ambient temperature followed by 48 hours in sealed plastic bags at 40℃.

The recent Asphalt Academy guideline for foamed bitumen treated materials(14), which can be regarded as the national industry standard for this treatment type, proposes a curing regime of 24 hours in the mould, then 72 hours at 40℃ in sealed plastic bags. This is expected to simulate approximately 6 months field curing.

Current research at the University of Stellenbosch into curing of foamed bitumen treated materials (Malubila[15]) has now focused on correlating laboratory and field moisture contents as the basis for a curing regime. At this stage it is clear from the work that target moisture contents (in relation to optimum moisture contents) will vary according to parent material type. The work is ongoing.

3.3. Summary

The foregoing simply confirms that the whole issue of curing for these types of mixes is neither clearly defined, nor apparently close to any agreement on the most appropriate method for South Africa.

Apart from some of the factors highlighted in the previous chapter that are regarded as likely to have significance (notably, achieving best conformity between field material and laboratory specimens) and which are not ostensibly recognised or addressed, there is the general concern that no real clarity as to the field condition being aimed for is evident overall. This could be partly attributable to the possibly obscuring influence of such other variable factors.

The following chapter touches on some recent international work in order to try and clarify the situation further.

4. INTERNATIONAL RESEARCH AND PRACTICE

In commencing the overview of international practice, the fairly recent major European OPTEL project(1) noted earlier seems a good starting point. In this case an underlying rationale was to look at the influence of both temperature and humidity on the rate of moisture departure on laboratory specimens(16). Moisture content change and compressive strength were monitored. Three temperature/relative humidity combinations were used: 18ºC/50% (designated reference conditions), 50ºC/50% and 50ºC/10%.

In this case the end point objective was the achieval of a compressive strength equivalent to that obtained after 30 days curing at the reference conditions, which presumably are regarded as simulating nominal field conditions. It was concluded that increasing the temperature at constant humidity (50% relative humidity, rh) did not significantly accelerate moisture loss, while 5 days curing at 50ºC and 10% rh gave equivalent compressive strength to the 30 day curing at 18ºC/50%rh. In all cases the comparable strength values were achieved at or near the lowest effective residual moisture content, which tended in all cases to a value of about 1% moisture content. Further, it was observed that there was a significant increase in the rate of strength gain as the moisture content approached within 0.5% or so of this minimum value.

It was noted that these findings raised further questions related to probable site behaviour, including the manner in which the free water was held within the material, and the phenomena governing the increase in cohesion/strength especially as the minimum moisture content is approached.

On these last two issues, it was concluded that temperature and rheological behaviour of the bitumen would have an influence, thus leading to the finding that it is probably more realistic to accelerate water departure by humidity reduction rather than temperature increase.

For practical purposes, this study duly confirms that there is no established standard European procedure for curing of bitumen-emulsion treated materials, further corroborated by the comprehensive study by Brown and Needham(17). In this case the research reported formed part of a three year study to investigate the fundamentals of emulsion breaking and mixture curing when cement was incorporated, thus being more aligned with South African practice. In this study, however, a slow setting cationic emulsion was used.

The mixes were distinctly high quality: 20mm maximum size graded granite aggregate conforming with the UK specification for Dense Bitumen Macadam (DBM), with 8.06% bitumen-emulsion (62% binder content) by mass (residual 4.7 to 5% bitumen content reported). Ordinary Portland cement was applied at 0, 1, 2, 3 and 4 % by mass to investigate the effect, and certain tests made use of hydrated lime and calcium chloride for comparison. Moisture contents (including 3% in the emulsion) were in the range 5.5 to 7% with additional water added with increasing cement content. In addition, certain tests for mechanical properties were duplicated using conventional hot-mix in which normal bitumen was substituted for the emulsion at a bitumen content of 4.7%.

While the stiffness moduli[Note12] of all emulsion treated mixes increased steadily with time, the effect of cement inclusion was distinct with the values, and rate of stiffness increase, being significantly higher with increase in cement. In the case of the cement-treated hot mix, there was no practical change.

Most significant, with regard to South African practice, is the indication that comparable stiffness moduli to the hot-mix (approximately 2,200 MPa) were achieved after about one month for the 1% cement addition, and just under one week for the 2% cement case, in each case with the stiffness continuing to increase with time. Curing and testing were undertaken at 20ºC and 50% relative humidity after specimen extraction from the moulds after 16 hours.

Subsequent oven drying of remaining specimens at 60ºC to constant mass after completion of these tests (approximately 3 months) to simulate "full curing" gave seemingly disproportionately high stiffness values. This was interpreted as suggesting that the higher temperature might affect the binder viscosity through perhaps oxidation or loss of components that are volatile at this temperature.

Since breaking of the emulsion has also been attributed to lime and calcium chloride addition, further comparative tests using OPC and lime (added at 1% by

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[12] Determined using the Indirect Tensile Stiffness Modulus test in the Nottingham Asphalt Tester

mass of aggregate), and $CaCl_2$ (at 1% by mass of emulsion), were undertaken. The addition of lime and $CaCl_2$ gave results virtually identical to those of the emulsion alone (with perhaps a slight enhancement) but neither had the same significant effect on stiffness as cement addition.

Measured Indirect Tensile Stiffness Modulus values for the emulsion alone, the lime and the calcium chloride, increased from about 300 MPa after 5 days to 1,200 to 1,500 MPa after three months or so. In contrast, the stiffness of the 1% OPC treated specimens increased from some1,300 MPa to more than 3,500 MPa for the same test period.

The clear indication is that the cement addition enhances the mix stiffness by stiffening the binder. This was checked from penetration tests on bitumen-emulsion/cement mixtures, using moisture contents based on what would be required in a real mix with aggregate, and an emulsion quantity and cement quantities of 8.1% and from 1 to 10% respectively for the same hypothetical mix (i.e. cement:emulsion ratios from 1:8.1 to 10:8.1).

These samples were firstly used to monitor the rate of emulsion breaking (which completed within 6½ hours for a cement content of 4% and more, within 24 hours for the 2 and 3% cement contents, and after 48 hours for the 1 cement content), at which stage a solid mass of bitumen-cement mastic was formed with a slightly yellow coloured clear water on top. The specimens were then kept at ambient temperature for a further 48 hours drying period and tested for penetration after then bringing them up to 25ºC in a water bath.

The bitumen in the emulsion was nominally 100 pen, and it was found that the results for 2% or more cement addition gave markedly reduced penetration (less than 30 pen at 3% and typically 10 pen and less from 4% upwards). The 1% addition showed an increase on the nominal penetration grade (112 pen measured) for reasons that were unclear, but attributed to possible entrainment of a small amount of water.

Overall the study gave very clear indications of the beneficial effect of even minimal cement inclusion with bitumen-emulsion, and seems to provide some indicators that could be useful in both this study and in the broader context of bitumen-emulsion treated material mix design.

Insight into current US thinking on bitumen-emulsion may be gained from a recent study on evaluation of asphalt (bitumen) binders used for emulsions, undertaken by the University of Minnesota for the Minnesota Department of Transport and reported in August 2003(18). The stated main objectives were to better understand the role of asphalt emulsions in recycled asphalt pavements and to develop the means to better characterise their properties related to field performance. This objective can obviously be considered a widespread, and by implication worldwide, focus which serves to emphasise the lack of clarity of the current situation.

In this case, the extent of the study was limited because of unavailability of well documented field data so that it was not possible to develop meaningful correlations between the laboratory data and actual performance. Thus the study, which essentially used two curing methods (air curing, and curing in the rolling thin-film oven apparatus) to evaluate the properties of four typical bitumen-emulsions used in Minnesota, characterised the binders in accordance with AASHTO MP1 and MP1a specifications (Superpave performance grade binder specifications).

The most important finding in the context of the present study, from the array of sophisticated tests undertaken, was that the air-curing method was identified as the curing method of choice.

Generally trying to ascertain what laboratory curing methods for bitumen-emulsion and foam treated materials are adopted internationally has tended to confirm that there is no conformity, whether within the United States, Australasia or elsewhere. The only claim found for a complete mix design system for cold mixes was in fact from Norway(19). In this case the laboratory curing regime (applied to both treatment types) would be 7 days (168 hours) oven drying at 40°C. An alternative in the event of lack of time (and subject to client approval) would be 72 hours at 60°C. However it would appear that these mixes would not include cement addition.

5. DISCUSSION AND THE WAY FORWARD

5.1. General discussion

At this juncture, it is clear that the foregoing overviews provide a clear indication of the difficulties in identifying the best approach to accelerated laboratory curing of cold bituminous mixes, and especially when cement is added (as is usually the case in South Africa). The reason for such difficulty can be stated very simply: no practical[Note13] accelerated curing method will provide a standard that can be universally adopted.

The underlying problem has been spelt out and acknowledged from the outset.

The nub of the problem is simply that field curing of these types of material will differ according to the fundamental conditions in the field at the time of construction. In particular this includes the temperature and humidity conditions, both of which have been shown to be the significant factors influencing rate of curing.

Consider the case for any specific mix constructed in the field. Assuming that all other physical mix parameters that influence curing rate are replicated in the laboratory (mixing; compaction and compaction technique; mix moisture content after compaction; grading; aggregate; type and quantity of binder and active filler), it should be readily appreciated that a "standard" [Note14] accelerated curing method cannot be consistently related to the field condition during the critical first few days to two weeks or so. Simply stated, the rate of strength/stiffness gain in the field of hypothetically identical sections will vary according to cyclical temperature and humidity conditions at the time.

When cognisance is then taken of the other factors that will influence curing of real materials, each of which will differ with each unique application (mixing; compaction; mix moisture content after compaction; grading; aggregate; type and

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[13] Not only implying a reasonably uncomplicated and readily implemented method but, more significantly, also targeted on reproducing key early life mix characteristics and properties

[14] Meaning a process in which temperature (and probably humidity, for these particular materials) regime is prescribed, together with curing period(s), and which by definition should give repeatable and reproducible test results

quantity of binder and active filler), the possibility of formulating a practical standard accelerated curing approach should be recognised as remote.

Significantly, it should be noted that this conclusion has been reached without recourse to further considering the possibly adverse influence of higher temperatures, as would normally be applied in accelerated curing, and over which there is already concern (viz, the substantial Optel study (refs 1 & 16), and the recent comprehensive Nottingham and Minnesota studies(17 & 18)).

This finding derives as a direct result of the relatively slow and continuing curing process of these materials, which can lead to measurable improvement in engineering properties over months and years, but should give sufficient change within the first few days or so to allow further construction or trafficking without deformation. In other words, the goal posts continue to move but in each case the amount and extent of movement is likely to differ with each unique application.

This behaviour is also the main reason that trying to derive the final or definitive engineering properties of these types of materials is both extremely problematic and ultimately somewhat futile.

It is problematic in that there is no clear indication of what the ultimate engineering properties will actually be in the field. The work at Nottingham highlights this(17): oven drying specimens at 60°C to constant mass after they have been allowed to ambient cure for some 3 months or so to obtain “fully cured” stiffness values led to the following observation.

> “The stiffness recorded for oven-cured specimens seemed disproportionately high compared with those after ambient cure. This raises the question as to whether oven curing at 60°C affects the binder viscosity through chemical changes such as oxidation or loss of components which are volatile at this temperature.”

Even if these “disproportionately high” values are accepted as a true reflection of the material’s potential, then from the ambient curing temperature trends it would imply that this state would only be achieved in years rather than months (which is in line with anecdotal evidence). This also assumes that this state is reached even if the material is not completely dried out, which would be more likely to reflect field conditions even in the relatively distant future.

It is somewhat futile in that the principal objective of determining the final engineering properties would be to use them to predict future performance.

If it is accepted that the engineering properties pertinent to long term performance (primarily stiffness and strength) continue to improve in the field over long periods, it appears practically impossible at this stage to estimate future performance with any real accuracy since each unique application will behave differently and according to the environment applying. Without comprehensive long-term performance data there is no valid yardstick since even full scale accelerated pavement testing (APT) can not simulate the longer term enhancements in engineering properties, either in extent or in rate of improvement.

Thus such testing will almost certainly be conservative, but to a degree which will be unknown from the APT "snapshot", since even the age at test is likely to influence performance observed during such testing.

In this respect it would undoubtedly be beneficial in developing our knowledge base to undertake repeated APT testing on a particular road section over a long period: say first test after 3 months, then say 1 year, and then say 3 years. It would be almost essential that the section is trafficked normally in the interim, to avoid the possibility of unrepresentative results, and by extension it should form part of a long-term pavement performance (LTPP) test so that the normal in-service performance and key parameters (such as traffic loading, deflections, types of distress and environment) are reliably monitored.

However it must be recognised that each application will differ. In this respect the proposed timing for APT testing seems intuitively acceptable to probably develop some reasonably robust performance relationships applicable more broadly.

A very compelling programme would be one in which the elements of APT, LTPP, and comprehensive laboratory testing are combined for, say, three replicate road sections (each including bitumen-emulsion and foamed bitumen sections) constructed in different regional environments. Obvious choices would be on the highveld in Gauteng, in a high humidity near-sea level area in KZN, and probably in an area of the Western Cape. Irrespective of feasibility, costs and logistics, an investigation of this scope and nature would yield a wealth of knowledge with value that ought to far outweigh the costs.

However this will not address the main current problem of providing pavement design guidance for practitioners that extends beyond the very limited range of material for which sophisticated transfer functions have been developed from limited APT performance.

A simplistic but realistic view would be that, provided the bituminous cold mix material has acceptable engineering properties when opened to traffic, then it should provide better serviceability than an equivalent unbound material with similar in situ stiffness (or any other material in which no improvement in the engineering properties would be anticipated). In other words, a practical and conservative start point for pavement designs likely to have acceptable future performance would be the current TRH4 granular base pavement designs(20).

While the development of suitable performance models for both bitumen-emulsion and foamed bitumen treated materials is outside the scope of this current study, it is considered that the foregoing observations must be borne in mind in the development of a meaningful design catalogue for these materials even if sophisticated transfer functions have not yet been developed.

5.2. The way forward

There should be no doubt at this stage that any form of standard accelerated laboratory curing is unlikely to provide a consistent and reliable method for categorising bituminous cold mixes as commonly used in South Africa.

These mixes can be broadly described as having residual bitumen contents of 1 to 3% by mass, and will usually include a cement addition of 1% or so, initially used with the anionic bitumen-emulsion to promote breaking, but now viewed as a key to enhancing the subsequent engineering performance as a road material beyond that of either the bitumen or cement alone.

Thus it appears that the binder produced in these pioneering applications was, in effect, an amalgam that possessed properties from an engineering standpoint that are more desirable than the component materials alone. While this was unexpected and therefore fortuitous, it is also clear from the foregoing that the relative proportions of the cement, bitumen-emulsion and water (both in the emulsion and any free water in the mix) are important.

The mixes produced from the earliest days therefore inadvertently provided the “magic” recipe adopted for later work, which has been used extensively in South Africa, and even adapted to foamed bitumen applications. Over the years, the successful performance of the ETBs especially provided the impetus for successive attempts to develop rational methods for their wider application. This study provides continued witness to the fact that, for all the intensive research work that has taken place during the past 15 years or so, there are still inexplicable gaps in our knowledge of the fundamental behaviour.

While it is hoped that this study will provide a clearer vision and, therefore, basis for rational further development and application of these materials, it must not be forgotten what the origin of all these efforts has been: the unexpectedly good long-term performance from an unlikely combination of cement, bitumen-emulsion, and mix moisture applied sparingly to otherwise low grade road building materials to make their use feasible.

Although our knowledge has advanced, even with the gaps referred to above, it is still far from complete. However tempting it currently appears to consider the concept of “customising” mixes by adopting different relative proportions of the main binder elements, to attain more cementitious or more bituminous mix characteristics, caution is therefore advocated until a much clearer understanding of the fundamental reactions is obtained. While it is clear that further research would be needed, this is to flag the possibility that (following from the observation above) unexpectedly poor long-term performance might be attained.

However, the way forward should accommodate the possibility of even more variation on the theme of trying other combinations of binders, and optimisation of the binding matrix.

In the interim, based on all available evidence, there appears to be a very good case for specifying the inclusion of 1% cement[Note15] to all bitumen-emulsion and foamed bitumen mixes, and using the mix design process just to determine optimum binder content. By adopting this approach, firstly, it aligns with the historic usage and proven performance of the bitumen-emulsion treated materials. Secondly, it acknowledges the seemingly greatly enhanced complex matrix development deriving from this. Thirdly, it will make subsequent evaluations of different applications and their performance significantly easier.

An outline of the mix design approach envisaged for road base course application, assuming that basic requirements such as parent material durability and soundness are satisfactory, would be to determine the bituminous binder content necessary for the mix to meet a target stiffness value within a realistic time period.

If for any reason the target stiffness cannot be met for a particular mix within an acceptable period using 1% cement, and with a maximum residual bitumen content of, say, 3%, then the mix design process should be repeated with the inclusion of 1.5% cement. If the same problem is found, it would be recommended to increase the cement content to a maximum of 2% and repeat the process.

In the event that this again fails to provide an acceptable result, then it might be concluded that this bituminous cold mix approach is inappropriate. Clearly for more uncommon applications (such as, for example, sands) the need for more extreme binder content range may be merited, but the principle of determining when a target stiffness is likely to be met remains the fundamental aim.

Given the two fundamental requirements of preliminary mix design (evaluating potential mixes for practical and economic application) and field application (especially determining when a particular treated layer is ready for subsequent construction processes), the pragmatic approach is very simple.

It is based on the following underlying needs and assumptions:

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[15] The use of 1% cement is regarded as a minimum “starting point” requirement which should be used, for the reasons given in the text, and which ought to be sufficient in most cases. The mix design process must still accommodate increasing this value, and should not exclude inclusion of, or substitution with, lime if found more appropriate.

- laboratory preparation, mixing and compaction should be to a time scale[Note16] reflecting probable or actual field conditions
- laboratory specimens should be prepared at probable or actual field compaction
- curing should reflect probable field conditions
- testing should be primarily to determine material stiffness[Note17]
- curing and primary testing requirements should be readily achieved in any materials testing laboratory
- curing and testing period should be as short as practically possible to enable reliable and repeatable results

These aspects are discussed in more detail in the following subsections.

5.2.1 Laboratory preparation

The best correlation of field and laboratory behaviour for these types of mixes will only be approached if the processes of laboratory mixing and compacting tend to conform with the likely field processes[Note16].

This is principally due to the complex binder component reaction which is likely to be primarily influenced by the timing of the addition of cement and the moisture content at that time, relative to the timing of the bituminous binder addition and any additional moisture. It is because the primary cementitious reaction will start on the addition of cement to the moist mix, and its subsequent development will almost certainly differ according to the timing of these processes. Specimen compaction should also be timed in accordance with the probable field process.

This does not necessarily imply that longer-term mix characteristics will be different, although this seems likely if bituminous binder is added after a significant delay, but until otherwise demonstrated it should be assumed that the early rate of mix stiffness/strength development would be affected.

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[16] It is implicitly assumed that laboratory preparation should also be undertaken within a temperature and humidity regime that also reasonably reflects field conditions

[17] On the assumption that basic material requirements such as durability and soundness are deemed satisfactory

Key elements are therefore to ensure that the parent material moisture condition is similar to that expected in the field prior to mixing, and that the timing of the additions of binder, additional moisture, and compaction are similar. It is also considered essential that the laboratory process should record the actual times of these actions as this will provide a more accurate basis for evaluating subsequent time-dependent behaviour.

In cases where no cement, or other modifiers, are used that would be considered to influence the behaviour it would still seem most prudent to adopt the same approach simply to reduce the possibility of variability.

For mix design purposes, in cases where the field construction process cannot be reliably foreseen (for example, conventional or deep-in-situ approaches), it would be judicious to undertake laboratory processing that reflects each most likely method. This would also add to the knowledge base in terms of quantifying the influence of these variable factors.

In the case of construction monitoring purposes, site sampling should be left as late as practically possible prior to site compaction with the aim that specimens would be laboratory compacted at nominally the same time as field compaction.

5.2.2 Specimen compaction

As noted in the earlier discussion the adoption of conventional "standard" compaction methods, which rely on prescribed numbers of blows of a compacting hammer, is considered wholly unlikely to best replicate field compaction for these types of material. The combination of pressure and vibration that a vibratory roller will produce would be dissimilar. The rate, and action, of densification will almost certainly be dissimilar. The absolute density is likely to be dissimilar.

While other compaction methods exist that may be more likely to achieve end results closer to field conditions, such as the gyratory compactor, or using a vibrating table and surcharge weight[Note18], these are generally of limited availability. This situation is unlikely to change in the foreseeable future, primarily due to cost and general applicability, and as a result will not address the

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[18] As specified in TMH1: Standard Methods of Testing Road Construction Materials, 1986, test method A11T

underlying need for a simple, inexpensive, and therefore potentially widely available, method.

A technique that may better meet this need was pioneered during the late 1960s in the UK for laboratory compaction of lean concrete[Note19]. It is the use of an electric vibratory hammer (Kango) fitted with a compaction foot, which was found by the writer to be very effective and practical. Compaction to “refusal” was the aim, implying that no additional densification was apparent, under the effect of vibration combined with the operative’s full weight. Variation in density attributable to operator (mass/ compactive effort) is minimal for practical purposes as refusal compaction is approached.

In those cases cube moulds of 150mm were used, and the compaction foot was 100 mm square. To avoid or minimise the occurrence of possible planes of weakness within the specimen, which would not occur in the field, the technique entailed compacting the loose material filled to the mould top relatively lightly to settle it, then adding additional material in a raised “collar” which would provide sufficient to fully compact.

This study has revealed that a similar technique has, in fact, been used for conventional asphalt materials (for example reference 21, reference 22), is described in a British Standard and Road Note 31(23, 24), and was regarded as providing a more appropriate reference density for design of hot-mix asphalt for severe traffic loading conditions using the relatively inexpensive equipment(21). In this case a compaction foot of 100 mm diameter was used in the 150 mm diameter Marshall mould, and it was noted that a kneading action more like the mode of compaction under a roller was imparted to the specimen.

Although the more recent study cited(22) showed the vibratory hammer compaction method to give similar results for permanent deformation resistance to those from the gyratory compactor, the indirect tensile stiffness modulus (ITSM) was somewhat lower than the results from either the gyratory or slab compaction methods (14% and 8% respectively). This finding is, however, not considered of particular relevance in the context of this study other than indicating a more

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[19] Lean concrete: a low water, low cement content concrete subbase that can only be compacted on site by vibratory roller

conservative estimate of stiffness from the particular test method. The critical criterion in any case remains the probable linear correlation of laboratory results with field stiffness.

Consequently it is proposed that this method of compaction be considered as a possibly more appropriate laboratory method in reproducing field conditions for these types of cold bituminous mix materials. If proven effective and reliable, it offers a low cost solution to one of the most fundamental problems in evaluating these types of materials.

In determining optimum moisture/fluid content for maximum dry density it is therefore clear that this method of compaction should also be more appropriate.

5.2.3 Laboratory curing to reflect field conditions

The crux of this study regarding accelerated laboratory curing is that there is no scope for any completely standardised method, since all available evidence confirms that this cannot represent the unique field conditions for any given application. Available evidence casts extreme doubt on the likelihood that the binder matrix development is consistent and independent of temperature and/or humidity conditions applying during curing.

Consequently the only practical method of laboratory curing, whereby direct comparison of laboratory and field properties is at all realistic, <u>is to adopt ambient curing</u>.

During construction it is clear that any laboratory sampling and specimen manufacture undertaken at or near the site should, for practical purposes, be at similar ambient conditions. However it is equally clear that where the laboratory work is conducted in a completely different environment, and/or even a different time of year, as might be the case during mix design, differences are likely to arise.

At this stage there is not sufficient data to make any reliable quantitative forecast of the influence of these effects on key early properties. However it should be anticipated that such predictions will become relatively straightforward once the knowledge base develops.

While it is therefore better that curing (and testing) be done under similar conditions to those likely to apply in the field whenever possible, from a practical standpoint it should also be quite realistic to undertake mix design where these conditions may differ with due consideration to possible differences in temperature and humidity. This is on the implicit assumption that the mix design process simply attempts to define the specific mix composition primarily in terms of bituminous binder content, and/or is used to differentiate between possible alternative treatments. While this is clearly the basis for current mix design methods, the adoption of ambient curing should avoid possible pitfalls arising from accelerated curing effects.

The proposed ambient curing regime is based on leaving specimens upright in their moulds until just prior to test, when they will be demoulded and tested. The mould containment ensures that moisture loss can take place only through the specimen top surface, with no moisture loss due to either lateral or downward movement, which is regarded as being reasonably representative of likely field moisture movement[Note20].

The specimens should be stored in shade outside so that they are exposed to both ambient temperature and humidity conditions day and night, but without direct exposure to either sun (which would “overheat” the specimen due to the conductivity of the metal mould) or rain (which effect is superficial, with exposure dependent on prevailing drying conditions, and effectively intangible).

While not exactly comparable with field conditions in that the top surface of a constructed layer is likely to be commonly exposed to sun in the daytime, the proposed approach will arguably closer reflect layer material that, for whatever reason, may not get such exposure. It can therefore be viewed as conservative, in that the stiffness/strength gain of the upper specimen is likely to be slower than on possibly major parts of a constructed layer, and more repeatable in that it avoids completely indeterminate conditions.

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[20] It is intended to use specimens of nominally 150 mm height and diameter, and tested upright, as discussed later. Lateral moisture movement in the field is unlikely, due to inherent equilibrium, while downward movement is only viewed as a possibility if field conditions are intrinsically unsatisfactory (i.e. excess free moisture, or dry surface of the supporting layer). It is acknowledged that there will always be differences between field and laboratory, but the proposed curing method allied with the suggested test method is viewed as providing the most realistic (and robust) way in which field conditions can be simulated for practical purposes

No attempt to closely cover or otherwise contain the individual specimen moulds should be made since this could alter the prevailing humidity conditions, and consequent binder matrix development.

5.2.4 Stiffness testing

The adoption of stiffness rather than, say, strength as a primary indicator of material acceptability must be fully understood. It is the most fundamental of engineering properties and, in the case of treated materials, a key indicator to when it would be permissible to carry traffic.

If the simple comparison with an untreated material is made, it will be readily appreciated that, firstly, the layer stiffness is a direct function of the grading, aggregate packing and compaction achieved in the field. Secondly, it will be acknowledged that the packed untreated material has no compressive or tensile strength as measured by any standard laboratory test.

Provided the material has adequate inherent strength to resist crushing or breakdown under traffic loading, and is sufficiently well compacted to minimise further significant compaction under traffic, its successful application stems from its ability to spread the traffic load. This is a direct function of its stiffness and consequently its ability to attenuate the effects of traffic load stresses with depth.

The pavement design process is then used to determine the layer thickness required that will ensure that stresses transmitted will not cause overstressing or unacceptable deterioration to the underlying layer(s) [Note21].

In the case of treated materials, especially those with relatively high stabilising agent content (viz, hot-mix asphalts, cemented bases, concrete), significantly higher stiffnesses (compared with the untreated parent aggregates) are achieved. While the composite material strength also increases, the higher stiffness induces higher horizontal stresses/strains that peak on the layer underside (in effect, due to bending action) and the pavement design process here determines the layer thickness to ensure that these induced stresses/strains are within an acceptable

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[21] While stated simplistically, in that the pavement design process seeks to optimise the layer configuration of a pavement system consisting of various disparate layers, this is nevertheless the basis of the evaluation

range not to cause unacceptable deterioration of the layer under repeated loading.

Essentially the strength is invariably high enough to prevent breakdown due to overstressing under traffic loadings, and it is the maximum induced tensile strains that are reduced (by increasing layer thickness) within acceptable limits. These will normally be limited within a small percentage of the nominal strain at break to ensure quasi-elastic behaviour[Note22].

The increase in stiffness is normally accompanied by increased strength but, as the nominal linear portion of the stress-strain response is effectively rotated anti-clockwise (as elastic modulus increases on conventional stress-strain diagrams), this can lead to a reduction in ultimate (failure) strain. For materials that continue to gain stiffness/strength over long periods, generally the stress-strain response also tends to have an increased proportion (based on ultimate strength) that better approximates linear behaviour.

It should also be recognised that ultimate strength/strain values can (and invariably will) be far more variable than stiffness (as defined by the nominal linear portion, or initial tangent modulus of the stress-strain response). Whereas this stiffness is a composite property for a given specimen that derives primarily from the parent material and binder matrix, ultimate strength/strain will be governed by the weakest element of the specimen which is inherently a more variable property.

Thus it should be appreciated that the material stiffness is the fundamental property and, more important, that the value derived from the initial nominally linear portion of the stress-strain response should be a more consistent and robust engineering characteristic. It should also be evident that there is no innate direct linear relationship between stiffness and strength. However there should be such a relationship between any rational method for measurement of stiffness, even if absolute values differ due to differences in the test method.

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[22] Most construction materials, and certainly those used in road construction, cannot be classified as elastic. However most do, for practical purposes, have an initial portion of their stress-strain response that approximates elastic behaviour and allows application of repeated loads without unacceptable deterioration

It should be further appreciated that the extent of the initial nominally linear portion of the stress-strain response, by which the stiffness is characterised, is also important. This is of course defined by a stress and corresponding strain value representing the end of the linear “elastic” portion, and these values should be recorded, and can be compared with existing reference stress/strain values to confirm adequacy and/or refine these criteria.

In the case of bitumen-emulsion and foamed bitumen treated materials which should be viewed, initially at least, as improved aggregate rather than a stabilised material, it is clear that acceptable initial stiffness values (for design and acceptance) could be based realistically on those of unbound materials.

This acknowledges the nature of these bituminous cold mix materials as adopted in South Africa, the relatively slow improvement in engineering properties with time, and the fact that all available evidence indicates that such improvements are only beneficial in terms of performance.

Furthermore this provides a fundamentally sound approach for initial pavement design in which it could be expected that performance of these materials will be at least as good as an untreated material having similar stiffness[Note23]. As should be inferred, it would be realistic to anticipate significantly better performance due to development of a stronger matrix structure and (for the bitumen-emulsion treated material) improved resistance to moisture-induced deterioration.

Unfortunately there is no standard laboratory test method that will provide the load (stress)/strain response necessary to determine initial stiffness. Strain measurement is the main shortcoming.

While it is possible, especially in research environments, to use for example linear variable differential transformers (LVDTs) for electronic measurement of strains/displacements this is not a realistic approach for general application. Possibilities of manual displacement monitoring using either dial gauges or demountable mechanical (demec) gauges during normal strength testing (e.g. UCS) can be excluded due to the relatively high rate of loading.

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[23] On the practical assumption that there is no inherent weakness in the bituminous cold mix material that would lead to premature breakdown in service

Similar to the earlier discussion regarding compaction technique, the same approach in identifying suitable equipment that is, or could be, widely available for stiffness testing has been followed. In this case it is evident that the test frame used for CBR tests is most likely candidate: it provides for the application of sufficient load[Note24] and measurement of displacement, and is widely available in materials testing laboratories.

Specific measurement of CBR is not advocated for various reasons, not least because it is not a direct measurement of stiffness and is unlikely to provide a unique linear correlation with stiffness. Thus any correlation would be material and application specific, in which case the fundamental property (stiffness) should be measured directly as described below.

In line with earlier detailed discussion, it is considered essential to use as large a specimen as practically possible, to load in the same principal direction that the material in the field would be loaded, to use direct measurement, and to use widely available equipment. The indirect tensile test, used for determining the resilient modulus of asphalts, is not considered appropriate or practical for these types of treated materials[Note25].

An inherent requirement is that as much of the specimen as possible should contribute to the test result, in order to get a more representative response and minimise fundamental variability. This points clearly to uniaxial compression testing of unconfined specimens, in which the initial stress-strain response is determined from applied load and displacement.

It is consequently proposed that specimens should be formed in the CBR mould (diameter 152.4 mm) and to the maximum thickness of 152.4 mm[Note26], using the proposed method of compaction. Specimens will be extruded just prior to test and tested unconfined, using a 152.4 mm diameter load platen. Loading would

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[24] Normally up to 100 kN, which on a 152.4 mm diameter specimen, will provide a maximum uniaxial compressive stress of approximately 5.5 MPa. This is more than sufficient to define the initial stress-strain response for practical purposes even if on (probably rare) occasion it may not cause actual failure

[25] Cylindrical specimens are strip loaded on each side across a diameter, and the cylinder is split by exceeding its tensile strength

[26] Assuming that the 25 mm thickness base plate specified for CBR testing in South Africa can be removed, otherwise to the maximum thickness with this in place

then also be applied in the same direction, relative to the compaction, as the field traffic loading.

The use of this specimen size would be considered to provide a sufficiently large sample size to be representative and also reduce possible effects of inherent variability. It is also seen as allowing for the full material grading, without artificially influencing compactibility by taking out or further breaking down, for example, particles above 19 mm. At worst, it would be recommended that only the occasional particles above, say, 50 mm should be removed prior to compaction.

By using the test frame normally used for CBR testing, it is further proposed that the same standard loading rate (1.27 mm/minute) be adopted to simplify the test process. The stiffness value deduced should allow reliable linear correlation with, for example, layer stiffness from field measurements or cores. The merit of using such a commonly available apparatus and standard loading rate ought to transcend the need for such correlation ultimately since, with widespread application, it should be possible just to specify a minimum, say, "CBR stiffness value" requirement.

The main drawback foreseen, especially where the test frames are computer controlled and incorporate load cells and LVDTs, is the probable need to take readings at a higher rate than used for conventional CBR testing (every 0.635 mm). This sampling rate may or may not be readily changed depending on the software. Ideally a full load/displacement response would be required in order to characterise the initial tangent modulus, but it would be anticipated that readings would be required approximately every 5 seconds or 0.1 mm displacement during the first minute.

This aspect can be reviewed in any subsequent testing programme designed to demonstrate the validity and merit of the proposed approach. A key element of such a programme would be to establish design stiffness criteria, comparison of laboratory results with field (cores), broader characterisation in terms of other test criteria, and ultimately validation of a reliable early (say 72 hour) prediction of when the design stiffness would be achieved.

The specific needs of such a test programme are outside the scope of the present study, but are seen as a clear next phase in following the proposed approach.

The findings so far indicate to the author that there is every likelihood that a simple early prediction method, based on this approach, should be feasible. This would then allow mix design evaluation to focus on simply identifying the composition that will provide the required early stiffness within an acceptable period from, say, 72 hour test results. The nature of the stiffness/strength development is such that the decision based on such an evaluation should be clear cut.

It should be emphasised that the designation 72 hours, rather than 3 days, is done purposely: it is to stress the critical importance, especially at early ages, of the precise period of curing until test for materials having time-dependent properties. Thus it is quite likely that a 3-day result represented by 64 hours (say, manufacture and compaction at the end of a normal working day, testing first thing on the third day) or 72 hours (say, manufacture and compaction, and testing on the third day, all done about the same time) will be inherently different.

While other aspects regarded as possibly contributing to the difficulties in interpreting the behaviour of these types of material have been discussed at length, this most fundamental one of time has not and need not. It is simply a given, but may nevertheless be overlooked or not paid sufficient attention. Thus, in line with the recommendation that the timings of laboratory sample preparation, mixing and compaction processes be logged, similarly the time of testing must be recorded. This again will aid in reducing some of the variabilities that will inevitably be present, and aid in subsequent rational evaluation.

5.2.5 Practicality of proposed approach

As noted earlier an underlying factor in determining a practical method for curing and then evaluating these types of materials has been to avoid the esoteric, identify the key elements, and subsequently acknowledge the intangibles arising from the nature of these materials and their application.

In this respect the methods proposed, if proven effective, should be readily applied in any materials testing laboratory.

As discussed at some length, apart from adopting ambient curing as patently the most reliable method to correlate laboratory and field results, the two most significant practical recommendations are to adopt vibratory compaction to refusal and to adopt stiffness as the primary indicator for design and acceptance.

In addressing these aspects the proposed approaches are regarded as providing the most practical methods to achieve the objectives on the broadest front.

6. CONCLUSIONS AND RECOMMENDATIONS

The objective of this project was to identify the most appropriate laboratory curing method(s) for bitumen-emulsion and foamed bitumen treated materials to ensure that laboratory testing should reliably characterise field properties.

The original methodology proposed included a literature study of both national and international practice to determine the curing methods currently in use, interviews with local practitioners to augment the broader literature survey and focus on local conditions, and an overview of fundamental behaviour to have a sound basis by which to review current curing practices. This was in order to identify those approaches that should be most robust.

The findings from the literature study and overview provided a clear insight into the problems of characterising these types of material, and various contributing factors have been identified that appear not to be addressed consistently in the process of trying to relate laboratory testing to field conditions. Curing is one such component and, while it became obvious that only one laboratory curing regime will provide any realistic comparison with field conditions especially during the critical early life, it was equally evident that an holistic approach to rational characterisation of these materials has been missing.

This is viewed as the principal reason that there continues to be uncertainty in the use of these treatments and, ostensibly, diminishing confidence in their application despite (in the case of bitumen-emulsion treatment) an exemplary track record when appropriately applied.

Consequently, this project has ventured considerably beyond the original brief since it is considered neither reasonable nor constructive to confine the study to the initial objective when it is clear that it cannot be viewed in isolation. This is because the curing regime alone will not ensure that laboratory testing will reliably characterise field properties.

The main conclusions arising from this extended study are summarised as follows:

i) There is no conformity either nationally or internationally on laboratory curing practices to ensure laboratory testing will reliably characterise field properties.

ii) Realistic characterisation of field properties by laboratory testing for these materials having time- and environment-dependent properties demands that laboratory preparation must closely reflect field conditions, especially regarding timing of mixing processes and compaction of specimens.

iii) Realistic characterisation of early field properties by laboratory testing for these materials having time- and environment-dependent properties demands that laboratory curing must closely reflect field conditions.

iv) Field properties for any given mix will vary in terms of rate of development, and possibly extent, due to differences in environmental/climatic factors, especially temperature and humidity which are key factors influencing development of binder matrix.

v) No standard laboratory curing method, in which time period, temperature and/or humidity are prescribed, will therefore give consistent correlation with key early field properties.

vi) Realistic characterisation of these materials having time- and environment-dependent properties demands that the process must identify when acceptable properties are attained that meet practical construction time considerations.

vii) Primary characterisation of field properties by laboratory testing for these materials must be based on a reliable, robust and fundamental indicator that is inherently consistent, and can allow direct comparison of field and laboratory results. Material stiffness is viewed as best meeting these requirements.

viii) Predictions of field performance from Accelerated Pavement Tests for these materials having time- and environment-dependent properties are likely to be conservative due to the longer-term enhancement of engineering properties which benefit performance, and to an extent that will be influenced by timing of such tests but which cannot presently be predicted.

ix) Practical guidance for practitioners on pavement design for these materials should draw on the established performance of “comparable” untreated materials, in which material stiffness provides a key point of comparison.

x) The bitumen-emulsion treated materials that have provided the long-term track record for these materials in South Africa invariably used a low percentage of ordinary Portland Cement to aid in breaking of the anionic emulsion. This practice has spilled over into the more recent adoption of foamed bitumen treatment.

xi) Anecdotal evidence and more formal studies indicate that the inclusion of a small amount of cement with bitumen-emulsion (typically with a ratio of up to 1:1), with sufficient moisture to promote (but not detract from) the reaction, will normally lead to the development of a complex bitumen-cement matrix. Such a complex matrix would undoubtedly be the source of the long-term and beneficial improvement in engineering properties that does not take place with bitumen or at the same protracted rate with cement.

The main findings from this study as summarised in the foregoing are considered to represent the key components that must be addressed in any rational method for determining the suitability, application and probable field performance of bitumen-emulsion or foamed bitumen treatment.

In this respect they are therefore viewed as providing a framework from which pragmatic development ought to ensure that some of the current technical confusion in making meaningful evaluations of these materials is minimised.

The scope for further work is regarded as considerable, particularly in terms of defining and refining criteria for future performance prediction, and developing the pavement design method to accommodate the broad scope of treated materials that could potentially be used.

Primary recommendations at this stage .and for which more complete details are given in this report are, however, as follows:

- Laboratory sample preparation must ensure that the parent material moisture condition is similar to that expected in the field prior to mixing, and that the timing of the additions of binder, additional moisture, and compaction are similar. The laboratory process[Note27] should record the actual times of these actions as this will provide a more accurate basis for evaluating subsequent time-dependent behaviour.

- Laboratory compaction of specimens should reflect the probable field conditions of vibration and pressure, which are not replicated in standard impact hammer compaction methods. An inexpensive method using a Kango vibratory hammer and compaction to refusal is proposed as providing a more realistic simulation and reference density.

- Laboratory testing should be primarily based on evaluating material stiffness within the nominal initial elastic range as a more consistent indicator of acceptable performance for construction purposes. The use of 152.4 mm diameter CBR specimens of nominally similar height should minimise variability and provide more reliable characterisation.

- Laboratory curing should be based on ambient conditions, in which specimens should be stored in shade outside so that they are exposed to both ambient temperature and humidity conditions day and night, but without direct exposure to sun or rain. No attempt to cover or otherwise contain the individual moulds should be made since this could alter the prevailing humidity conditions and subsequent matrix development.

- Testing the unconfined specimens in uniaxial compression in the CBR frame should be feasible, in which the piston displacement is monitored against applied load to provide the stress-strain response and define the initial elastic modulus. Specimens will be extruded just prior to test, and the time at test recorded accurately to enable meaningful monitoring of time-dependent changes.

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[27] It is implicitly assumed that laboratory preparation should also be undertaken within a temperature and humidity regime that also reasonably reflects field conditions

- Inclusion of 1% cement, in line with the earliest applications of bitumen-emulsion treatment that have provided the track record for these materials, should be specified for both bitumen-emulsion and foamed bitumen applications. The mix design process is then used to identify the bitumen content necessary to yield a target material stiffness within an acceptable period under the environmental conditions pertinent to the application. This will draw on past successful experience and provide a sound basis on which to further develop the knowledge base.

- A preliminary laboratory programme should be undertaken to assess the feasibility of the proposed approach, to tie in the laboratory results with both other stiffness characterisation tests and field stiffnesses, and to monitor changes over a period of a few weeks. The primary aim would be to define target stiffnesses for field acceptance purposes, and develop a simple prediction method from, say, 72 hour test results to estimate when the target stiffness should be achieved.

- A national long-term test programme to allow development of reliable pavement design criteria for these materials should be initiated. It is envisaged that this would include identical pavement structures having both bitumen-emulsion and foamed bitumen base sections constructed in, say, three different environmental areas. Monitoring would include periodic Accelerated Pavement Testing, Long Term Pavement Performance monitoring and comprehensive supporting laboratory programme. This should enable much of the present uncertainty to be clarified, and provide the culmination of rational development for these materials.

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Akzo Nobel Asphalt Applications: one of the world's leading companies in its field. It delivers chemicals, emulsion plants, microsurfacing and slurry seal machines, cold-mix plants, injection systems for adhesion promoters and new technologies for road construction and maintenance. Head office Sweden.

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Appendix A:
Project proposal as approved