HALF-WARM FOAMED BITUMEN TREATMENT, A NEW PROCESS

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Abstract

For decades pavement engineers have been aware that the temperature of the aggregate during stabilisation with foamed bitumen influences the quality of cold-mix. This has led to the establishment of recommended lower limits for aggregate temperatures, depending on ambient conditions. The significant benefits that can be achieved through the moderate heating of aggregates before foamed bitumen stabilisation have been ignored however. This paper explores the considerations and possible benefits of heating a wide variety of aggregates (in type and gradation) to temperatures above ambient but below 100ºC before the application of foamed bitumen, in terms of particle coating, compaction and engineering properties. The process is termed “Half-warm Foamed Bitumen Treatment ”.

1. INTRODUCTION

The foamed bitumen process requires hot bitumen to be expanded into foam through the addition of a small percentage of moleculised water. The foam is immediately mixed with cold, moist aggregates. One of the major advantages of the foam process over conventional HMA, is the energy saving in terms of drying and heating aggregates. The application of this foamed bitumen process has experienced a renaissance in many countries of the world, especially with advances in the static plant mixers and cold in situ recycling machinery and the availability of the technology.

At present, mineral aggregate of both marginal and recycled materials is being treated using this technique and applied as base and sub-base layers in road construction. There are limitations in applying the process to some materials, however, particularly where the gradations have a gap between the sand particles and coarser particles. Since the inception of foamed bitumen back in 1957, all efforts have been focused on treating materials at ambient temperature. This has probably been the case to maximise energy and cost savings in a process that appears to operate adequately without any heating of aggregate, making it suitable for application in cold in-place recycling.

For many years pavement engineers have been aware of the influence of aggregate temperature on the performance of foamed bitumen mixes. However, the approach to aggregate temperature has generally been to establish a minimum critical temperature at which foamed bitumen treatment can be carried out without any detrimental effects to dispersion of the binder within the mix. Bowering and Martin (1976) refer to a “critical temperature” range of between 13°C and 23°C for the minimum aggregate temperature before foam treatment, below which mixes of poor quality are obtained. No mention is made of the influence of temperatures in excess of 23°C, mainly because it is not possible to be practised using conventional cold in-place recycling techniques and static plant mixers.

The CSIR (1998) state that heating of aggregate will increase binder dispersion within a foamed bitumen mix and aid in the coating of the larger aggregates. These postulations, along with many others have not been substantiated, however, and the temperature of the aggregate after mixing and mechanisms of foamed mix improvement remain unexplained.

One aspect of energy additions to foamed-mixes that has been investigated with some degree of success has been the heating of already blended foamed bitumen mix. Roberts *et al* (1984) published results on the heating of foam treated recycled materials where the densities and engineering properties (tensile strength and stability) were substantially improved. Buschkuhl *et al* (1990) investigated the heating of foamed-mix with incinerator slag to 60°C in order to improve low stability values for the mix. Increases of 25% to 158% in stability values were noted for the mix. Similar trends were noted by Bowering and Martin (1976) and Eggers *et al* (1990), where post-mix heating temperatures of 110°C and 115°C were selected.

The University of Stellenbosch, South Africa in conjunction G van Hees en Zonen carried out some preliminary tests on non-continuously graded materials where the moist mineral aggregates were heated to temperatures of less than 95°C ***prior to*** mixing with foamed bitumen. Improvements in the consistency of the mix through moderate energy application appeared significant, so a pilot research project was launched in collaboration with Delft University of Technology to investigate "Half-warm foamed-mixes". This paper reports on some of the findings of the pilot study into half-warm foamed mixes.

2. BACKGROUND CONSIDERATIONS

A literature study on the foamed bitumen process as applied to cold, damp materials is required before an experimental design can be carried out for foamed bitumen treatment of half-warm mineral aggregate. This study, supplemented with recent research has highlighted focus areas for careful consideration.

2.1 Energy considerations

Conventional hot mix asphalt (HMA) uses a large proportion of its energy in the evaporation of the aggregate's water before mixing. The conversion of water into steam requires the latent heat of steam to be overcome, shown as the step in Stage 2 of Figure 1, which is a 500 times higher energy demand than the specific heat required by water per degree Celsius temperature change. The energy jump has been calculated using standard heat and thermo-dynamic considerations, and is influenced most significantly by the moisture content of the mineral aggregate. In practise, the energy demands for heating of aggregates are some 10 to 20% higher than those given in Figure 1, due to the losses through radiation etc. that have been ignored in this simplified approach.

The advantages of remaining in the sub-boiling temperatures i.e. working entirely within Stage 1 of Figure 1, are apparent. Half-warm mixes, which are intended to remain entirely within Stage 1, will therefore enjoy the energy benefits illustrated and at the same time could improve the properties of the mix. The increase of aggregate temperature in excess of 100°C is not recommended for a number of reasons:

- energy consumption,
- moisture losses from the aggregate during mixing can reduce compactibility, and
- total moisture loss with the bitumen becoming a continuum and rut resistance advantages being lost.

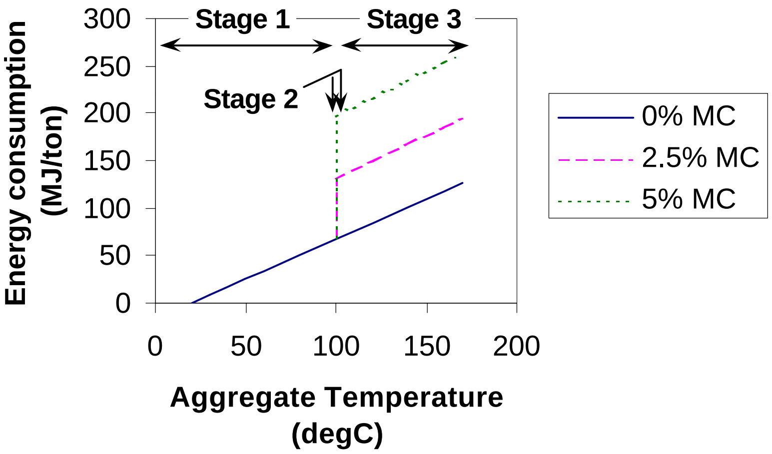

Figure 1: Energy consumption of mineral aggregate with temp. of 20°C and varying moisture content, relative to equilibrium aggregate temperature

The influence of the aggregate temperature at the time of mixing, on the equilibrium temperature of the mix is significant. Jenkins (For 1999) has shown that, the addition of bitumen at 180ºC in the foamed form will only increase the temperature of the mix by some 7°C to 10°C and that the original temperature of the aggregate has the dominant effect.

The temperature gradient between the aggregate and the foamed bitumen will influence the rate of collapse of the foam. This occurs even though bitumen has relatively poor thermal conductivity properties, because in a foamed state, the surface area of bitumen that makes contact with the aggregate is high and the film thickness of bubbles is extremely thin, making the rate of heat transfer rapid. When the foam temperature is marginally higher than 100°C and the aggregate is at less than 30°C, the equilibrium temperature of the mix will be approximately 38°C. The rate of collapse of the foam and hence the rate of viscosity increase of the binder during mixing, will therefore be rapid. Conversely, if the aggregate is at 90°C (after preheating), the equilibrium temperature of the mix will be marginally lower than 100°C. The bitumen will therefore remain at lower viscosity for a longer period during mixing, encouraging coating and dispersion in the mix.

The rate of transfer heat from the foamed bitumen to the aggregate can be estimated through the use of the coefficient of thermal conductivity of bitumen (γ = 0,17 Joule/m.s.Kelvin), which is 10 to 20 times lower than that of Limestone and Granite respectively. Considering bitumen bubbles making contact with mineral aggregate, using a plausible film thickness of 0,01mm for the bitumen from (Jenkins, For 1999), implies that 189 Joules of energy can be transferred from the bitumen at 110°C to aggregate at 20°C in 1 second. This would enable one gram of bitumen to experience a reduction in temperature of 90°C! The high surface area of contact and the thin films of bitumen in the foam mass, permit rapid transfer of heat to the aggregate, therefore.

2.2 Particle coating

The coating of the mineral aggregate particles of an asphaltic mix has an influence on the performance of the mix. Improving the distribution of binder within a bituminous mix can increase the durability, resistance to water damage and consistency of that mix. For this reason, some road authorities specify a minimum film thickness of binder on the aggregate. Particle coating is especially significant to foamed-mixes where the droplets or “spot-welds” of bitumen provide the tensile strength in the mix and if they are more evenly distributed, it could create a more continuous network or web of binder, which would increase the fatigue resistance of the mix.

Ruckel *et al* (1982) state that foamed bitumen should be concentrated in the fine sand and silt fractions and that little or no coating of particles larger than 9,5mm should occur in mixes produced at ambient temperature. In addition, Ruckel *et al* state that the foamed-mix should be free of combined bitumen particles larger than 1,6mm. It is reasonable to expect the size of particle completely coated with bitumen to increase as the mix temperature increases, if the physics of a particle is considered.

By simplifying the individual particles into spherical shapes, the relationship between surface area and volume can be established. The formulae for the volume and area of one particle are as follows:

$$A = 4\pi r^2 \qquad \text{……(Eq.1)}$$

$$V = \frac{4}{3}\pi r^3 \qquad \text{…….(Eq.2)}$$

From Equations 1 and 2, it can be seen that as the particle size (or radius) increases, that the volume increases at a rate r/3 faster than the surface area. The same ratio applies to mass : surface area, where particles have the same specific gravity. This has a particular bearing on mixtures of foamed bitumen and mineral aggregate, where the foamed bitumen has a temperature of 105°C to 120°C and the aggregate of some 10°C to 35°C. As the particles of mineral aggregate make contact with the foamed bitumen they acquire heat from the foam bubbles. Three possible scenarios have been identified for the metastable foamed bitumen:

1. If the particle penetrates the foam bubble, it may be burst mechanically leaving bitumen droplets either attached to or separate from the particle.
2. If a large particle makes contact with a foam bubble, high energy transfer will occur, reducing the steam pressure in the bubble causing it to collapse and reducing the temperature and hence increasing the viscosity of the bitumen, causing less coating of the particle surface as mixing continues.
3. If a small particle makes contact with the foam bubble, less heat is transferred, leaving the bubble either intact or deflated, but allowing the bitumen to retain heat and a lower viscosity which will encourage coating on the relatively smaller surface area as mixing continues (before equilibrium temperature of the entire mix is reached).

A critical particle size will therefore occur in a specific mix, where complete coating is no longer possible. Ruckel *et al* (1982) without the foregoing explanation, state that this critical diameter is that of fine sand for foamed-mix at ambient temperature. This critical diameter is not fixed, however, as it is related to the type and temperature of the aggregate, amongst other factors.

In addition to these scenarios, the number of particles of various sizes should be considered too. The ratio of the number of particles of different sizes having the same mass is $r_1^3:r_2^3$. This indicates that during the mixing process, the probability of contact of a particle of a given radius with it's own foamed bitumen bubble(s) will be inversely proportional to the third power of the radius of the particle. The necessity of including sufficient proportions of the fraction <0,075mm in the mix, which has been widely published in literature, becomes apparent. The filler fraction has an extremely high probability of particle contact with foam bubbles and will prevent the bitumen droplets from cohering to one another instead of adhesion to the mineral aggregate.

In the context of the above-simplified physics of foamed bitumen mixing and distribution, the possible benefits of heating the aggregate before mixing can be appreciated. As aggregate is heated, so the energy transfer from foamed bitumen to an aggregate particle during mixing will be reduced allowing the bitumen to remain at a lower viscosity and to completely or partially coat larger particles. Hence, the critical particle size that is completely coated may be increased.

2.3 Threadlike binder structure

The nature and geometry of the binder distribution in a foamed bitumen mix has been described by Jenkins (For 1999), where a network of threadlike bitumen strands has been observed in cold mix mortar. The formation of binder threads is caused by fragmentation of a collapsed foamed bitumen bubble with the bitumen of sufficiently low viscosity coating a particle either partially or completely, followed by excess binder adhering to another particle during mixing. Movement of one particle relative to the other results in elongation of the bitumen threads within the fluid medium of water (similar to the ductility test, only at a faster displacement rate over a shorter distance).

The length and thickness of the bitumen threads are dependent on the volume of free bitumen, the bitumen viscosity (grade and temperature), bitumen ductility and relative displacement of particles. A mixing time that is too long can result in breakage of threads and may be detrimental to a mix. In particular, the opportunity for rebuilding of threads will depend most on the temperature of the mix. Half-warm foam mixes with higher equilibrium temperatures, therefore, will provide greater opportunity for extended mixing times and improved "reinforcement" of the mix with a binder web.

2.4 Factors considered in the study

As a feasibility study, the factors that could influence the behaviour of half-warm foamed mixes require investigation. These primarily include:

- Aggregate type and gradation
- Aggregate temperature (at mixing and compaction).
- Associated factors e.g. the moisture content of the mix at the various stages of the production process.

A wide variety of materials require selection for the investigation, to assist in identifying possible boundaries between suitable and unsuitable aggregates. The different material types, gradations and aggregate temperatures selected, are shown in Table 1. The effects of these factors are measured in terms of the changes in mix properties, including particle coating, mix volumetrics and engineering properties.

Table 1: Overview of Half-warm Foamed Mix Experiment

MIXES	FACTORS	EFFECTS
Continuously graded virgin materials	Parent material	Visual observation
Semi-gap graded virgin	Bitumen grade	Workability/Spreadability
RAP and RAP+virgin	Foam characteristics	Gyratory compaction
SMA	Mixing method and time	Volumetric properties
ZOAB (Porous Asphalt)	Mixing Temperature 30ºC to 95ºC	Selected ITS and SCB Tests
Gravel	Compaction Temperature 20ºC to 70ºC	
Sands	Mixing Moisture Content	
	Compaction Moisture Content	

3. RESULTS OF FEASIBILITY STUDY

3.1 Moisture regime

Past research into foamed bitumen mixes has shown that moisture in the mixture plays a vital role in both the dispersion of the foamed bitumen, as well as the shelf-life, compaction and properties of the mix. In the case of the half-warm mix, the raised equilibrium temperature has the effect of exciting some water molecules to such a degree that moisture is rapidly lost from the mix, making this an important aspect to monitor. Not only does the raised temperature of the aggregate influence the viscosity of the foam as it subsides, but the moisture regime too.

The moisture regime in half-warm foamed bitumen mixes has been monitored at various stages in the laboratory production process. Using the data from seven different mixes, at an average of four different temperatures each, a relationship has been established for the loss in moisture during half-warm foamed bitumen treatment. This relationship is outlined in Equation 3.

$$MC_f = 0.640*MC_I - 0.0232*T_a - 0.093*BC + 2.978 \qquad \text{……..(Eq.3)}$$

Where,

MC_f = Final moisture content immediately after mixing (%)
MC_I = Initial moisture content immediately before mixing (%)
T_a = Temperature of Aggregate (ºC)
BC = Binder content of foamed bitumen (% m/m of agg)

The coefficient of correlation for this relationship that has intentionally been kept simple, ignoring factors such as aggregate type, absorption, mixing methodology etc, is acceptable ($R^2 = 0.60$) considering its intended application. It provides a useful estimation of the moisture loss that needs to be compensated for when using the half-warm process. For the relationship to remain valid, the bitumen should be below

190ºC, the mixing time should not exceed 20 seconds (in the laboratory) and the aggregate temperature should range between 45ºC and 98ºC.

The selection of a mixing moisture content of 65% to 85% of optimum moisture content for the various mixes, in accordance with the “fluff point” or minimum bulk density for mixing, in insufficient therefore. Up to 2.5% of moisture will be lost during mixing with aggregate at 90ºC. An adjustment should be applied to this initial moisture content using Equation 3. The actual moisture content after mixing should also be monitored in order to make adjustments for more accurate results. If not accounted for, the moisture deficit can have detrimental consequences in terms of particle coating, balling and compaction.

Experimentation has shown that, both cold and heated water can be added to the heated aggregate as mixing moisture, but that the latter visibly improves binder dispersion and particle coating.

3.2 Temperature effects on Particle Coating

Prediction of a specific aggregate temperature that would result in optimal foamed mix properties is not possible using currently available literature. Convoluted effects of mix temperature on moisture regime, binder viscosity and alterations to the threadlike binder structure could invalidate simple postulations of “higher temperatures produce superior mixes”. A sensitivity analysis of a number of mixes with regard to aggregate temperature is required therefore. Generally, aggregate temperatures ranging between 30°C and 90°C have been considered for this purpose.

Particle coating is one of the mix properties investigated in the sensitivity analysis. Although Ruckel *et al* (1982) state that foamed bitumen will be concentrated in the fine sand and silt fractions for mixes produced at ambient temperature, this does not provide an indication of changes in particle coating at elevated aggregate temperatures.

The changes in binder distribution with different aggregate temperatures at mixing have been verified through the investigation of a Hornfels material of continuous grading. Visual improvements in distribution of the binder and particle coating through heating of the aggregates before foamed mixing in a Hobart® Mixer, were significant. The mix was inspected and divided into three binder coating categories and the results are summarised in Figure 2.

1. *Practically uncoated particles*, with less than 20% binder coverage.
2. *Partially coated particles*, with 21% to 99% coverage, and
3. *Completely coated particles*, with 100% coverage.

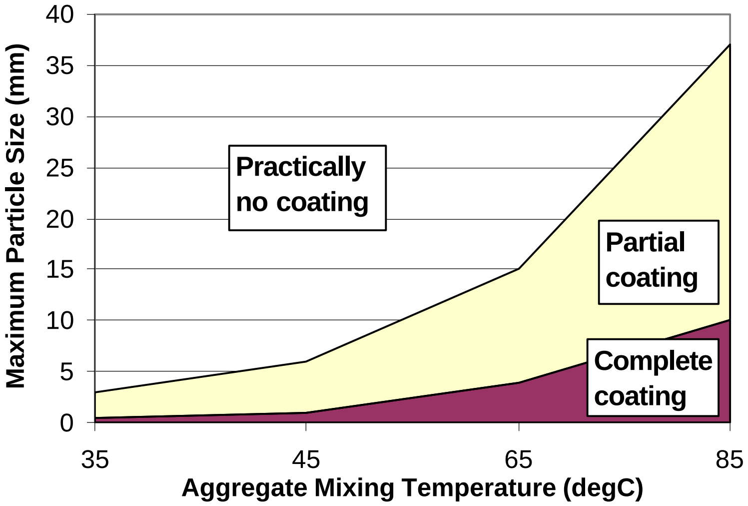

Figure 2: Effect of Aggregate Temperature on Particle Coating for a Continuously Graded Hornfels mixed with Foamed Bitumen

The influences of aggregate temperature on particle coating were found to be similar to those illustrated in Figure 2, for semi-gap graded materials, as well as natural gravel and sand. Significant darkening of the mix is apparent as the mixing temperature of the aggregate is increased. This is not the case, however, for Stone Mastic Asphalt and Porous Asphalt mixes. These mixes showed some improvement in particle coating but further stripping of the binder from the larger aggregate occurs during mixing.

Two fundamentally different approaches may be used for the half-warm foam treatment of reclaimed asphalt pavement (RAP) materials:

- The conventional approach to foamed mixes i.e. the addition of at least 4% filler, as well as water to assist in binder dispersion.
- Heating the RAP to half-warm temperatures and applying a moderate percentage of foamed bitumen without any other additions.

Visually, these two approaches provide markedly different mixes. The first approach produces a good quality cold mix with some natural colour of the aggregate still apparent. This indicates partial coating in the presence of water and filler. The second method, particularly at temperatures in excess of 85°C, produces a mix that closely resembles HMA i.e. black and completely coated, even though the RAP itself may have stone colouring due to some fractured faces.

Additional differences in the two approaches are also noted in terms of the shelf-life of the mixes. The water and filler assist in providing a workable mix at ambient temperature, whereas the half-warm RAP mix without filler or water, particularly when heated to 87°C, requires placement and compaction at 65°C minimum. The differences in the two approaches are summarised in Table 2.

Table 2: Characteristics of different Half-warm Foamed RAP mixes

RAP supplements	Filler + Water	None
Particle Coating with bitumen	Partial	Complete
Shelf-life	Good	Very poor

3.3 Workability of half-warm foam mixes

Although no limits have been established for the cohesion of half-warm mixes, this parameter provides a measure of workability of a mix. Cohesionless material will experience segregation and a mix with high cohesion will be difficult to spread and will tear.

The cohesion of half-warm foamed mixes has been measured using a vane shear device. Two different materials were tested in this way at relatively loose consistencies after foamed treatment i.e. three blows of the Marshall hammer were applied to each mix followed by testing of the material in the mould. The trends in the cohesion relative to the aggregate mixing temperature are shown in Figure 3 (each point on the graph is an average of three tests).

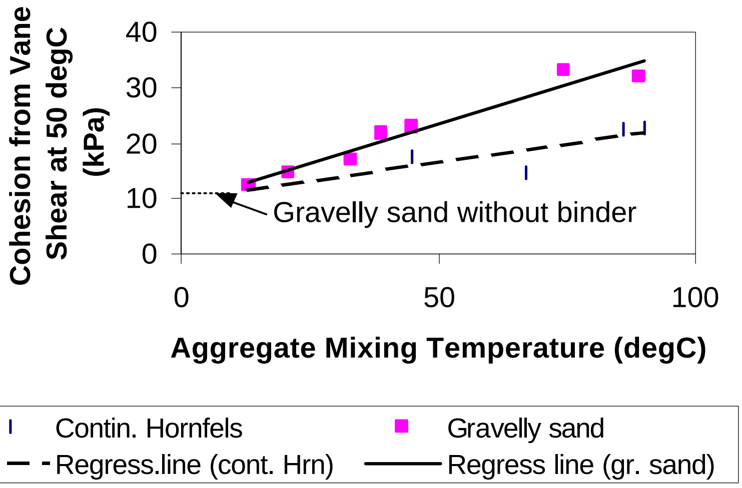

Figure 3: Influence of Mixing Temperature on Cohesion for Half-warm Foamed Bitumen Mix

The figure illustrates the improvement in shear strength of a foamed-mix with increasing mix temperature, for two different material types with separate gradations. The trend is most likely to have resulted from improved continuity of the binder in the mix, as the aggregate interlock is not temperature dependent and will remain constant. Even within a range of ambient mixing temperatures (10ºC to 45ºC), the materials exhibit a notable increase in cohesion.

The implications of the trends in cohesion measurements on the predicted workability of the half-warm foam treated materials are less significant than the possible improvements in mix performance. Not only will increased cohesion result in a raised limit for the shear envelope of the material in question, but improved continuity of the binder in the mix could improve the tensile strength of the mix. These conclusions would require verification through appropriate testing procedures.

3.4 Compaction of Half-warm Mixes

Previous research has consistently yielded the conclusion that an increase in the density of (foamed) bitumen mixes results in an improvement in various engineering properties of the material. In particular, the stability and stiffness of (foamed) bituminous mixes have been shown to increase with higher levels of compaction. In addition, it has been shown by Eggers *et al* (1990) that increasing the compaction temperature of foamed mix increases the density of the mix and consequently the material properties are improved.

The findings of Eggers *et al* have been found to be applicable to half-warm foamed mixes too. Continuously graded Hornfels mixed at 90ºC with foamed bitumen has been shown to yield a decrease in air voids of 7% to 4% as the compaction temperature increased from 34ºC to 76ºC. This initial investigation was carried out at a constant mixing temperature. The influence of mixing temperature on compaction and mix properties has not yet been addressed in research and requires attention.

A sensitivity analysis of selected mineral aggregates with varying mixing temperatures is necessary to study the effects of the half-warm process on compaction. The gyratory compactor provides a useful tool for the analysis as different levels of compaction may be utilised dependent on the type of material and anticipated levels of traffic usually encountered by such a material. This included 147 gyrations for continuous and semi-gap graded, 75 gyrations for gravel, 60 gyrations for ZOAB and SMA and 46 gyrations for sandy gravel. Compaction occurred at ambient temperature and each test was repeated for statistical reliability. The standard Superpave settings of 1,25° angle of gyration, 600 kPa ram pressure and 30 revolutions per minute were applied by the gyratory compactor. Besides slight variation in the compaction moisture content, the aggregate temperature at mixing was the only variable in this aspect of the experiment. This facilitates a comparison of the densities for different aggregate mixing temperatures.

Gyratory compaction curves have been plotted using the volumetric parameters of the mixes (an average of the duplicate specimens). With very few exceptions, the half-warm mixing temperature of the aggregate did not appear to have a significant influence on the compaction properties. No specific trends are notable with regard to mixing temperature and compaction levels. Slight variations in moisture levels are more likely to have caused the differences in void content of the continuously graded half-warm mix in, as shown on Figure 4. The results of the semi-gap graded materials appear remarkably similar to these results.

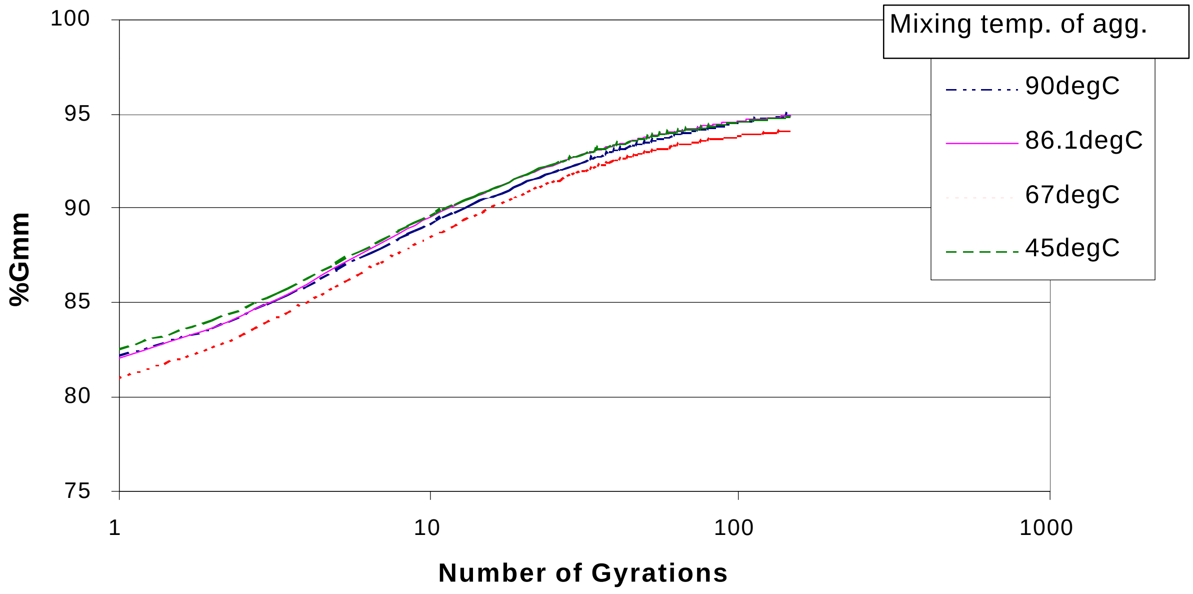

Figure 4: Gyratory compaction curves for continuously graded half-warm foamed mix for a variety of aggregate mixing temperatures, compacted at ambient temperature (28°C)

The results of the compaction of the Porous Asphalt (ZOAB) and SMA mixes also provided good repeatability and little influence of the temperature of the aggregate during mixing. The final void content for the ZOAB was 17%, whilst the SMA mix provided an unrealistically high 9% final void content.

Reclaimed asphalt pavement (RAP) with its inherent visco-elastic component before treatment provides a useful insight into the behaviour of half-warm foamed mixes. The two approaches possible for the RAP mix viz. inclusion or exclusion of filler and water before foam stabilisation, have been investigated in terms of compactibility and the gyratory curves are superimposed in Figure 5.

The half-warm RAP mixes that have been supplemented with filler and water and heated to a variety of mixing temperatures yield little variation in density when compacted at ambient temperature. This is consistent with the other materials treated using the half-warm foamed mix process.

The half-warm RAP mix with only foamed bitumen added provides greater variability. Noting that the RAP at 87°C mixed with foamed bitumen (without filler or water) was compacted at 65°C to provide workability, whereas the other RAP heated to 58°C was compacted at ambient temperature, the aggregate mixing temperature is not necessarily the main consideration. An influence of compaction temperature and moisture regime, rather than mixing temperature appears to have a greater influence on the compactibility of half-warm foamed mixes. This is due to the binder viscosity for a 150/200 penetration bitumen being in the ideal range for compaction when the equilibrium temperature of the mix is above 65°C. Compaction, however, is not the only criterion. More importantly the variations in engineering properties of the foamed mix, outlined in Section 3.5, provide a deeper insight into these mixes.

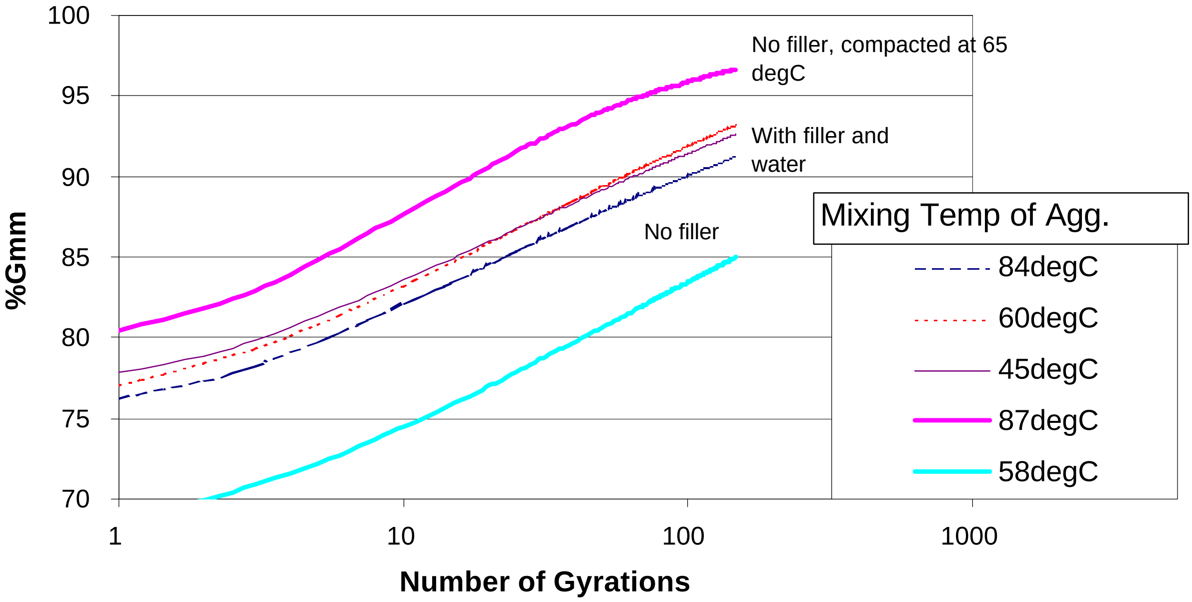

Figure 5: Gyratory compaction curves of half-warm foamed RAP at different mixing temperatures, compacted at ambient temperature (28 ºC) unless otherwise indicated

3.5 Selected mechanical tests

The Indirect Tensile Strength (ITS) test provides a measure of a mixture's resistance to fatigue cracking and has therefore been selected to investigate the influence of aggregate temperature on the mix properties. This test is extensively used for cold-mix and hot-mix asphalt laboratory design procedures in South Africa. The ITS is recognised as not being a highly repeatable parameter, so correlation coefficients of high value cannot be expected for any relationships involving tensile strength of half-warm mixes. The results should be viewed in terms of general trends rather than definitive relationships, therefore.

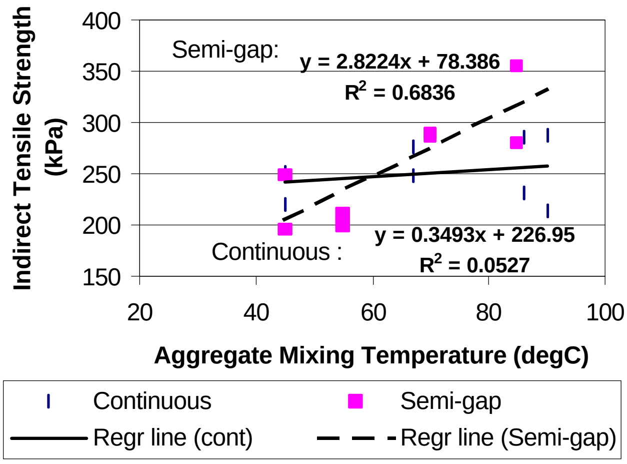

Figure 6: Tensile strength versus aggregate temperature for continuous and semi-gap graded foamed mix, cured at 40°C for 72 hours

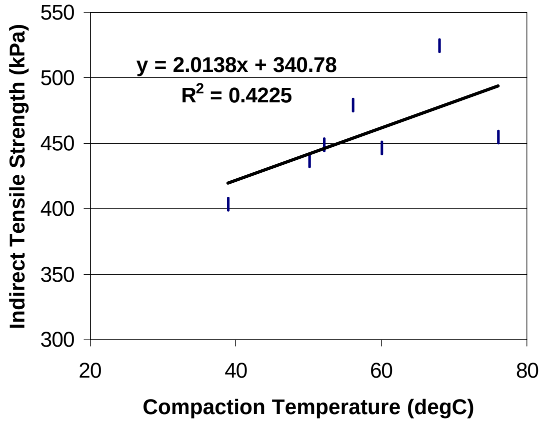

Figure 7: Tensile Strength versus compaction temperature for continuous graded foamed mix, cured 6 weeks inside at ambient temperature

Specimens for the mechanical testing were prepared using the gyratory compactor, followed by a standard curing technique. Figure 6 illustrates the relationship between aggregate mixing temperature and ITS for the continuously and semi-gap graded aggregates. Although there is significant scatter, an overall trend of increase in tensile strength with elevated mixing temperatures is evident, especially for the semi-gap graded mixture. Similar inferences were established for both a granite gravel and a gravelly sand mix using the ITS and SCB (Semi-circular Bending) Tests respectively, with a relationships closely resembling that of the semi-gap graded materials. The same positive trend holds true for effects of the compaction temperature on the mix properties, as shown in Figure 7, which concurs with the findings in the literature.

As with the compaction investigation, two different approaches were employed in the foamed treatment of the RAP materials i.e. with and without filler and water supplementation. Where water and filler are added to the RAP mix before heating and applying the foamed bitumen, a mixture is produced that has typical cold-mix attributes. The mix has moderate tensile strength, comparable to and somewhat higher than other cold mixes.

On the other hand, foamed bitumen added to the RAP at raised temperatures without additional filler and water, negates the shelf-life characteristics of foamed bitumen but produces a mix with far superior engineering properties. The RAP that has been heated to 60°C for mixing with foamed bitumen (without water or filler) and cooled to ambient temperature, has very poor workability; whilst the RAP heated above 80°C is totally unworkable after cooling, as indicated in Table 2. As a result, half-warm RAP mixes produced at >60°C without water require compaction at elevated temperatures (65°C has been utilised). These mixes produce a significant difference in the tensile strength, compared with foamed RAP cold mix. The elevated mixing and compaction temperatures and lack of water produce a foamed mix with tensile strengths equivalent to and higher than many HMA mixtures, as shown in Figure 8, which is a significant finding.

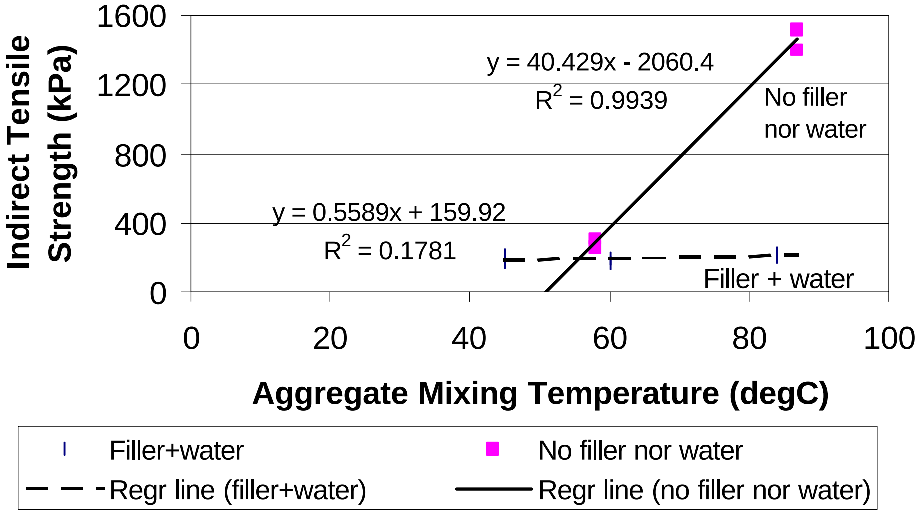

Figure 8: Tensile Strength versus aggregates temperature for RAP (4% BC) treated with 2% foamed bitumen (150/200 penetration) for all mixes

The testing of tensile strength should not be regarded as the sole criteria for the adjudication of the benefits of half-warm foamed mixes however. Resistance to permanent deformation and low temperature cracking, which have not yet been considered, should also be investigated for these materials.

4. CONCLUSIONS

Although cold-mixes with foamed bitumen binder have been successfully produced at ambient temperatures, scope exists for the improvement of mix performance through the addition of a moderate measure of energy before blending with the foam. An investigation into the foamed bitumen stabilisation of half-warm materials has provided the following conclusions:

- The heating of aggregates above ambient temperatures but below 100°C prior to mixing with foamed bitumen does have an impact on the mixture produced. Visual observations indicate that the coverage of aggregate particles by the binder increases as the aggregate temperature rises i.e. particle coating is improved. In particular, larger aggregate particles can be completely coated with bitumen, and the extent of the partial coating is also improved.
- The distribution of the binder is improved in the foamed bitumen process through the heating of aggregates prior to mixing. As the temperature of the mineral aggregates is increased, so the dispersion of the binder improves. The continuity of the binder in the mix has been measured with the vane-shear device, yielding increased cohesion values with higher mixing temperatures.
- The compactibility of half-warm foamed mixes is influenced predominantly by the compaction temperature and fluid content of the mix rather than the aggregate temperature at time of mixing.
- Two possibilities exist for the compaction of half-warm foamed mixes viz. compaction at ambient temperature or elevated temperature. Most of the mixes in this study were compacted at ambient temperature, which simulates road layerwork construction utilising the half-warm mixes as a cold-mix. However, this investigation and other research published in the literature have also shown that

elevated compaction temperatures (even between 65°C and 85°C) yield substantial benefits in terms of mix performance.

- The tensile strength of a foamed bitumen mixture is enhanced through the heating of aggregates above ambient temperatures but below 100°C. A trend of increasing Indirect Tensile Strength and Semi-Circular Bending Tensile Strength has been noted for all of the half-warm foamed mixes investigated, albeit with notable variance. This indicates that improved fatigue resistance of the mixes could be expected, although fatigue or performance testing with repetitive loading is necessary to verify and quantify this phenomenon.
- With the addition of water to enhance binder dispersion in the half-warm foamed mix, the tensile strength of the mix increases moderately (due to the heating of the aggregate) but remains in the same order as that of cold mixes. The addition of water restricts the tensile strength from increasing to the levels of HMA.
- Moisture is lost during mixing in the half-warm foamed process as a result of excitation of the water molecules by the heated aggregate. Cognisance should be taken of the moisture content at mixing in order to maximise binder dispersion whilst minimising loss of adhesion.
- Reclaimed Asphalt Pavement (RAP) Materials show great potential for treatment with the Half-warm Foamed Bitumen process. In particular, RAP that is heated to between 80°C and 95°C and stabilised with foamed bitumen without the addition of filler or moisture, produces asphalt comparable to HMA. Such a mix cannot be termed a “cold mix” however, and must be compacted at temperatures above 65°C to maintain workability and compaction levels. The addition of filler and moisture to the RAP in the half-warm process does enhance cold-mix qualities, but forfeits tensile strength and performance in the process.
- SMA and ZOAB type mixes show potential for application in the half-warm foamed bitumen process, but several aspects of mix production require improvement. In particular, the mixing process requires attention as well as the incorporation of some bitumen emulsion to improve coating.
- Resistance to moisture susceptibility was not investigated in this limited feasibility study, but the improved coating of larger aggregates by the binder through the addition of heat indicates that moisture resistance is likely to improve.

This investigation has been a feasibility study aimed at covering a wide range of prospective materials for treatment using the half-warm process and as a result has a relatively low statistical reliability. This is manifest in the moderate to high variability in the results. Additional tests are required to develop a more accurate assessment of the trends and hence more reliable confidence limits particularly for materials intended for use in large-scale trials.

Enhanced foamed-mix performance can only be speculated upon from the limited laboratory testing undertaken to date, but the improved engineering properties obtained for half-warm foamed mixes have stimulated additional research, which is in progress.

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REFERENCES

Bowering R.H. and Martin C.L., 1976. **Foamed Bitumen Production and Application of Mixtures : Evaluation and Performance of Pavements**. Proceedings Association of Asphalt Paving Technologists. New Orleans, USA. Pp 453-477

CSIR Transportek, 1998. **Foamed Asphalt, Mix Design**. Website http:\\foamasph.csir.co.za:81/chap4.htm

Roberts F.L., Engelbrecht J.C. and Kennedy T.W., 1984. **Evaluation of Recycled Mixtures Using Foamed Asphalt**. Transportation Research Record 968. Pp 78-85

Buschkühl G., Gapski J. and Gründel R., 1990. **Bituminöse Tragschichten aus Müllverbrennungssasche und Schaumbitumen**. Diplomarbeit, Fachbereich Bauingenieurswesen, Fachhochschule Hamburg. Germany.

Eggers C., Holzhausen M. and Bartels J., 1990. **Bituminöse Tragschichten aus Müllverbrennungssasche und Schaumbitumen under besonderer Berücksichtigung von unterschiedlichen Tensiden**. Diplomarbeit, Fachbereich Bauingenieurswesen, Fachhochschule Hamburg. Germany.

Jenkins K.J., For 1999. **Mix Design Considerations for Cold and Half-warm Bituminous Mixes with emphasis on Foamed Bitumen**. Unpublished PhD Thesis (to be submitted in late 1999). University of Stellenbosch.

Ruckel P.J., Acott S.M. and Bowering R.H., 1982. **Foamed-Asphalt Paving Mixtures: Preparation of Design Mixes and Treatment of Test Specimens**. Transportation Research Record 911. USA. Pp 88-95