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The Compaction Potential of Foamed and Emulsified Bitumen Treated Material

Summary Report

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Abstract:

The purpose of the study was to investigate the effect of emulsified or foamed bitumen treatment in combination with an active (cement) or inert (fly-ash) filler on the compaction characteristics and engineering properties of two road-building materials. Two aggregates with different gradings and Atterberg Limits were selected for the study, namely a crushed hornfels and decomposed granite. These materials were treated at two levels of each of the bituminous binders and two levels of each of the fillers as well as with different combinations of binders and fillers. Sufficient material was prepared at each treatment combination to allow for the compaction of three specimens for each of the compaction methods, namely vibratory table, gyratory and modified AASHTO compaction.

Each material showed a clear preference for a particular compaction method, vibratory table compaction for the crushed hornfels and gyratory compaction for the decomposed granite. Foamed and emulsified bitumen treatment generally caused a reduction in the level of compaction of both types of aggregate. Little justification could be found for the use of foamed or emulsified bitumen in the case of the crushed stone other than the clear improvement in compaction when emulsified bitumen is used on its own at a low to intermediate binder content. A combination of cement and either emulsified or foamed bitumen had clear benefits in terms of both the UCS and ITS of the decomposed granite. No general distinction could be made between foamed and emulsified bitumen treatment based on the results from the study but there are specific situations where one binder type seems to produce better results.

Cement had a negative effect on the compaction of the aggregates but a positive effect on the engineering properties of the aggregates. Little motivation could be found for the use of fly-ash as filler with either type of bituminous binder.

Recommendations are provided on a single volumetric density specification for plant treatment of recycled aggregates. The specification was initially developed from laboratory test results and further refined with results from selected field test sections. Procedures to determine the appropriate laboratory compaction equipment and density specification for deep in situ recycling projects are also recommended.

Keywords: compaction, foamed bitumen, emulsified bitumen, cement, fly ash

Proposals for implementation:

Related documents:

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EXECUTIVE SUMMARY

The purpose of the investigation presented in this report was to assess the effect of emulsified and foamed bitumen treatment in combination with active or inert fillers on the compaction characteristics and engineering properties of different types of road-building material with the aim of developing a realistic density specification for these materials. On account of time and budget constraints the investigation was limited to only two materials and is not intended to be comprehensive investigation of the compaction potential of bituminous treated material. The study consisted of two phases, the first phase being a laboratory study and the second phase a field validation of the findings from the laboratory study.

Two types of aggregate with different gradings and Atterberg Limits were selected for the laboratory study, a crushed hornfels and a decomposed granite. These materials were treated at two levels of each of the bituminous binders and two levels of each of the fillers as well as with different combinations of the binders and fillers. Sufficient material was prepared at each treatment combination to allow for the compaction of three specimens by each of the compaction methods namely, vibratory table, gyratory and modified AASHTO compaction.

The results from this study again highlight the complexity of the compaction of road-building material which is further complicated by the addition of bituminous binder and filler. Although there seems to be some logic governing compaction, the rules seem to change from situation to situation depending on the nature of the aggregate (grading and Atterberg limits), the compaction method, the type of bituminous binder (foamed bitumen or emulsified bitumen), the type of filler and the binder and filler contents. This makes it very difficult to formulate a set of consistent compaction guidelines that will ensure the selection of the most appropriate compaction equipment, type of bituminous binder, type of filler and the filler and binder content levels. A few general observations are nevertheless made, although these may be contradicted by individual results found in the data.

The differences between the grading and Atterberg Limits of the two materials used in the investigation resulted in different optimal compaction methods for the two materials. The crushed hornfels with a continuous grading and low PI was more conducive to vibratory table compaction, whereas the decomposed granite with a more uniform grading preferred gyratory compaction. This is probably caused by insufficient fine material in the crushed hornfels to form a compaction paste in which the larger particles are suspended, orientated and moulded during compaction. Stone–to-stone contact therefore occurs in the large particle matrix and is lessened during the rebound cycle of vibratory compaction, thus enabling the larger particles to re-orientate and pack together more tightly. The decomposed granite, which had a surplus of fine material with a relatively high PI by comparison with the maximum density grading, preferred the kneading action of gyratory compaction. The larger particles were probably suspended in a compaction paste formed by the relatively plastic fine material and the kneading action of the gyratory compaction could mould the material into the optimal packing pattern.

Evaluating the results from the compaction study merely on the gravimetric density or the density expressed as a percentage of some arbitrary reference density resulted in misinterpretation of the compaction results. It was soon realised that the compaction results had to be assessed in terms of volumetric composition. Distinction was therefore made between the total volume filled with aggregate, filler and bituminous binder and the volume filled with solids (aggregate and filler) during compaction.

In general the following observations are made regarding the compaction of the materials although, as stated earlier, individual exceptions to these observations can be found in the data:

- Crushed hornfels
    - Vibratory table compaction
        - Low to intermediate emulsion contents (below 1.5 %) used without a filler had a strong positive effect on the compaction of the crushed hornfels;
        - Cement used in combination with emulsion had a negative effect on the compaction of the crushed hornfels;
        - Cement used in combination with foamed bitumen had no effect on the compaction of the material;
        - Fly-ash used in combination with emulsion had less of a negative effect on compaction than cement used with emulsion;
        - Fly-ash used in combination with foamed bitumen had no effect on the compaction of the material;
        - Increasing percentages of foamed bitumen and emulsion had a negative effect on the compaction of the material when used together with the fillers.
    - Gyratory compaction
        - Fly-ash generally had a positive influence on the compaction of the material, whereas cement had a negative effect;
        - Increases in binder content had a negative effect on the compaction of the material in terms of the volume of solids for both foamed bitumen and emulsion used in combination with cement and fly-ash.
    - Mod. AASHTO compaction
        - Cement and fly-ash alone had a negative effect on the compaction of the material;
        - Increasing binder content had a negative effect for both foamed bitumen and emulsion;
        - The use of a filler in combination with foamed bitumen reduced the negative effect resulting from increasing the binder content mentioned above.
- Gauteng granite
    - Vibratory table compaction
        - Only a few clear trends could be observed;

    - Fly-ash on its own had a positive effect on the compaction of the material whereas cement had a negative effect;
    - Increasing binder contents using both foamed bitumen and emulsion had a slight negative effect on the compaction in terms of the volume of solids.
- Gyratory compaction
    - Cement generally had a negative influence on the compaction when used on its own or in combination with foamed bitumen or emulsion;
    - Fly-ash was neutral in terms of its effect on compaction both on its own and when used in combination with binder;
    - Increasing emulsion contents had no effect on the compaction of the material;
    - Increasing foamed bitumen contents had a slight negative effect on the compaction of the material.
- Mod. AASHTO compaction
    - Neither cement nor fly-ash had any discernable influence on the compaction;
    - Both emulsion and foamed bitumen had the same negative impact in terms of a decrease in volume of solids with an increase in binder content.

The intermediate percentage of emulsified bitumen acted as a compaction lubricant for the vibratory compaction of the crushed hornfels in terms of both volume filled and volume of solids. This benefit of emulsified bitumen treatment was, however, not found using gyratory or mod. AASHTO compaction on the crushed hornfels. Vibratory type of compaction is, however, the preferred compaction method for this type of material both in the laboratory and in the field and emulsified bitumen at low to intermediate binder content levels (<1.5 %) may therefore assist as a compaction aid for crushed stone and to improve the workability of recycled old crushed stone bases.

Using the optimal compaction method and compacting to refusal density it was possible to maintain the volume filled above 86 per cent and the volume of solids above 84 per cent for most of the combinations of emulsified or foamed bitumen and cement or fly-ash, except for the high binder content levels. In the case of the decomposed granite it was possible to maintain the volume of solids above 78 per cent for almost all the combinations tested. This volume of solids percentage is equivalent to the volume of solids of the untreated material compacted to 100 per cent of modified AASHTO maximum dry density.

Although the UCS and ITS may not be the most appropriate parameters for the assessment of bituminous treated material, the compaction study produced specimens suited to these tests. UCS and ITS tests were therefore done on the compacted and cured specimens. In terms of the UCS and ITS engineering properties of the materials, the following observations are made:

- Crushed hornfels
    - Unconfined compressive strength, UCS
        - The UCS of the material is dominated by the cement content and the UCS increases with increasing cement content regardless of the negative impact of cement on the compaction of the material;
        - Increasing binder content has a negative effect on the UCS of the material but this is less pronounced for foamed bitumen than for emulsion;
        - Fly-ash has no benefit in terms of the UCS of the material regardless of the general positive influence of fly-ash on the compaction of the material.

    - Indirect tensile strength, ITS
        - The observations relating to the UCS of the material also apply to the ITS of the material.
- Gauteng granite
    - Unconfined compressive strength, UCS
        - Cement on its own causes some improvement in the UCS of the material;
        - Foamed bitumen and emulsion on their own cause an increase in the UCS of the material but to a lesser extent than cement on its own;
        - The combination of both foamed bitumen and emulsion with cement had a more advantageous effect than either the cement or binder on its own. Specimens with an intermediate binder content of emulsion yielded better results than those with a high binder content;
        - The use of fly-ash with emulsion only reflected the improvement in UCS obtained from the emulsion;
        - The combination of fly-ash with foamed bitumen caused some improvement to the UCS of the material but not as much as the combination of foamed bitumen with cement.
    - Indirect tensile strength, ITS
        - Cement on its own improved the ITS of the material;
        - Binder on its own, either foamed bitumen or emulsion, increased the ITS to almost the same extent as that produced by cement on its own;
        - The combined effect of foamed bitumen or emulsion with cement resulted in the greatest improvement in the ITS of the material;
        - Fly-ash, both on its own and in combination with binder, only reflects the improvement in ITS achieved by the use of the binder.

In the case of the crushed hornfels, the UCS requirements of the TG2 guideline for foamed bitumen treated material are easily achieved by the addition of cement, either on its own or in combination with either emulsified or foamed bitumen. The ITS of the crushed hornfels is also largely dictated by the cement content with the binder content having little effect. Any of the TG2 material classes may be achieved in terms of ITS with the correct combination of bituminous binder and cement, whereas none of the classes can be achieved using bituminous binder on its own or in combination with fly-ash. Based on the results from this study, other than adding emulsified bitumen at an intermediate level to act as a compaction lubricant, there is little motivation from a UCS and ITS strength point of view, to use either foamed or emulsified bitumen with crushed stone. . There may, however, be other considerations in favour of adding bituminous binder, such as the improvement of the workability of an old crushed stone base layer that is being recycled and the retention of the fines in the layer in the long term, and/or improving the water resistance of the material.

The UCS of the decomposed granite is determined by the cement content, binder content and the interaction between the cement and binder. Any of the TG2 material classes can be achieved in terms of UCS by using the correct combination of emulsified or foamed bitumen with cement, whereas only the lowest class is achieved using fly-ash at a high binder content. The UCS and ITS strengths achieved for this material using a combination of bituminous binder and cement exceeded the strengths achieved when either of these stabilizing agents was used on its own. In terms of the engineering properties of this material there is definite benefit in using a combination of either foamed or emulsified bitumen with cement. There seems to be no preference for emulsified or foamed bitumen treatment in terms of UCS and ITS results.

The UCS and ITS requirements of the TG2 document could therefore be achieved for both materials using different combinations of foamed or emulsified bitumen in combination with cement. Very little motivation could be found for using fly-ash as filler in terms of either compaction or the engineering properties of the two aggregates used in the investigation.

The variability of the laboratory permeability tests is such that only the difference between the untreated and treated material could be detected. The permeability of the untreated material is generally higher than that of the treated material.

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Two separate tentative volumetric-based density specifications were set, based on the results from the laboratory study. It was recommended that these tentative specifications be validated by density results from a number of field test sections.

The objectives of the validation phase of the project were clearly defined and included assessing the following hypotheses and formulating outcomes for each hypothesis:

- 1st hypothesis: The most appropriate type of laboratory and field compaction equipment is determined by the grading of the material to be compacted;
- 1st outcome: Guidelines on the selection of appropriate laboratory and field compaction equipment;
- 2nd hypothesis: The use of a gravimetric density specification for foamed and emulsified bitumen treated material is not sufficient and should be replaced by a volumetric specification;

- 2nd outcome: A laboratory and field validated volumetric compaction specification for foamed and emulsified bitumen treated material.

A third objective was added to the project during execution of the project:

- Compare gravimetric and nuclear gauge dry density readings for selected test sites and make a recommendation on the use of nuclear density gauges for quality control purposes on foamed and emulsified bitumen treated layers.

A number of field test sections were used during the validation phase of the project. These included:

- A foamed bitumen treated (FBT) recycled crushed hornfels (CS) base from the N7 near Cape Town, previously tested with the Gautrans HVS;
- A foamed bitumen treated (FBT) recycled CTB from P243/1 near Vereeniging, previously tested with the Gautrans HVS;
- An emulsified bitumen treated (EBT) recycled CTB from P243/1 near Vereeniging, previously tested with the Gautrans HVS;
- A foamed bitumen treated (FBT) recycled asphalt (RAP) section on P504 near Shongweni;
- A foamed bitumen treated (FBT) decomposed granite natural gravel section on P504 near Shongweni;
- A foamed bitumen treated (FBT) sand and calcrete mixture from MR439 between Mseleni and Phelendaba.

Background information on the field test sections was obtained from people involved in the construction of the sections (interviews, questionnaires and e-mails), as well as from research reports and papers published on the test sections.

Except for one of the project sites included in the field investigation, reliable binder contents were obtained when a sufficient number of binder content tests were done on individual cores taken from the sites. It is the opinion of the author that binder content control testing could be included in the quality control process on foamed and emulsified bitumen treatment projects if proper statistical sampling is done. This will, however, have a cost implication to be considered by the client, engineer and contractor. It is recommended that binder content control testing should be introduced on important foamed and emulsified bitumen treatment projects if the client deems it necessary. It is recommended that a minimum of 3 binder content tests should be done per bulk sample from each control testing location after the material is properly mixed and quartered.

Most of the binders from the field test sections showed aging with the binder from P504, which had been longest in service, showing the most aging. The penetration, softening point and chemical analysis results for both the foamed and residual emulsified bitumen from P243/1 contradict the results from all the other sites and the binder is much softer than expected, even by comparison with new binder. The anomalous binder properties from this site cannot be explained and this site needs to be investigated in detail.

Based on a limited set of results, nuclear density gauges seem to be sufficiently reliable to be used for density control testing on foamed and emulsified bitumen treatment projects if these are properly calibrated. Based on the limited results available, the density results from the nuclear gauges seem to be conservative. The use of nuclear density gauges should be continued on foamed and emulsified bitumen treatment projects. The applicability of the device on specific projects should be verified on the construction trial section by taking nuclear gauge readings at certain locations and removing cores at these locations after curing for laboratory density tests. The nuclear and laboratory density data obtained in this manner from the construction trial section should be used to calibrate the nuclear gauge for the specific project.

The effect of aggregate grading on the compaction of the material was confirmed by the results from the validation phase. Not only does the deviation of the grading from the maximum density grading curve determine the level of density that is achieved, but the grading of the material also determines the preference of the material in terms of the type of compaction action that will result in the highest possible density being achieved. This preference for a particular compaction action is not related to the energy of the compaction method because the sequence of preference is not the same for the two materials investigated, since the compaction energy remained constant for each compaction method.

The current practice on recycling projects of taking a bulk sample from behind the recycler and then compacting this material using modified AASHTO compaction to set a reference density may be detrimental to the performance of the road as modified AASHTO compaction yielded the lowest densities for the treated material tested during this project. A very low density specification is therefore set in terms of the maximum dry density for modified AASHTO compaction. Setting a volumetric density specification will alleviate this problem but is only possible for plant treatment of recycled material where the final recycled grading, ARD of the aggregate and the binder content can be determined accurately during the design phase. Such a volumetric density specification is impractical to apply to deep *in situ* recycling projects.

The selection of appropriate compaction equipment applies to laboratory compaction for material design and quality control as well as to field compaction. In the case of laboratory compaction, circumstances are different for plant and *in situ* treatment of recycled material. In the case of plant treatment it is recommended that a laboratory compaction optimisation investigation be done as part of the material design using modified AASHTO, gyratory and vibratory compaction. Commercial equipment is available for modified AASHTO and gyratory compaction and the Kango hammer is recommended for vibratory compaction. The compaction method yielding the best results can then be specified for quality control in the field laboratory.

Unfortunately, as the final recycled grading is not known during the design stage for deep *in situ* recycling, it is recommended that the material recycled during a construction trial be sampled and compacted using all three laboratory compaction methods, namely modified AASHTO, vibratory and gyratory compaction. The optimal compaction equipment may thus be identified and specified for the main construction project. Although the optimal compaction equipment depends on the type of material, significant changes in material characteristics would have to occur to require more than one type of laboratory compaction equipment in the field laboratory because of material changes. In such cases, separate construction trials would have to be conducted for the different materials.

In terms of the selection of suitable field compaction equipment, communication with practitioners appears to indicate that they generally feel that the selection of compaction equipment should be left to the discretion of the contractor. Most practitioners felt that the construction of a trial section would be extremely valuable in ironing out construction difficulties, including the selection of the right compaction equipment and sequence. Although the construction of such a trial section might assist in the selection of appropriate compaction equipment, higher densities might be possible if the optimal compaction equipment were selected. It is the author's opinion that sufficient evidence has been obtained from the laboratory study to justify a compaction equipment selection guideline or at least to justify some attempt being made during the construction of the trial section to optimise the selection of field compaction equipment.

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ACKNOWLEDGEMENTS

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1. INTRODUCTION

Field and laboratory results from past research projects indicate that the addition of foamed bitumen during the recycling process may cause a reduction in the compaction density achieved with a concurrent increase in the permeability of the layer. On the other hand, experienced practitioners have claimed that emulsified bitumen acts as a compaction lubricant, causing a reduction in volume and an associated increase in density when the emulsion breaks.

This project aimed to investigate the issues mentioned above through a combination of limited laboratory and field studies in order to make recommendations on a field density specification for foamed and emulsified bitumen treated mixes. The laboratory phase of the project consisted of the following main components:

- The investigation of the effect of foamed and emulsified bitumen on the compaction potential of crushed stone and natural gravel samples; and
- A comparison of the ease of compaction and refusal density of the treated material with that of untreated material. The permeability and engineering strength parameters (UCS and ITS) of the compacted specimens were also determined in the process. The UCS and ITS tests were selected merely because the compaction processes produced specimens that were compatible with these tests. However, it is not implied that these are the most suitable tests for the design of emulsified and foamed-bitumen-treated materials.

The following variables were included in the laboratory project:

1. Material types – natural gravel and crushed stone;
2. Binder/filler types – cement, inert filler (fly ash), emulsified bitumen, foamed bitumen and combinations of these; and
3. Compaction methods – modified AASHTO, vibratory table and gyratory compaction.

The outcome of the laboratory investigation may be summarised by the following main points:

- The optimal laboratory compaction equipment that resulted in the maximum densification of the material differed for the two materials used in this study;
- The level of compaction that was achieved for each of the materials at a given combination of bituminous binder and filler depended on the type of compaction equipment that was used;
- The use of only a gravimetric density specification may be misleading when working with a multi-phase material consisting of aggregate, filler, bitumen, water and air. In general the total volume filled is maintained with increasing quantities of bitumen but the volume of solids is reduced;

- A tentative laboratory-based volumetric specification was given for crushed stone and natural gravel type materials treated with foamed or emulsified bitumen.

Based on these observations and conclusions, it was recommended that the tentative volumetric density specification from the laboratory study be validated with results from a field study on selected sites. The intention of the validation phase was to test the following hypotheses and to formulate the outcomes as described below if the results from the project allow:

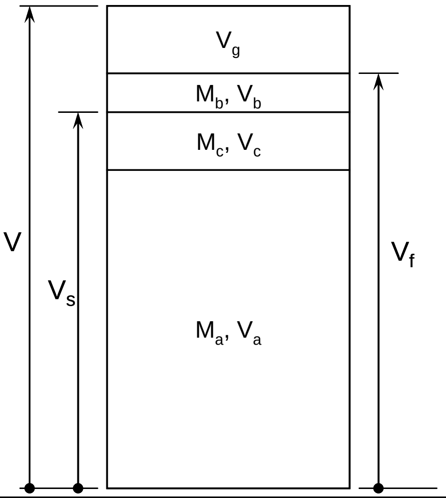
- 1st hypothesis: The most appropriate type of laboratory and field compaction equipment is determined by the grading of the material to be compacted;
- 1st outcome: Guidelines on the selection of appropriate laboratory and field compaction equipment;
- 2nd hypothesis: The use of a gravimetric density specification for foamed and emulsified bitumen treated material is not sufficient and should be replaced with a volumetric specification;
- 2nd outcome: A laboratory and field validated volumetric compaction specification for foamed and emulsified bitumen treated material.

An additional aspect to be investigated was added to the project after discussions at the Road Pavements Forum in November 2005 concerning the use of nuclear density gauge readings for quality control purposes. This aspect fell outside the scope of the project proposal and could only be investigated during the field testing at sites in KwaZulu-Natal as the field testing at the other sites had already been completed at that time. The results from the investigation of this aspect are therefore not definitive and only serve as an indication of the viability of using nuclear density gauges on foamed and emulsified bitumen treated material.

2. BACKGROUND INFORMATION

2.1. Volumetric calculations

The density specification recommended for plant treatment projects is based on the volumetric composition of foamed and emulsified bitumen treated material. The volumetric portions of the aggregate, filler and binder are calculated from the equations below if the apparent densities of the aggregate, γ_a, filler, γ_c, and binder, γ_b, are known, with the variables defined in Figure 1.



V = Total volume

V_s = Volume of solids

V_f = Volume filled

V_g = Volume of air

M_b, V_b = Mass and volume of bitumen

M_c, V_c = Mass and volume of filler

M_a, V_a = Mass and volume of aggregate

M_d = Mass of dry mixture (aggregate, filler, binder)

Figure 1. Volumetric composition of a composite material

$$V_a = \frac{M_d}{\gamma_a \left(1 + p_c + p_b + p_b\, p_c\right)}$$

$$V_c = \frac{p_c M_d}{\gamma_c \left(1 + p_c + p_b + p_b\, p_c\right)}$$

$$V_b = \frac{\left(p_b + p_b\, p_c\right) M_d}{\gamma_b \left(1 + p_c + p_b + p_b\, p_c\right)}$$

where p_c and p_b are the percentages of cement and bitumen by mass.

The volume of solids, V_s is calculated from $V_a + V_c$ and the volume filled, V_f from $V_a + V_c + V_b$.

In cases where the individual masses of the aggregate and filler are not known, such as when the combined mass of the aggregate and filler is obtained from a field core on which a binder recovery was done, the mass, M_s, and apparent density, γ_s, of the solids are determined directly, reducing the calculations to:

$$V_s = \frac{M_d}{\gamma_s (1 + p_b)}$$

$$V_b = \frac{p_b M_d}{\gamma_b (1 + p_b)}$$

2.2. Maximum density grading

One of the earliest investigations into the relationship between the grading of granular material and the density that may potentially be achieved during compaction of the material was done by Fuller and Thompson in 1907 followed by Talbot and Richart in 1923, who developed a mathematical formulation for the maximum density grading curve:

$$p = \left(d/D \right)^n$$

where p = percentage passing a sieve size with opening "d"
D = maximum stone size of the aggregate
n = a constant

Several researchers have since found that grading curves with n-values of 0.5 result in the highest density being achieved.

The deviation of the actual grading curve of a material from the maximum density grading associated with the maximum particle size of the material is used in this report. The deviation at the sieve with opening "d" is calculated from the difference between the percentage passing this sieve on the maximum density grading curve and the actual grading curve, as illustrated in Figure 2.

$$e_d = \left(p_d^m - p_d^a \right)^2$$

where e_d = deviation from the maximum density grading for sieve size "d"
p_d^m = percentage passing the d-size sieve for the maximum density grading
p_d^a = percentage passing the d-size sieve for the actual grading

The Root Mean Square Error (RMSE) deviation is then calculated according to:

$$RMSE = \sqrt{\frac{\sum_{d=1}^{N} e_d}{N}}$$

where "N" is the number of sieves used to characterize the grading of the material.

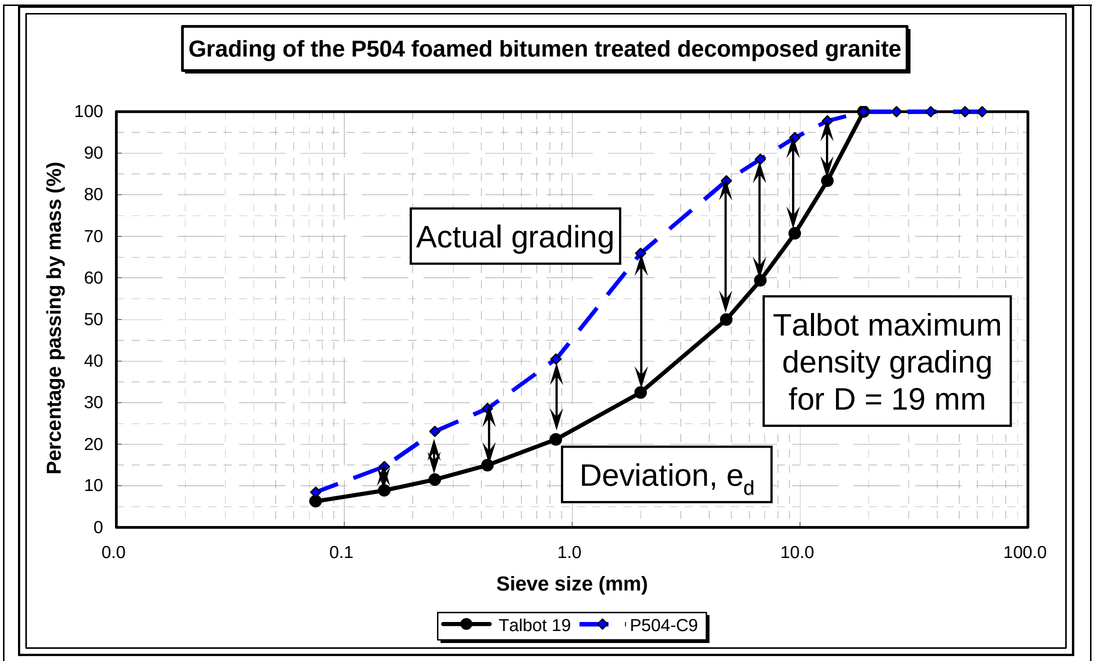


Figure 2. Deviation of the actual grading of the material from the maximum density grading

3. EXPERIMENTAL DESIGN

Two types of material were selected for the laboratory phase of the study, namely crushed stone and natural gravel. Crushed hornfels was obtained from a commercial source in the Western Cape and decomposed granite from a stock-pile in the Diepsloot (Gauteng) area. The basic material properties of the hornfels are summarised in Table 1 and those of the decomposed granite in Table 2. Two types of filler were included in the investigation, a CEMII/A-L 32.5 cement as an active filler and fly-ash as an inert filler. The initial consumption of stabiliser was determined for the two materials used. Since the cement and fly-ash influence the optimum moisture content of the mix, as well as the maximum dry density characteristics, both these parameters were determined for every combination of natural gravel and crushed stone with cement and/or fly ash. The apparent relative densities (ARD) of the materials used in the study are summarised in Table 3.

Table 1 Properties of crushed hornfels material

Atterberg limits		
Liquid Limit	17	
Plastic Limit	14	
Plasticity Index	3	
Linear shrinkage	0.8	
Grading analysis		
Sieve size (mm)	**Passing sieve (%)**	
37.5	100.0	
26.5	92.5	
19.0	81.3	
13.2	70.6	
9.5	60.4	
6.7	50.7	
4.75	43.9	
2.0	26.8	
0.85	17.1	
0.425	13.0	
0.25	10.7	
0.15	9.1	
0.075	7.3	
Modified compaction values		
Treatment	**Optimum moisture content (%)**	**Maximum dry density (kg/m^3)**
Natural	6.1	2 323
Cement 1%	6.0	2 345
Cement 2%	5.8	2 342
Fly ash 1%	6.2	2 323
Fly ash 2%	5.5	2 350

Table 2 Properties of decomposed granite material

Atterberg limits	
Liquid Limit	27
Plastic Limit	20
Plasticity Index	7
Linear shrinkage	1.9

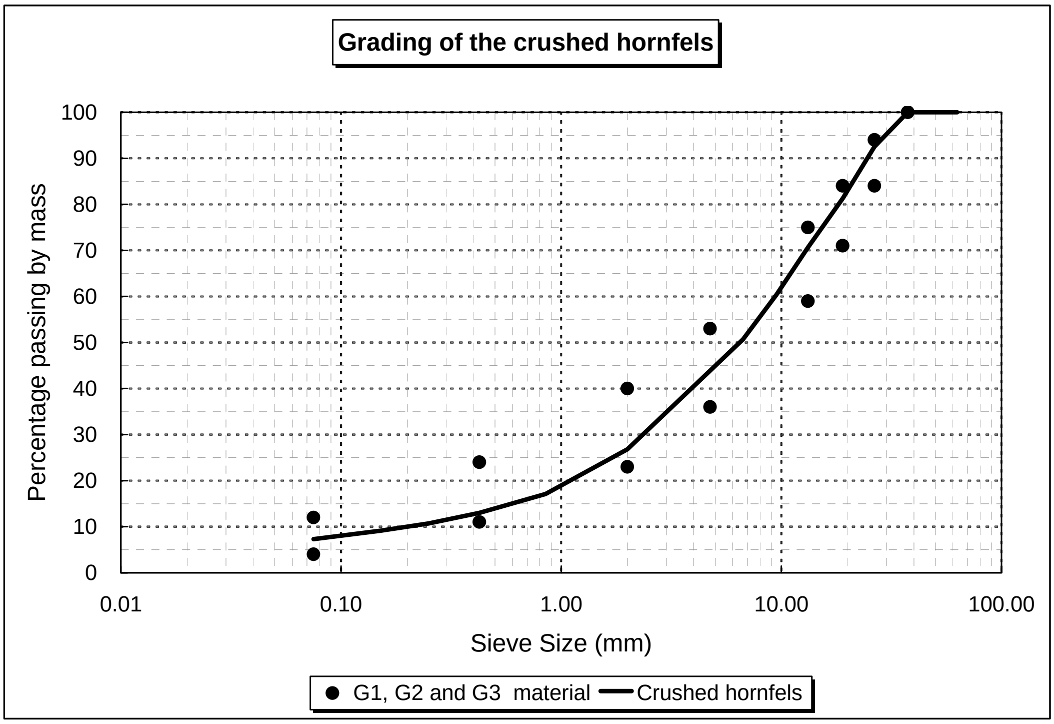
Grading analysis	
Sieve size (mm)	**Passing sieve (%)**
37.5	100
26.5	97.4
19.0	94.4
13.2	90.3
9.5	85.1
6.7	79.7
4.75	78.6
2.0	56.9
0.85	29.5
0.425	17.5
0.25	12.7
0.15	9.9
0.075	7.4

Modified compaction values		
Treatment	**Optimum moisture content (%)**	**Maximum dry density (kg/m^3)**
Natural	8.3	2 066
Cement 1%	8.2	2 065
Cement 2%	8.2	2 048
Fly ash 1%	8.2	2 045
Fly ash 2%	8.2	2 053

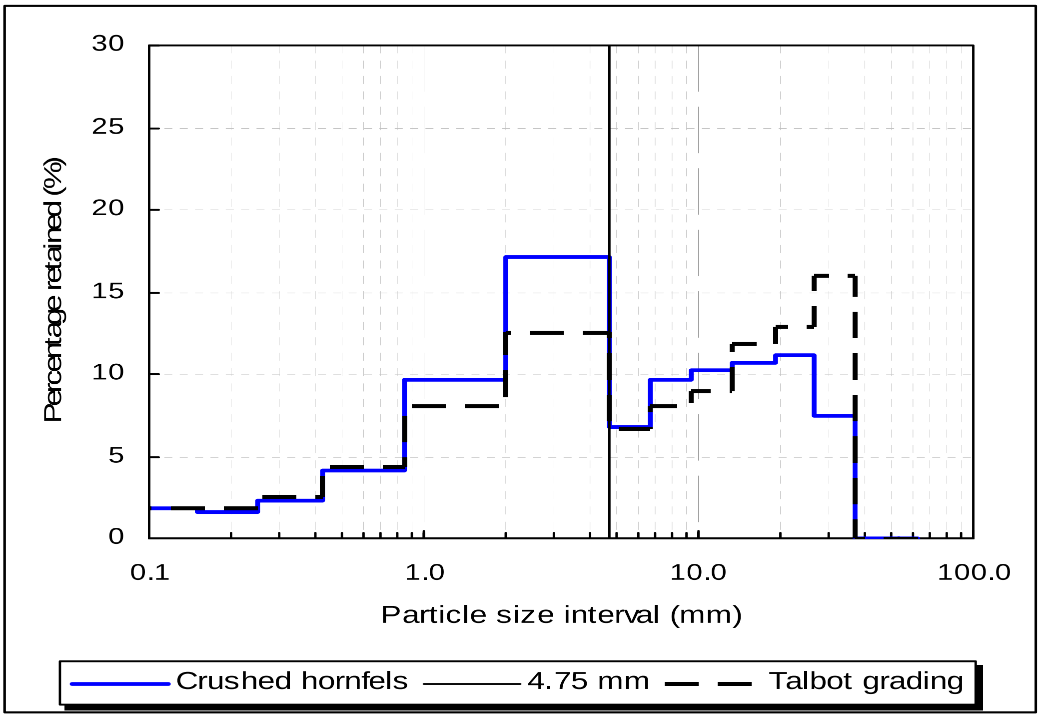
Table 3 Weighted average Apparent Relative Density (ARD) of the materials used in the study

Apparent Relative Density (ARD)	
Crushed hornfels	2.722
Decomposed granite	2.646
Cement	3.150
Fly-ash	2.180
Bitumen	1.010

The gradings of the crushed hornfels and the decomposed granite are plotted on Figure 3 and Figure 4 respectively. It is clear from these figures that the hornfels met the specifications for G1 to G3 material, whereas while the decomposed granite fell outside the G4 grading envelope for uncrushed natural gravel for sieve sizes 2.0 mm and above. Both materials had a maximum particle size of 37 mm and less than 7.5 % material passing the 0.075 mm sieve, which is close to the lower limit of 5 % set for foamed bitumen treatment but which allowed for the fines to be supplemented with the two types of filler. The difference in grading between the two materials is highlighted by the percentage retained plots in Figure 3 (b) and Figure 4 (b). The Talbot grading for optimum compaction is plotted as a reference on these graphs. It can be seen that the decomposed granite had an excess of material smaller than 4.75 mm and a lack of coarse material (> 4.75 mm) by comparison with the Talbot grading.

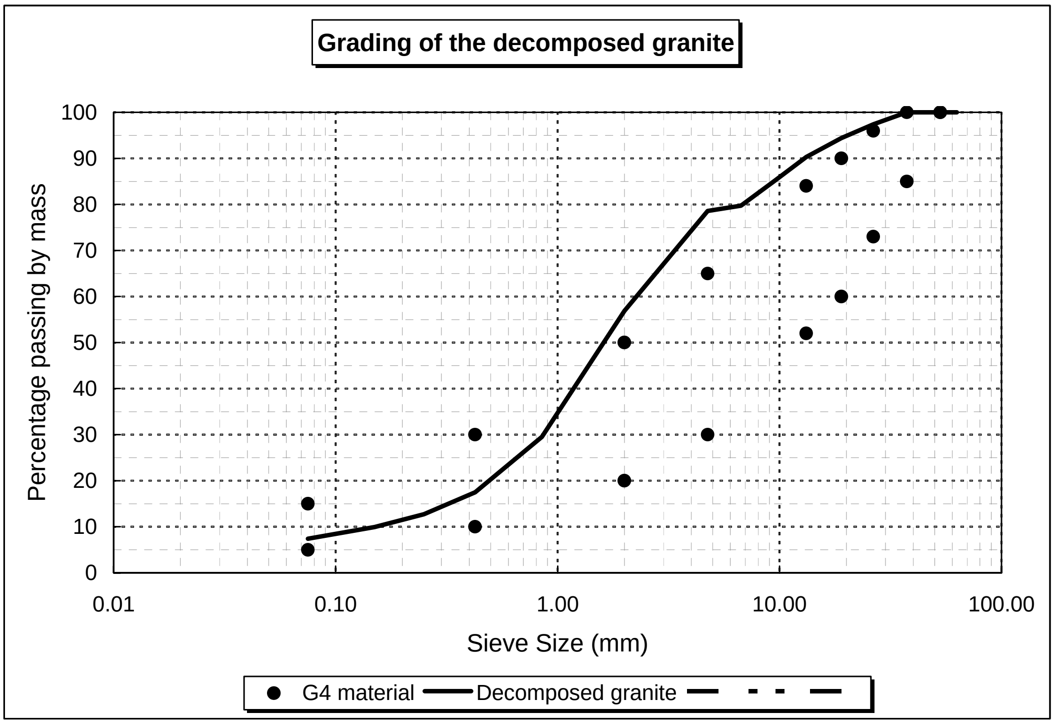


(a) Grading plotted for percentage passing each sieve

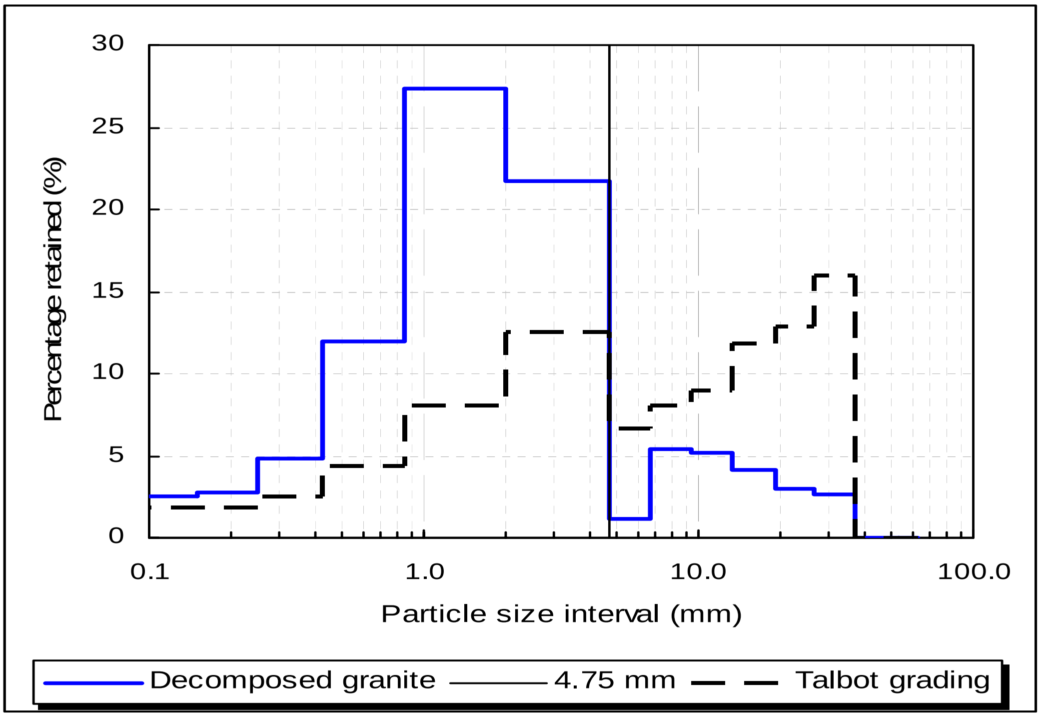


(b) Grading plotted for percentage retained on each sieve

Figure 3. Grading of the crushed hornfels



(a) Grading plotted for percentage passing each sieve



(b) Grading plotted for percentage retained on each sieve

Figure 4. Grading of the decomposed granite

Table 4 sets out the combinations of binder and filler used for both the crushed hornfels and the decomposed granite, with the residual binder content given in brackets for emulsified bitumen treatment. Mix designs were done for the emulsified bitumen treatment of the decomposed granite and crushed hornfels to determine what would be considered as low and high binder contents for each of these materials. The binder contents for the foamed bitumen treatment were selected so as to equal the residual binder content of the emulsified bitumen treatment. In addition to this, the high binder content for the crushed hornfels was selected so as to agree with the binder content of the recycling project on the N7 near Cape Town.

Table 4 Experimental design matrix

Binder type	Filler type and content	Bituminous binder content (%)		
		None	Low	High
Decomposed granite				
Foamed bitumen	None	0	1.5	3.5
	Cement 1%	0	1.5	3.5
	Cement 2%	0	1.5	3.5
Emulsified bitumen (60% binder)	None	0	2.5 (1.5)	5.8 (3.5)
	Cement 1%	0	2.5 (1.5)	5.8 (3.5)
	Cement 2%	0	2.5 (1.5)	5.8 (3.5)
Foamed bitumen	None	0	1.5	3.5
	Fly ash 1%	0	1.5	3.5
	Fly ash 2%	0	1.5	3.5
Emulsified bitumen (60% binder)	None	0	2.5 (1.5)	5.8 (3.5)
	Fly ash 1%	0	2.5 (1.5)	5.8 (3.5)
	Fly ash 2%	0	2.5 (1.5)	5.8 (3.5)
Hornfels				
Foamed bitumen	None	0	0.9	2.25
	Cement 1%	0	0.9	2.25
	Cement 2%	0	0.9	2.25
Emulsified bitumen (60% binder)	None	0	1.5 (0.9)	3.75 (2.25)
	Cement 1%	0	1.5 (0.9)	3.75 (2.25)
	Cement 2%	0	1.5 (0.9)	3.75 (2.25)
Foamed bitumen	None	0	0.9	2.25
	Fly ash 1%	0	0.9	2.25
	Fly ash 2%	0	0.9	2.25
Emulsified bitumen (60% binder)	None	0	1.5 (0.9)	3.75 (2.25)
	Fly ash 1%	0	1.5 (0.9)	3.75 (2.25)
	Fly ash 2%	0	1.5 (0.9)	3.75 (2.25)

Specimens were prepared in triplicate and compacted to refusal density using vibratory table and gyratory compaction respectively for each combination of filler and bituminous binder used in the experiment. Specimens were also prepared in triplicate and compacted using modified AASHTO compaction, with the volume and compaction energy being kept constant. Efforts were coordinated in the laboratory to compact specimens as soon as possible after mixing.

The moisture content at compaction was determined for each mix from surplus material oven-dried to a constant mass. The volume and wet mass of each compacted specimen were determined immediately after compaction. These data, together with the moisture content, were used to perform gravimetric density calculations. The gravimetric density was found not to be useful as it masks the composition of the compacted specimens in terms of aggregate, filler and binder. All the gravimetric density results were therefore converted to volumetric portions of aggregate, filler and binder using the ARD values listed in Table 3 and the mix proportions listed in Table 4. Once the volumetric portions of the individual material components were known, the Volume of Solids (V_s), which is equal to the combined volume of the aggregate and filler and the Volume Filled (V_f), which is equal to the sum of the Volume of Solids and Volume of Bitumen (V_b), could be calculated. The Volume of Solids (V_s) and Volume Filled (V_f) are used extensively in the evaluation of the compaction results in this report. The vibratory table compaction results, gyratory compaction results and the modified AASHTO compaction results are provided in the Appendices of the Technical Memorandum.

The compacted specimens were allowed to cure for 28 days at 100 % humidity at temperatures of between 20 and 25ºC, after which the mass and volume of each specimen were determined again prior to strength and permeability testing. Unconfined Compressive Strength (UCS) tests were performed on the specimens compacted on the vibratory table, Indirect Tensile Strength (ITS) tests on the specimens compacted in the gyratory compactor and permeability tests on the specimens compacted using modified AASHTO compaction. Specimens were not soaked prior to UCS and ITS testing and were tested at the equilibrium moisture content after 28 days curing.

The intention of the validation phase of the project was to test the following hypotheses and to formulate the outcomes as described below if the results from the project allowed:

- 1st hypothesis: The most appropriate type of laboratory and field compaction equipment is determined by the grading of the material to be compacted;
- 1st outcome: Guidelines on the selection of appropriate laboratory and field compaction equipment;
- 2nd hypothesis: The use of a gravimetric density specification for foamed and emulsified bitumen treated material is not sufficient and should be replaced by a volumetric specification;
- 2nd outcome: A laboratory and field validated volumetric compaction specification for foamed and emulsified bitumen treated material.

A third objective was added to the project after discussions at the Road Pavements Forum in November 2005 concerning the use of nuclear gauge density readings for quality control purposes. The general belief in the industry is that the nuclear density gauge does not give reliable density measurements on foamed and emulsified bitumen treated material because the hydro-carbon in the bitumen affects the moisture content reading. This aspect fell outside the scope of the original proposal and could only be investigated from the field test results for sites in KwaZulu-Natal, as field testing at the other sites had already been completed by then. The results from the investigation of this aspect are therefore not definitive and only serve as an indication of the viability of using nuclear density gauges on foamed and emulsified bitumen treated material. The following objective was, however, added:

- 3rd project objective: Compare gravimetric and nuclear gauge dry density readings for selected test sites and make a recommendation on the use of nuclear density gauges for quality control purposes on foamed and emulsified bitumen treated layers.

Lastly, the properties of the binder recovered from cores taken from a number of field test sections were determined to investigate potential changes in binder properties caused by aging of the bitumen. The properties of aged binder have no impact on the primary objective of the study, which was to develop a density specification for foamed and emulsified bitumen treated material.

Data from a number of test sections were used in the validation phase of the project. The following field test sections were selected based on the information available on these sections:

- A foamed bitumen treated (FBT) recycled crushed hornfels (CS) base from the N7 near Cape Town, previously tested with the Gautrans Heavy Vehicle Simulator (HVS);
- A foamed bitumen treated (FBT) recycled CTB from P243/1 near Vereeniging, previously tested with the Gautrans HVS;
- An emulsified bitumen treated (EBT) recycled CTB from P243/1 near Vereeniging, previously tested with the Gautrans HVS;
- A foamed bitumen treated (FBT) recycled asphalt (RAP) section on P504 near Shongweni;
- A foamed bitumen treated (FBT) decomposed granite natural gravel section on P504 near Shongweni, KwaZulu-Natal;
- A foamed bitumen treated (FBT) sand and calcrete mixture from MR439 between Mseleni and Phelendaba, KwaZulu-Natal.

4. DATA ANALYSIS

4.1. Comparison of compaction methods

Three compaction methods were used during the laboratory phase of the study. It was therefore possible to draw a comparison between the compaction results achieved using the different compaction methods by plotting the frequency distribution histograms of the Volume Filled data combined per aggregate type. The frequency distribution histogram of the volume filled for the crushed hornfels and for the decomposed granite are shown in Figure 5 and Figure 6 respectively.

In general, the highest volume filled for the crushed hornfels was achieved using vibratory compaction, with gyratory compaction being second and modified AASHTO compaction third. In the case of the decomposed granite the highest volume filled was obtained with gyratory compaction, followed by modified AASHTO compaction and lastly by vibratory compaction. Each of the materials therefore had a preference in terms of optimal compaction method which was not related to the compaction energy, as the compaction energy for the two materials remained the same for each compaction method. However the ranking of the compaction methods from best to worst was not consistent for the two materials.

By comparison with the maximum density grading, the decomposed granite has a lack of +4.75 mm material and excessive -4.75 mm material. This relatively high portion of -4.75 mm fine material and the relatively high PI of the material may explain the good compaction results achieved with the kneading action of the gyratory compactor. The fine material with a relatively high PI therefore created a compaction paste in which the coarse material is suspended and the coarse material matrix is moulded in this compaction paste by the kneading action of the gyratory compactor. The gyratory compaction action would be similar to the kneading action of a pneumatic tyre roller or pad-foot roller.

The crushed hornfels, on the other hand, does not contain sufficient fines relative to the coarse (+4.75 mm) material to form a compaction paste. Stone-to-stone contact is achieved even in the loose state and the material has to be shaken into a dense packing matrix which suits the action of the vibratory table. The action of the vibratory table with the surcharge load placed on top of the material would be similar to vibratory roller compaction in the field.

The range of volume filled results is higher for the crushed hornfels (82 – 93 %) than for the decomposed granite where the bulk of the data lie between 74 and 90 %. The difference between the two materials is even greater when the volumes of solids data are compared, with the crushed hornfels achieving 78 to 90 % and the decomposed granite 72 to 83 %. This difference between the volumes of solids is attributed to the difference between the gradings of the two materials, with the grading of the crushed hornfels being closer to the optimal grading for compaction.

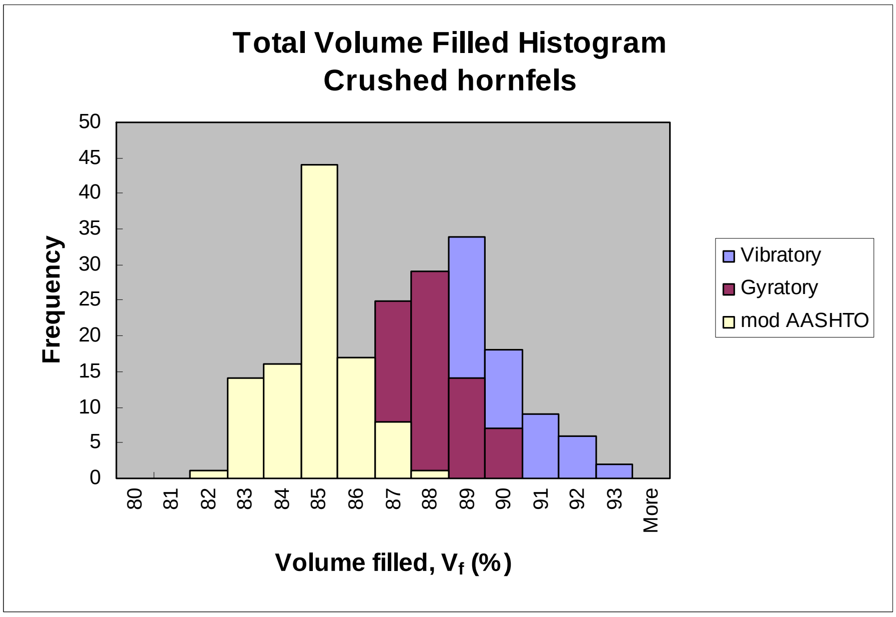


Figure 5. **Frequency distribution histogram of the volume filled for the crushed hornfels**

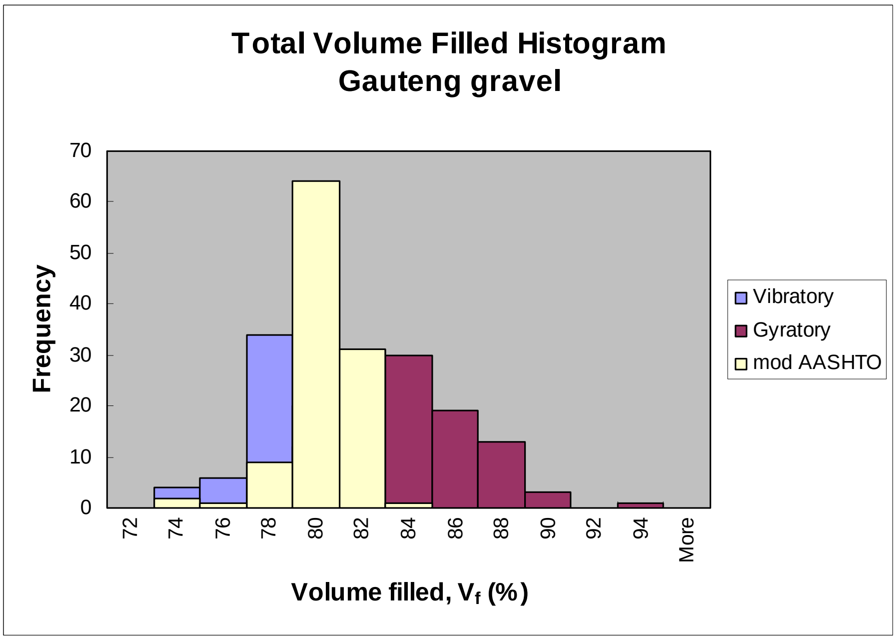


Figure 6. **Frequency distribution histogram of the volume filled for the decomposed granite**

There are therefore two issues that should not be confused in terms of the effect that aggregate grading has on the compaction of road-building material:

- Firstly, the aggregate grading determines the density that is achieved for a given compaction method;

- Secondly, the aggregate grading determines the preference of the material in terms of the compaction method (energy and compaction technique) that yields the highest density.

The role of the aggregate grading in determining the level of density that is achieved for a given compaction method is further supported by the results in Figure 7. The volume of solids, V_s, achieved with modified AASHTO compaction is plotted against the RMSE deviation of the actual grading from the maximum density grading for the aggregates used during both phases of this study. The gradings of the aggregate at the time of compaction and not the grading of the aggregate recovered from the cores are used in the plot. The results clearly show a correlation between the RMSE deviation from the maximum density curve and the volume of solids that is achieved. This correlation is, however dependent on the compaction method that is used.

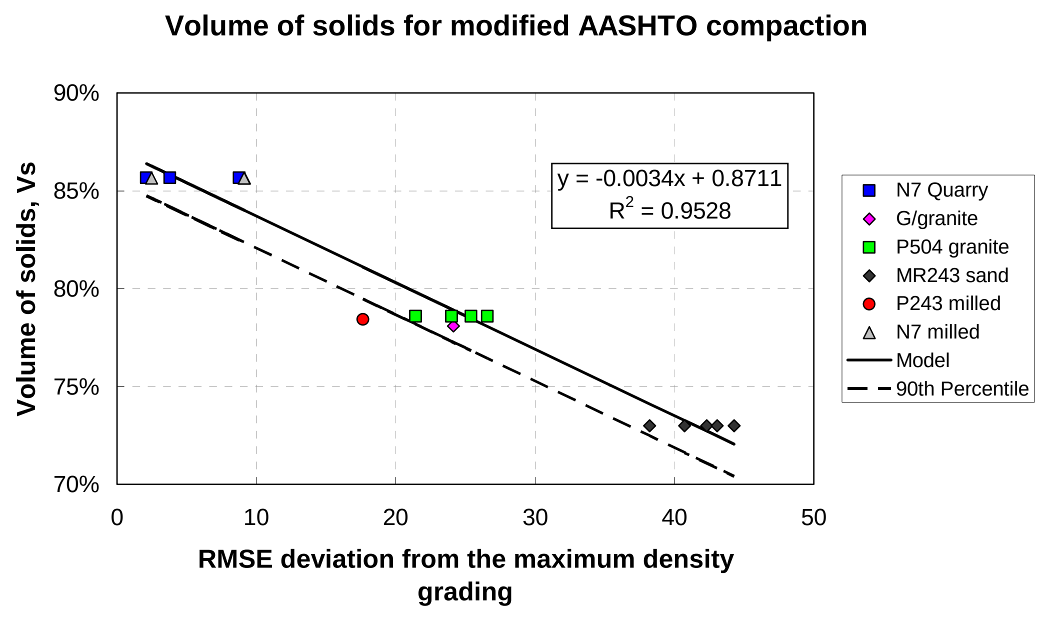


Figure 7. Volume of solids achieved with mod. AASHTO compaction on a range of aggregates used in the study

The volume of solids results achieved using three compaction methods on the two aggregates for all the combinations of binder type, filler type, binder content and filler contents used during the laboratory study are summarised in Figure 8 andFigure 9..

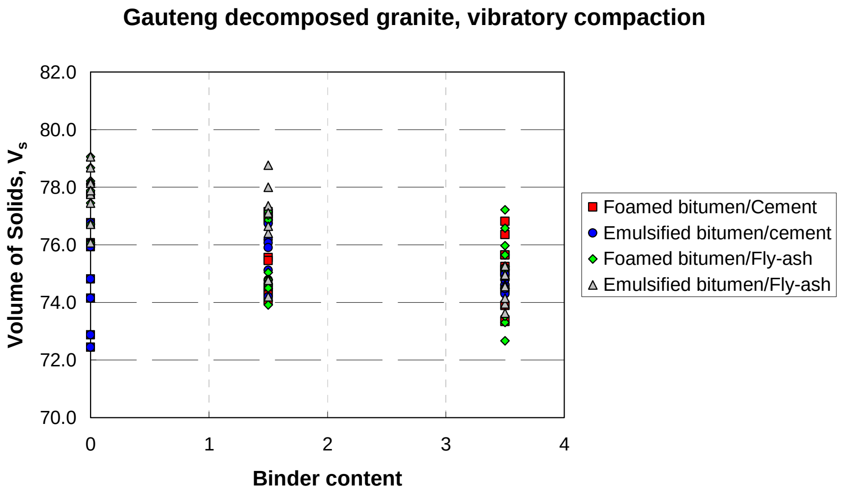
Similar densities were achieved for the untreated decomposed granite from Gauteng using modified AASHTO and gyratory compaction. The addition of binder in the form of foamed bitumen or emulsified bitumen displaces solids to a greater extent when modified AASHTO compaction is used than when gyratory compaction is used. Vibratory table compaction generally resulted in lower densities except at the highest binder content level where the density achieved using vibratory table compaction is on par with the density achieved using mod. AASHTO compaction. Overall, considering all the levels of binder content, the decomposed granite has a preference for gyratory compaction.

In the case of the crushed hornfels the highest densities were achieved using vibratory table compaction followed by gyratory and mod. AASHTO compaction. The trend in terms of the displacement of solids with increasing binder content is similar for vibratory table and mod. AASHTO compaction but the density achieved using vibratory table compaction far exceeds that achieved using mod. AASHTO compaction. In general the crushed hornfels seems to have a preference for vibratory table compaction.

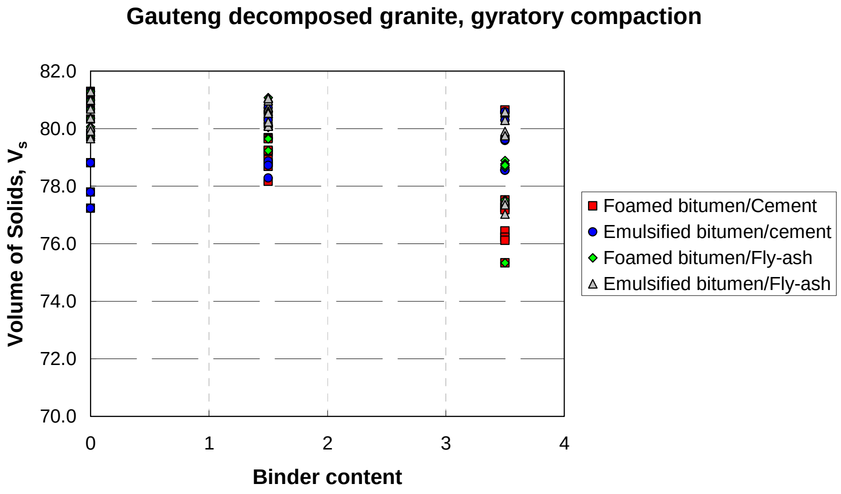
The preference for a particular compaction method is clearly not dependent on the compaction energy alone as the sequence of compaction method preference would have been the same for both materials in this case since the compaction energy remained the same for a given compaction method, regardless of the type of material. The compaction "technique" therefore clearly plays a role in the density that is achieved on materials with different gradings and Atterberg limits and a compaction equipment selection guideline such as the one in Figure 5.4 in TG2 (Asphalt Academy, 2002) therefore has merit. Unfortunately, the choice of compaction equipment for field construction is often limited to steel drum vibratory rollers. Although pad-foot and pneumatic tyre rollers (PTRs) may be considered, the pad-foot cannot be used if only a surface treatment is applied as the indentations from the pads reflect on the surface causing water to pond on the surface. The PTRs are mostly used for finishing the compaction of the layer.

The selection of compaction equipment is not only of interest during field compaction but also for laboratory compaction during both the material design and quality control phases. Based on the data presented in Figure 8 andFigure 9, the current practices of sampling material immediately behind the in situ recycler and compacting it with mod. AASHTO compaction effort to set the reference density for field compaction and almost exclusively using steel drum vibratory rollers for field compaction are not favourable to the optimal compaction of the material. These statements are illustrated by considering the compaction results for the decomposed granite for all the combinations of treatment types that were tested at 3.5 % binder content. Modified AASHTO compaction yields V_s results in the range of 71 to 75 % for this particular material. Sampling the material behind the recycler and compacting it in the field laboratory using modified AASHTO compaction effort would therefore yield a reference density for compaction control in this range. The V_s results for this material using the optimal laboratory compaction technique (gyratory compaction) are, however, in a range from 75 to 81 % far exceeding the reference density obtained using modified AASHTO compaction effort. Using vibratory rollers for field compaction will result in V_s levels of 73 to 77 % if the laboratory vibratory compaction results are assumed to be representative of field vibratory compaction.

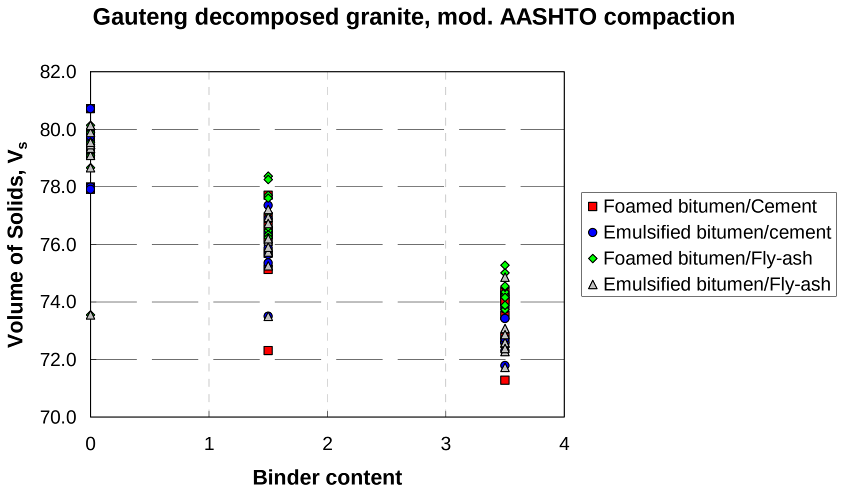
The reference density for compaction will therefore be between 71 and 75 %, the field densities will be between 73 and 77 % and are therefore likely to exceed the density specification. However the actual compaction potential of the material is between 75 and 81 %. This material will therefore be compacted well below its potential during construction.



(a) Vibratory table compaction

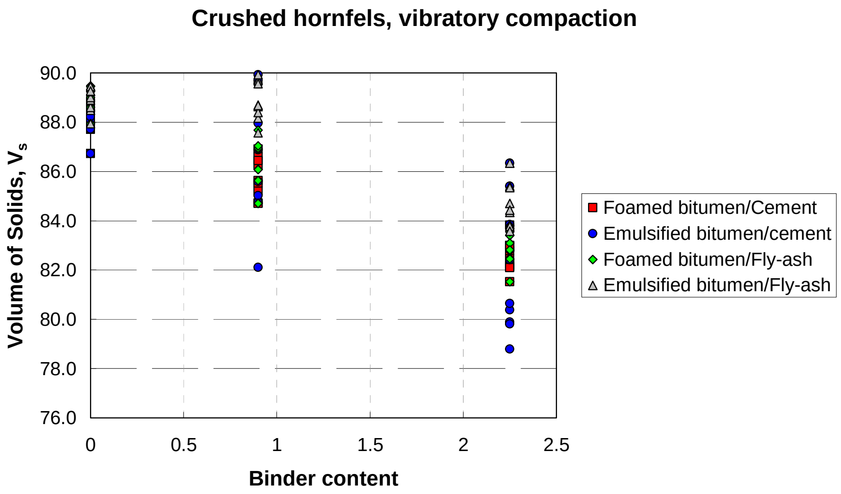


(b) Gyratory compaction

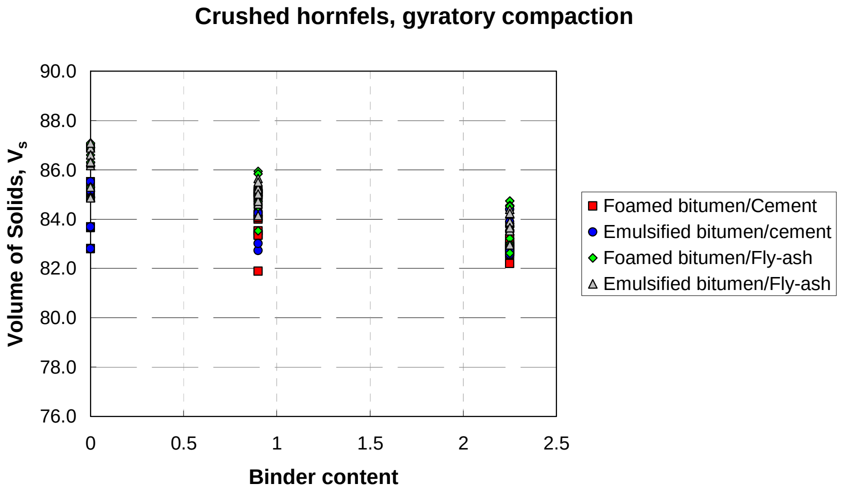


(c) Mod. AASHTO compaction

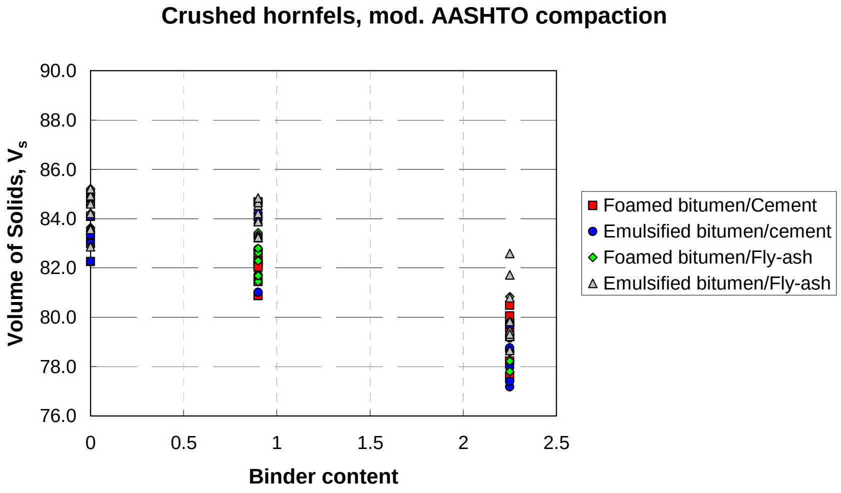
Figure 8. Volume of solids achieved with three compaction methods on the decomposed granite during the laboratory study



(a) Vibratory table compaction



(b) Gyratory compaction



(c) Mod. AASHTO compaction

Figure 9. Volume of solids achieved with three compaction methods on the crushed hornfels during the laboratory study

4.2. Comparisons of treatment combinations

Part of the aim of the study was to draw comparisons between the ease of compaction of:

- the untreated aggregates;
- the aggregates treated with only cement or fly-ash;
- the aggregates treated with only foamed or emulsified bitumen; and
- the aggregates treated with different combinations of cement or fly-ash and foamed or emulsified bitumen.

A Least Square Difference (LSD), multiple ANOVA statistical analysis technique at 95 % probability based on the pooled variance of the data was used to analyze the data for a given combination of compaction method, aggregate type, filler type and bituminous binder. This method is based on the t-distribution and tests for significant differences in the dependent variable given multiple independent variables at more than two levels. The variables, for a given combination of aggregate type and compaction method were defined as:

- Dependent variables:
  - Volume filled, V_f
  - Volume of solids, V_s
  - Unconfined Compressive Strength, UCS
  - Indirect Tensile Strength, ITS
  - Permeability, Perm
- Independent variables:
  - Residual emulsified bitumen content, EBC
  - Foamed bitumen content, FBC
  - Cement content, CC
  - Fly-ash content, FAC

The UCS and ITS tests were introduced in the project because the specimens produced from the compaction testing were suitable for UCS and ITS testing. No special significance is implied regarding the use of the UCS and ITS in the design of emulsified and foamed bitumen treated material. A statistical analysis had to be done for each dependent variable individually.

In general the following observations are made regarding compaction of the materials although individual exceptions to these observations can be found in the data:

- Crushed hornfels
  - Vibratory table compaction
    - Low to intermediate emulsion contents (below 1.5 %) used without a filler had a positive effect on the compaction of the crushed hornfels;

        - Cement used in combination with emulsion had a negative effect on the compaction of the crushed hornfels;
        - Cement used in combination with foamed bitumen had no effect on the compaction of the material;
        - Fly-ash used in combination with emulsion had less of a negative effect than cement used with emulsion;
        - Fly-ash used in combination with foamed bitumen had no effect on the compaction of the material;
        - Increasing percentages of foamed bitumen and emulsion had a negative effect on the compaction of the material when used in combination with either fly-ash or cement.
    - Gyratory compaction
        - Fly-ash generally had a positive influence on the compaction of the material, whereas cement had a negative effect;
        - Increases in binder content had a negative effect on the compaction of the material in terms of the volume of solids for both foamed bitumen and emulsion used in combination with cement and fly-ash.
    - Mod. AASHTO compaction
        - Cement and fly-ash alone had a negative effect on the compaction of the material;
        - Increasing binder content had a negative effect for both foamed bitumen and emulsion;
        - The use of a filler in combination with foamed bitumen reduced the negative effect of increasing binder content mentioned above.
- Gauteng granite
    - Vibratory table compaction
        - Very few clear trends could be observed;
        - Fly-ash on its own had a positive effect on the compaction of the material whereas cement had a negative effect;
        - Increasing binder contents using both foamed bitumen and emulsion had a slight negative effect on the compaction in terms of the volume of solids.
    - Gyratory compaction
        - Cement generally had a negative influence on compaction when used on it own or in combination with foamed bitumen or emulsion;
        - Fly-ash was neutral in terms of its effect on compaction either on its own or used in combination with binder;
        - Increasing emulsion contents had no effect on the compaction of the material;
        - Increasing foamed bitumen contents had a slight negative effect on the compaction of the material.

  - Mod. AASHTO compaction
    - Neither cement nor fly-ash had a discernable influence on the compaction;
    - Both emulsion and foamed bitumen had the same negative impact in terms of a decrease in volume of solids with an increase in binder content.

The intermediate percentage of emulsified bitumen acted as a compaction lubricant for the vibratory compaction of the crushed hornfels in terms of both volume filled and volume of solids results. This benefit of emulsified bitumen treatment was, however, not found when crushed hornfels was subjected to gyratory or mod AASHTO compaction. Vibratory type of compaction is, however, the preferred compaction method for this type of material in the laboratory and in the field and emulsified bitumen at low to intermediate binder content levels (<1.5 %) may therefore be used as a compaction aid for crushed stone and to improve the workability of recycled old crushed stone bases.

In terms of the engineering properties the following observations are made:

- Crushed hornfels
  - Unconfined compressive strength, UCS
    - The UCS of the material is dominated by the cement content and the UCS increases with increasing cement content, regardless of the negative impact of cement on the compaction of the material;
    - Increasing binder content has a negative effect on the UCS of the material but this is less for foamed bitumen than for emulsion;
    - Fly-ash provides no benefit in terms of the UCS of the material, regardless of the general positive influence of fly-ash on the compaction of the material;
  - Indirect tensile strength, ITS
    - The observations relating to the UCS of the material also apply to the ITS of the material.
- Gauteng granite
  - Unconfined compressive strength, UCS
    - Cement on its own brings about some improvement in the UCS of the material;
    - Foamed bitumen and emulsion on their own bring about an improvement in the UCS of the material but to a lesser extent than cement on its own;
    - The combination of both foamed bitumen and emulsion with cement had a more advantageous effect than either the cement or binder on their

own. Specimens with intermediate binder content levels of emulsion yielded better results than those with high binder content levels;
    - The use of fly-ash with emulsion only reflected the improvement in UCS obtained from the emulsion;
    - The combination of fly-ash with foamed bitumen resulted in some improvement to the UCS of the material but to a lesser extent than the combination of foamed bitumen with cement.
- Indirect tensile strength, ITS
    - Cement on its own resulted in an improvement in the ITS of the material;
    - Binder on its own, both foamed bitumen and emulsion, results in an improvement in ITS almost on a par with the improvement associated with cement on its own;
    - The combined effect of foamed bitumen or emulsion with cement resulted in the greatest improvement in the ITS of the material;
    - Fly-ash on its own and in combination with binder only reflected the improvement in ITS achieved from the use of the binder.

In the case of the crushed hornfels, the UCS requirements of the TG2 guideline for foamed bitumen treated material are easily achieved by adding cement on its own or in combination with either emulsified or foamed bitumen. The ITS of the crushed hornfels is also largely determined by the cement content, with the binder content having little effect. Any of the TG2 material classes may be achieved in terms of ITS with the correct combination of bituminous binder and cement, whereas none of the classes can be achieved by using bituminous binder on its own or in combination with fly-ash. Other than adding emulsified bitumen at an intermediate level to act as a compaction lubricant, from a purely strength point of view there is probably little motivation to use either foamed or emulsified bitumen. There may, however, be other considerations in favour of adding bituminous binder, such as the improvement of the workability of an old crushed-stone base layer that is being recycled and the retention of the fines in the layer in the long term or improving the water resistance of a material.

The UCS of the decomposed granite is determined by the cement content, binder content and the interaction between the cement and binder. Any of the TG2 material classes can be achieved in terms of UCS using the correct combination of emulsified or foamed bitumen with cement, whereas only the lowest class is achieved using fly-ash at a high binder content. There seems to be no preference for emulsified or foamed bitumen treatment in terms of UCS results. The same applies to the ITS results of the decomposed granite. In terms of the engineering properties of this material there is a definite benefit in using a combination of either foamed or emulsified bitumen with cement.

The variability of the laboratory permeability tests is such that only the difference between the untreated and treated material could be detected. The permeability of the untreated material was generally higher than that of the treated material.

4.3. Binder and nuclear density results

The binder content results are summarised in Figure 10 . The solid bar indicates the variation in the binder content of the cores and the vertical lines indicate the extreme variation from the minimum to the maximum values determined on the individual slices taken from the cores. In general the results indicate that the average binder content per core can be determined with a fair degree of confidence if the core is subdivided and the binder content is determined on each of the subdivisions. The variation in the average binder contents results also generally covers the design binder content except for the foamed bitumen treated RAP section from P504 which contained old bitumen in the RAP.

The binder content results from MR439 are, however, highly variable. Two of the five cores that were tested, MR439 A17 and MR439 B20, had average binder contents of 4.1 and 4.2 % respectively, close to the design binder content value of 4.0 %. The other three cores had average binder contents well below the design binder content. No mention is made by Millar and Nothard (2004) of problems during the foaming process and they reported that in general the actual bitumen quantity used was within 0.5 % of the design bitumen quantity. The bitumen quantities are, however, believed to have been calculated from the bitumen consumption per batch of material that was foamed and not from representative samples of the treated material.

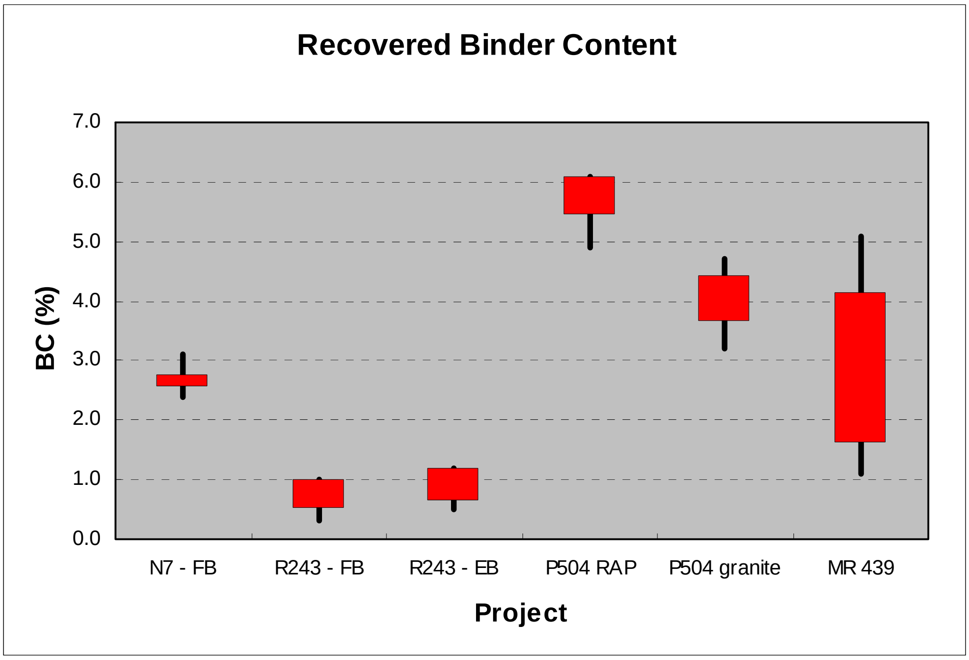


Figure 10. Binder content results for the projects used in the validation phase

Figure 11 shows the nuclear field density results for the KwaZulu-Natal sites plotted against the gravimetric densities determined from the cores in the laboratory. There is a fair agreement between the nuclear and laboratory density results. The nuclear density readings are also generally lower than the laboratory results, implying that the nuclear gauge would be conservative when used for quality control on construction projects.

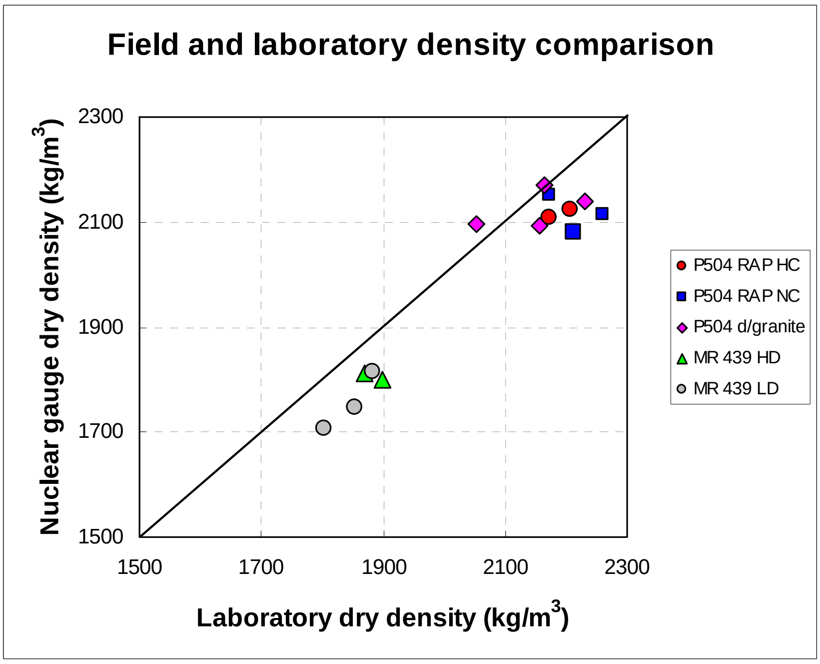


Figure 11. Correlation between nuclear gauge and laboratory gravimetric dry density results

The binder property results of the binder recovered from selected cores taken from the field test sections are summarised in Table 5 . This table also indicates the approximate age of the sections. The results for both the foamed and emulsified bitumen sections of P243/1 near Vereeniging are unexpected. The penetration far exceeds that of the original binder and the softening point is well below that expected. The original chemical analysis results for the bitumen from the foamed and emulsified bitumen treated sections did not fully agree but repeat testing reported in Table 6 showed good agreement between the results for the bitumen from the two sections. The penetration, softening point and chemical analysis results from both these sections indicate that the binder is very soft after 5½ years. No explanation could be found for these binder properties and this aspect needs to be investigated further.

The binder from the foamed bitumen treated decomposed granite section in P504 shows aging after 10½ years of service with a significant reduction in the penetration from 15 -20 mm prior to foaming to 2 mm currently.

Table 5 Properties of the binders recovered from selected cores from the field test sections

	N7-FB	R243-FB	R243-EB	P504 granite	MR439 A14	MR439 A19	NATREF 60/70
Penetration (10^{-1} mm)	50	> 250	> 250	20	65	39	-
Softening point (^{o}C)	51	34	34	63	50	54	-
Ash (%)	1.0	1.1	1.0	2.4	2.1	1.8	-
Saturates	3 - 6	3 – 6	3 - 6	3 - 6	3 - 6	3 - 6	3 - 6
Aromatics	29	49	53	25	28	27	37
Resins	53	32	56	40	47	46	44
Hex Asphaltenes	13.8	3.2	6.2	21.6	12.1	14.8	15.3
Total	97 - 103	87 - 90	118 - 121	90 - 96	90 - 96	91 - 97	99 -101
Approximate age (years)	3,5	5,5	5,5	10,5	3,3	3,3	-
Original binder	80/100 CALREF	80/100 NAREF	60 % cationic	150/200 Engen	Unknown	Unknown	

Table 6 Results of the repeat testing of the binders from R243/1 near Vereeniging

	R243-FB	R243-EB
Penetration (10^{-1} mm)	> 250	> 250
Softening point (^{o}C)	35	37
Ash (%)	1.1	1.0
Saturates	3 - 6	3 - 6
Aromatics	52	50
Resins	56	54
Hex Asphaltenes	5.1	8.3
Total	116 - 119	115 - 118

4.4. Assessment of a volumetric density specification

In terms of assessing the potential move from a gravimetric density specification to a volumetric density specification the obvious question to address is the reason for the change. Such a change would be unnecessary if the gravimetric dry density of foamed and emulsified bitumen treated materials, as measured directly during most construction projects using nuclear gauges or sand replacement methods, were directly related to the volume of solids in the material matrix. In Figure 12 shows the volume of solids for all the crushed hornfels specimens compacted during the laboratory study for all combinations of binder type, binder content, filler type and filler content is plotted. Figure 13 shows a similar plot for the Gauteng granite gravel. These plots again confirm the preferences of the two materials for different compaction methods.

There is fairly good correlation between the gravimetric density and the volume of solids for the crushed stone. In this case the gravimetric density may be used as a fair indication of the volume of solids and could therefore be used for a density specification. The data for the Gauteng gravel, however, show a separation into three different correlations.

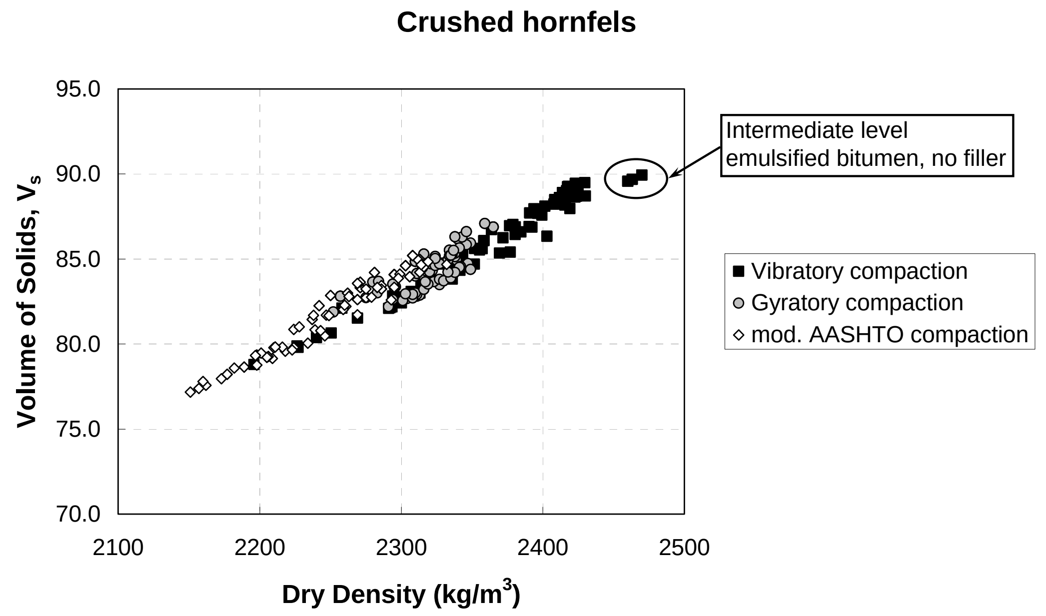


Figure 12. **Volume of solids plotted against the gravimetric density achieved with for the crushed hornfels**

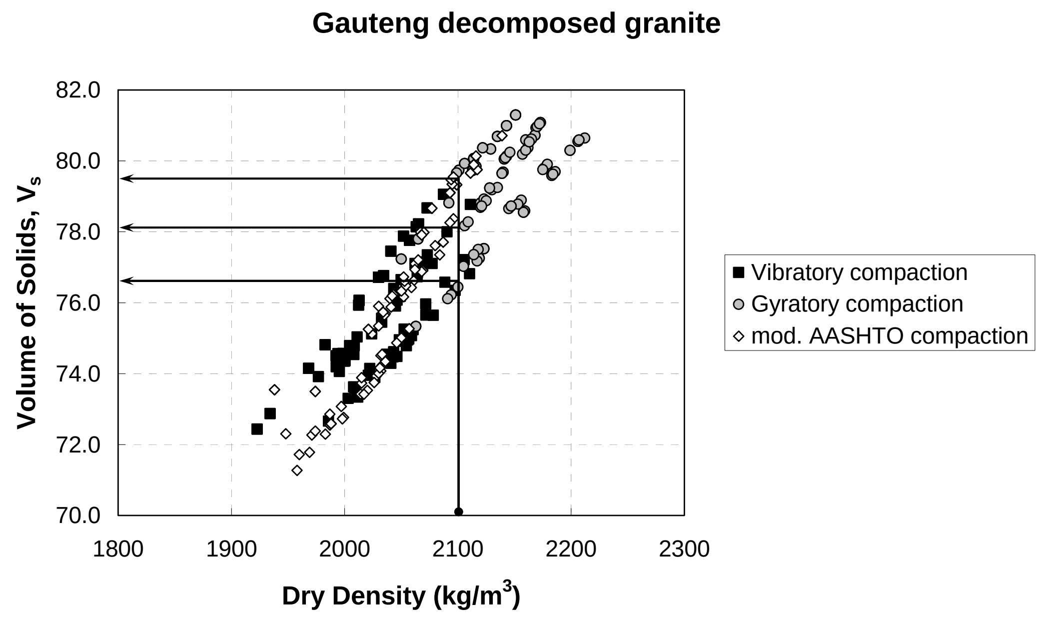


Figure 13. Volume of solids plotted against the gravimetric density achieved for the Gauteng granite

Figure 14 shows a similar plot to Figure 13 but only for the gyratory compaction method on the Gauteng granite. It is clear from this plot that the separation is caused by the binder content, confirming that the addition of binder displaces solids in the material matrix. Similar results are also obtained for vibratory table compaction and mod. AASHTO compaction as well as for the crushed hornfels, although to a lesser extent. Binder content had a lesser effect in the case of the crushed hornfels, as the apparent density of the hornfels is considerably higher than that of the granite and the binder contents were in a lower range than for the granite. The binder therefore plays a lesser role in determining the gravimetric dry density of the hornfels.

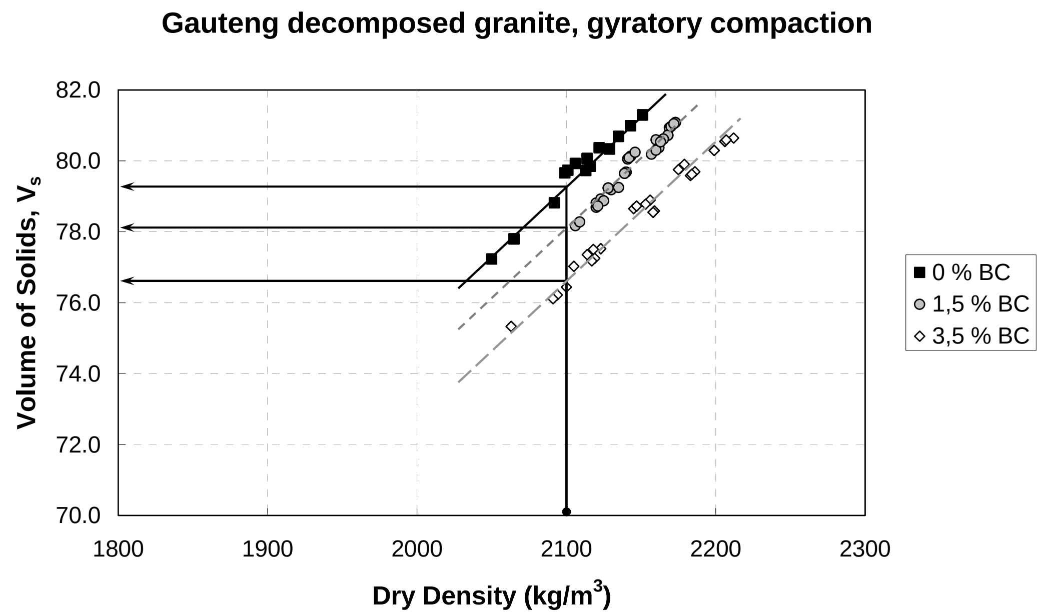


Figure 14. Volume of solids plotted against the gravimetric density achieved with gyratory compaction on the Gauteng granite

As shown in Figure 14, substantial differences occur in the volume of solids at a given gravimetric dry density. If the field density is therefore specified in terms of a gravimetric dry density of 2100 kg/m^3 and achieved during construction, the actual volume of solids packed into the material matrix could vary from about 76.5 % to 79.5 %, which is substantial. The use of a volumetric density specification in terms of the volume of solids in the material matrix is therefore justified.

Figure 15 shows the volume of solids determined from the cores taken from the field test sections plotted against the volume of solids for the mod. AASHTO maximum dry density of the untreated, recycled aggregate. The shaded rectangle on the right of the diagram represents the tentative laboratory-based volumetric density specification for recycled crushed stone products treated with foamed or emulsified bitumen and requiring a volume of solids exceeding 84 %. The solid diagonal line across the diagram represents the tentative laboratory-based volumetric density specification for recycled natural gravel products treated with foamed or emulsified bitumen and requires that the volume of solids of the treated material equals the volume of solids of the untreated recycled aggregate. As can be seen in Figure 15 most of the data from the field test sections fall below this line and the tentative laboratory-based specification is probably too stringent. If a 2% reduction is allowed for the volume of solids of the treated material from the volume of solids for the untreated material, the bulk of the field data exceeds the requirement represented by the dotted line in Figure 15.

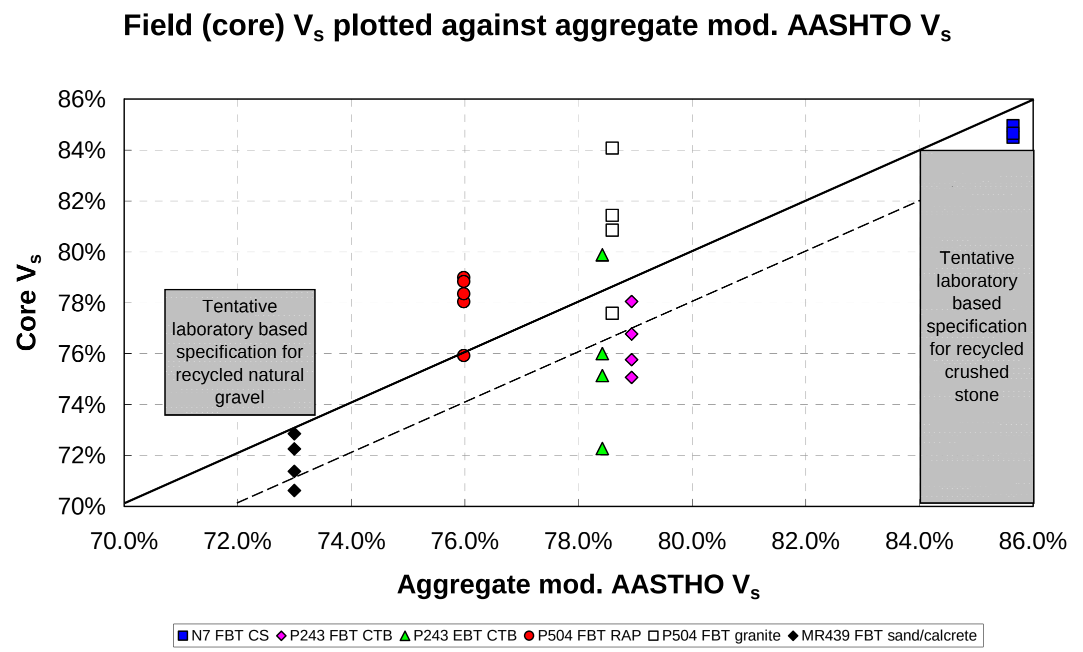


Figure 15. **Volume of solids for field test sections plotted against the volume of solids of the mod. AASHTO maximum dry density of the recycled aggregate**

Using this approach it is therefore possible to formulate a single volumetric density specification covering recycled crushed stone and natural gravel material including fine grained sandy material. Unfortunately this specification can only be implemented on plant treatment recycling projects where the final recycled grading, ARD of the recycled aggregate and binder content are known. Deep *in situ* recycling projects require the identification of the optimal laboratory compaction equipment during the construction trial after which the gravimetric density achieved on material sampled behind the recycler may be specified for the uniform section of the project from which the material was sampled.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Although the UCS and ITS parameters may not be the most appropriate parameters for the design of bituminous treated material, the UCS and ITS requirements of the TG2 document can be achieved for both materials using different combinations of foamed or emulsified bitumen in combination with cement. In the case of the crushed stone, cement treatment on its own produced results on a par with those from combined treatment with cement and bitumen. However, with regard to the natural gravel that was tested, the combined treatment with cement and bituminous binder resulted in better strength than treatment with only cement or only bituminous binder. Very little justification could be found for using fly-ash as filler in terms of the engineering properties of the two aggregates used in the investigation.

Except for one of the project sites included in the field investigation, reliable binder content results were obtained when a sufficient number of binder content tests had been done on individual cores taken from the sites. Binder content control testing could thus be included in the quality control process on foamed and emulsified bitumen treatment projects if proper statistical sampling is done. This would, however, have a cost implication to be considered by the client, engineer and contractor, as at least three binder content tests would have to be done on each core taken from the layer.

Based on a limited set of results, nuclear density gauges seem to be sufficiently reliable to be used for density control testing on foamed and emulsified bitumen treatment projects if these are properly calibrated. Based on the limited results available, the density results from the nuclear gauges seem to be conservative.

Most of the binders from the field test sections showed aging, with the binder from P504 which has been longest in service, showing the most aging. The penetration, softening point and chemical analysis results for both the foamed and residual emulsified bitumen from P243/1 are in contrast to the results from all the other sites and the binder is much softer than expected, even by comparison with a new binder. The anomalous binder properties from this site cannot be explained and this site needs to be investigated in detail.

The effect of aggregate grading on the compaction of the material was again confirmed by the results from the study. Not only does the deviation of the grading from the maximum density grading curve determine the level of density that can be achieved, but the grading of the material also determines the preference of the material in terms of the type of compaction action that will result in the highest possible density being achieved. This preference for a particular compaction technique is not related to the energy of the compaction method, as the sequence of preference is not the same for the two materials investigated, whereas the compaction energy remains constant for each compaction method.

The current practice on recycling projects of taking a bulk sample from behind the recycler and then compacting this material using modified AASHTO compaction to set a reference density may be detrimental to the performance of the road. Setting a volumetric density specification is, however, only possible for plant treatment of recycled material where the final recycled grading, ARD of the aggregate and the binder content can be determined accurately during the design phase. The application of such a volumetric density specification is impractical for deep *in situ* recycling projects.

5.2. Recommendations

Binder content control testing should be introduced on important foamed and emulsified bitumen treatment projects if the client deems it necessary. It is recommended that a minimum of 3 binder content tests should be done per bulk sample from each control testing location after the material has been properly mixed and quartered.

The use of nuclear density gauges should be continued on foamed and emulsified bitumen treatment projects until better technology becomes available. The applicability of the device on specific projects should be verified on a project-by-project basis during the construction of the trial section by taking nuclear gauge readings at certain locations and removing cores at these same locations (after curing the layer) for laboratory density tests. The nuclear density gauge may be calibrated in this way for the specific project but the density specification should never be relaxed based on conservative results from nuclear density devices.

The selection of appropriate compaction equipment applies to laboratory compaction for material design and quality control as well as to field compaction. In the case of laboratory compaction, circumstances are different for plant and *in situ* treatment of recycled material.

In the case of plant treatment it is recommended that a laboratory compaction optimisation investigation be done as part of the material design using modified AASHTO, gyratory and vibratory compaction methods. Commercial equipment is available for modified AASHTO and gyratory compaction and the vibratory hammer is recommended for vibratory compaction. The compaction method yielding the best results can then be specified for quality control in the field laboratory.

Unfortunately, during the design stage the final recycled grading is not known for deep *in situ* recycling, in which case it is recommended that the material recycled during a construction trial should be sampled and compacted using all three laboratory compaction methods, namely modified AASHTO, vibratory and gyratory compaction. The optimal laboratory compaction equipment may thus be identified and specified for the main construction project. Although the optimal compaction equipment depends on the type of material, significant changes would have to occur in material characteristics to require more than one type of laboratory compaction equipment in the field laboratory because of material changes. In such cases, separate construction trials would, in any case, have to be conducted for the different materials.

In terms of the selection of suitable field compaction equipment, communication with practitioners appears to indicate that they generally feel that the selection of compaction equipment should be left to the discretion of the contractor. Most practitioners felt that the construction of a trial section is extremely valuable for ironing out construction difficulties, including the selection of the right compaction equipment and sequence. Although the construction of such a trial section may assist in the selection of appropriate compaction equipment, higher densities may be possible if the optimal compaction equipment is selected. It is the author's opinion that sufficient evidence has been obtained from the laboratory study to justify a compaction equipment selection guideline or at least to justify some attempt being made during the construction of the trial section to optimise the selection of field compaction equipment.

An additional aspect of field compaction that was raised by contractors is the effect that the supporting structure has on the compaction of deep *in situ* recycled layers. In the case of deep *in situ* recycling projects, the condition of the pavement foundation is dictated by the existing pavement and there is little that can be done to improve the support conditions. Contractors felt that compaction problems on deep *in situ* recycling projects are often related to poor support conditions not providing a sufficient anvil for compaction. One improvement that could be considered is the use of impact compaction to compact the subgrade before recycling. However criteria need to be developed that can be applied during the rehabilitation investigation to enable subgrades that require improvement to be identified.

6. REFERENCES

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