ASPHALT MIX DESIGN AND ANALYSIS TOWARDS IMPROVING COMPACTIBILITY OF WEARING COURSE MIXES IN THE WESTERN CAPE

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1 INTRODUCTION

The University of Stellenbosch in co-operation with Zebra Bituminous Surfacing CC. undertook an investigation into the compactibility of typical wearing course mixes used in the Western Cape. The harshness of these mixes without natural sand has several disadvantages including higher costs, inconsistent compaction quality and compaction failures.

The study focussed on measures to improve the compactibility of asphalt wearing course mixes in the Western Cape. Factors investigated included:

- Gradation,
- Nature of the filler (particle size distribution),
- Binder content,
- Filler content,
- Filler/binder ratio, and,
- Compaction temperature

The investigation was carried out by evaluating the volumetric properties of laboratory compacted wearing course specimens and selected variation of certain influencing factors. Mechanical tests were carried out to evaluate the performance properties of the laboratory mix. Special consideration was given to the characterisation of the filler and filler/binder system of the mixes. Fine aggregate angularity tests were performed. These were done to investigate the degree of internal friction and to evaluate the workability of the sand fraction.

The influence of ageing was not investigated although all gyratory compacted mixes were aged at 150 ºC for one hour prior to compaction. The use of natural sand was only considered an option in the advanced stage of this study.

This paper often makes mention of the term *compactibility*, which has been analysed as a volumetric property of an asphalt mixture directly related to the Voids In the Mix (VIM). Therefore, the *compactibility* of a mix was judged in terms of VIM at a specific compaction level. The *compactibility* of a number of mixes compacted at the same binder content and compaction level was ranked in terms of VIM.

2 METHODOLOGY & TEST PROGRAMME

The number of different tests undertaken for the study was extensive. The study began with characterisation of sand, filler and filler/binder systems. This included:

- Particle size distribution or hydrometer tests on four different fillers: M1 from Contermanskloof (Western Cape), M2 from Port Elizabeth, M3 from Eerste River (Western Cape) and M4 from Eikenhof
- Softening point tests done on binder and filler/binder systems at varying percentages of bulk volume of filler i.e. 30, 50, 60 and 70 percent.
- Sliding plate rheometer tests on the filler/binder systems as for the softening point tests at 25 ºC and 40 ºC.
- Fine aggregate angularity tests on crusher dust, sand and combined crusher dust and sand samples from the Contermanskloof and Eerste River quarries.

Phase 1 analysis and testing included:

- Marshall mix design of the plant mix at 4.7 % design binder content received from the client.
- Marshall mix design performed on a laboratory mix at 4.7 % design binder content made up of sieved aggregate gradings at the University of Stellenbosch.
- Gyratory compaction tests at various binder contents (4.5, 5.0, 5.5 and 6.0 percent).
- Gyratory compaction tests to assess the compactibility of the laboratory mix at 100 ºC and 160 ºC.
- Mechanical testing of the laboratory mix included dynamic creep, indirect tensile strength and stiffness tests (in indirect tensile mode) at binder contents of 4.7 and 5 percent. Specimens for these tests were gyratory compacted to 4 percent VIM.

Phase 2 analysis and testing included:

- Gyratory compaction tests on alternative continuously graded mixes. The *n*-values (gradation exponent), binder contents (Pb) and filler contents (F) of these mixes were varied as shown in Table 1.

Table 1. Phase 2 gyratory compaction matrix

n	0.2			0.3			0.4		
Pb	2.5	4.5	6	2.5	4.5	6	2.5	4.5	6
F	6.5	6.5	6.5	4 6.5	4 6.5	4 6.5	6.5	6.5	6.5
n	0.5			0.6			0.7		
Pb	2.5	4.5	6	2.5	4.5	6	2.5	4.5	6
F	4 6.5	4 6.5	4 6.5	6.5	6.5	6.5	4 6.5	4 6.5	4 6.5

- Gyratory compaction tests on two other mix designs, one from Pennsylvania USA and the other from Sydney, Australia. These are named Penn and Astec respectively. These were done at three binder contents i.e. 2.5, 4.5 and 6 percent. This range of binder content was selected to achieve significant differences in mix compactibility.

Phase 3 analysis and testing included:

- Gyratory compaction tests on the experimental mixes with filler contents of 5.5 and 6.5 percent at binder contents of 4.5, 5.0, 5.5 and 6 percent. Experimental mixes were established by slightly coarsening the original gradation and varying the filler content
- Mechanical testing of the experimental mixes included dynamic creep tests at 40 ºC and 60 ºC. Specimens for these tests were gyratory compacted to 4 percent VIM.

The investigation was limited to the compactibility of wearing course mixes having a maximum aggregate size of 19 mm and a gradation that falls within the COLTO (COLTO, 1998) gradation specification for a coarse continuously graded mix (COLTO coarse). The mixes comprised Hornfels from the Peninsula quarry and 60/70-pen grade bitumen from the CALREF refinery. The penetration of the bitumen was measured as 63 and the softening point as 48 C. No natural sand and no active fillers such as lime or cement were used in the mixes.

As part of the sliding plate rheometer tests, a Shell (SAPREF) 60/70 pen bitumen was also tested.

Unless otherwise stated, all mixes were compacted using the Superpave gyratory compactor after being aged in a forced draft oven at 150 ºC for one hour. The mixing temperatures of the mixes were between 150 ºC and 160 ºC and the compaction temperatures between 135 ºC and 150 ºC.

The findings of the volumetric tests motivated additional investigation using accelerated pavement testing (APT) of on-site trial mixes with adjusted filler/binder ratios. It should be noted that the mixes selected were different from the mixes used previously, and included a mix containing natural sand. The objective of the APT was to verify whether adjustment to the filler binder ratios improved compactability, or compromised the rut resistance of these mixes. Two tests were performed using the Model Mobile Load Simulator (MMLS Mk3). In the first test, the following mixes were investigated:

- 9 mm COLTO medium continuously graded wearing course (filler/binder ratio 1.3 (by mass))
- 13 mm COLTO medium continuously graded wearing course (filler binder ratio 1.4 (by mass))
- 19 mm continuously graded wearing course, with 10 % natural sand (filler/binder ratio 1.2 (by mass))

The 13 mm mix was the reference mix in both tests and is from here on referred to as 13 mm*. For the second test, the 9 mm wearing course was replaced by another 13 mm wearing course with filler/binder ratio of 1.1 (mass). The second 13 mm mix is from here on referred to as 13 mm**.

The APT tests were to be done at an average temperature of 55 ºC. Asphalt slabs were compacted at the University of Stellenbosch using a Kango hammer with a modified compaction head. Slabs were manufactured using retained samples (at room temperature) obtained from Much Asphalt (Pty) Ltd., (Eerste River) in paper bags. These mixes were slowly reheated in a draft oven and compacted at ± 140 ºC to approximately 7% VIM. The slab compaction was controlled using a steel mould of known volume.

3 CHARACTERISATION OF SAND, FILLER AND FILLER/BINDER SYSTEMS

3.1 Softening point & Sliding plate rheometer tests

The filler material from the Contermanskloof quarry (M1) was chosen as the reference filler. The Belgium mix design method (OCW, 1997) uses the increase in the softening point (Ring & Ball) of a filler/binder mixture with increase of the filler content, i.e. the stiffening of the mastic, to determine the optimum mastic composition. Based on the Belgium experience, a mastic composition that ensures an increase in softening point temperature of between 12 ºC and 16 ºC is required to balance the mix requirements in terms of durability (flexible mastic, permeability etc.) and stability (stiff mastic).

Kandhal (1981) concluded that the lower limit is applicable and suggested limiting criteria on changes in softening point temperature of 12 ºC. Values above this may result in mortars that are too stiff. From Figure 1, it can be seen that an increase in the filler content has a stiffening effect on the mastic, resulting in an increase in the softening point of the mastic. The Contermanskloof filler (M1) has the lowest stiffening effect and the Eikenhof filler (M4) the highest.

To determine the optimum filler/binder ratio to optimise the stiffening influence of the filler (and still provide good rut resistance) an increase in softening point of 12 ºC was used.

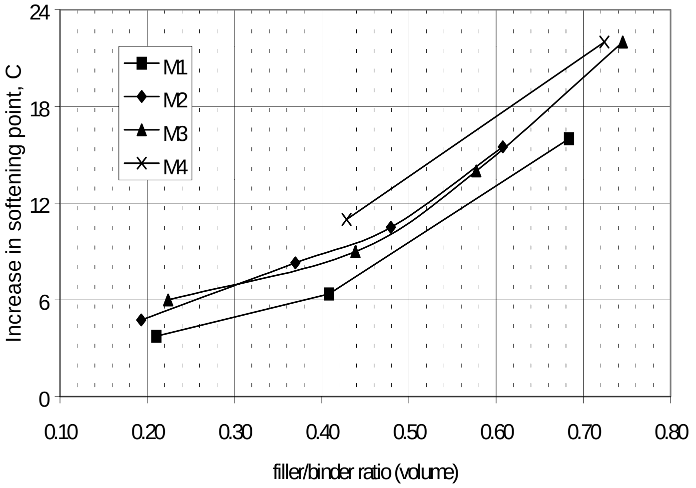

Figure 1. Increase in softening point of mastic

From Figure 1, the optimum filler/binder ratio for the M1 filler in the order of 0.57 (on a volume basis). On a mass basis, this relates to a filler/binder ratio of about 1.5. The optimum filler/binder ratios for the other three fillers were lower than 1.5. The filler/binder ratio of the plant mix at an optimum binder content of 4.7 percent was 1.6 mass basis), which is slightly higher than the maximum of 1.5 to optimise the stiffening effect.

The sliding plate rheometer is used to measure viscosity. Since viscosity is a measure of shear resistance, it may be used to assess the stiffening effect of fillers. The slope of a log (shear stress) – log (shear rate) rheogram is a measure of shear susceptibility. Sliding plate rheometer tests were done at two temperatures, 25 ºC and 40 ºC. These results verify the findings of the softening point tests with regards the stiffening behaviour of the M1 filler (Smit & van de Ven, 2000). The ranking of shear susceptibility from lowest to highest was consistently M4, M3, M2 and then M1. It was also found that the viscosity of the M1 mortar increased significantly when the percentage bulk volume of filler increased above 60 percent.

From the softening point and sliding plate rheometer results it may be concluded that the optimum range of filler/binder ratios for the Contermanskloof filler (M1) is between 1.3 and 1.5 (on a mass basis).

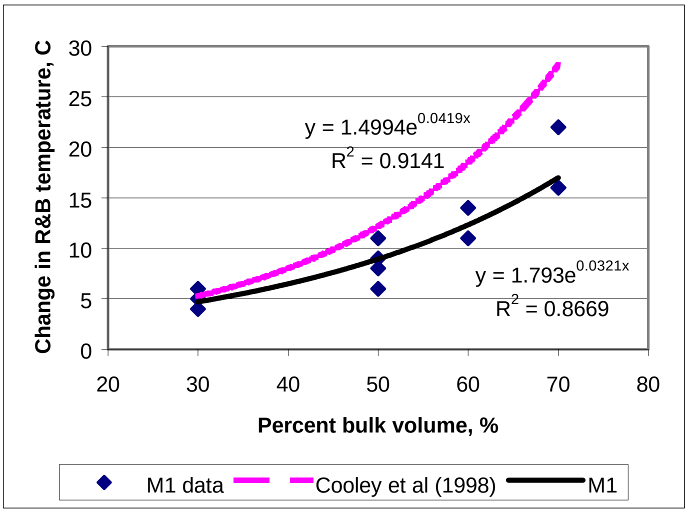

Figure 2. Stiffening of study filler/binder mortars

Comparing the filler/binder results to the findings of Cooley *et al* (1998), the stiffening effect with increase in percentage bulk volume of filler follows the same trend (see Figure 2), although correlation is not as good. The use of percentage bulk volume of filler as a unique parameter to predict stiffening is useful, as Cooley et al showed it to be applicable to all fillers.

3.2 Particle size distribution

From the hydrometer tests (ASTM method D422-63) on the four fillers, the M1 and M3 fillers were found to have a high percentage (35 percent) of material smaller than 10 micron. Shashidar & Romero (1998) found that the stiffening effect of fillers tends to increase with decreasing particle sizes below 10 micron. This high percentage of material smaller than 10 micron is almost twice that of the M2 and M4 fillers used in other parts of the country. This provided motivation for the investigation of stiffening potential. Figure 1 does not validate the findings of Shashidar & Romero, as fillers M1 and M3 did not create the highest stiffening. However, the analysis should be carried out on a volumetric basis (percentage of volume), rather than a volume ratio (filler/binder).

3.3 Fine aggregate angularity (FAA)

Fine aggregate angularity tests (AASHTO TP33, 1993) were carried out on crusher dust (C/D), sand (Z) and combined crusher dust and sand samples (10 percent sand by mass of total mix) from the Contermanskloof and Eerste River quarries. Methods A and C of AASHTO TP33 were used. Materials were oven dried before testing. Six (6) tests on the different materials were done.

The FAA Method A results indicate that the crusher dust from both quarries in the Western Cape should offer sufficient internal friction for rutting resistance. The FAA values of the sands, however, are significantly lower in comparison. The results indicate that the addition of natural sand to asphalt mixes may reduce the internal friction of the sand fraction of a mix considerably.

4 PHASE 1 – THE JOB MIX

The job mix evaluated was a standard 19 mm wearing course mix used in the Western Cape. This particular mix has a gradation that falls within the COLTO specification and has a design binder content of 4.7 percent, a relatively large crusher fraction of 40 percent i.e. material passing the 2.36 mm, and filler content of 7.7 percent. The mix is harsh and difficult to compact, even during initial construction/paving. These mixes are typically paved in 40 mm lifts.

It should be noted that the job mix as reported was manufactured in the plant and not a laboratory mix. Small variations in gradation and binder content consistent with plant mixes are therefore accounted for. This approach allows a better understanding of the mix volumetric properties anticipated in the field. The Marshall volumetric properties obtained from the supplier indicated that the mix compacts quite readily. Theoretically, voids filled with binder (VFB) should increase with the addition of binder beyond 5.5 percent binder content, but does not.

To confirm the volumetric properties of the plant mix as reported by the asphalt supplier, a Marshall mix design was done at the University of Stellenbosch. Mixes were compacted at a temperature of 135 ºC directly after mixing at a temperature of 160 ºC without ageing. These mixes were constituted in the laboratory using sieved aggregate gradings. The volumetric properties of this Marshall mix design differed significantly from the volumetric properties as reported by the supplier. At the design binder content of 4.7 percent, the voids in the mix after Marshall compaction were in excess of 5 percent indicating that the mix was relatively harsh and difficult to compact. The minimum voids in the mineral aggregate (VMA) occurred at a binder content of 5.5 percent and there was a definite increase in the VFB with the addition of binder beyond 5.5 percent. The reason for the discrepancy between the results is unknown. One possible reason could be differences between the laboratory and plant mixes.

Based on the volumetric results of the mix design done at Stellenbosch, an optimum binder content in the order of 5.2 percent would have been more appropriate for the mix in question. The lower optimum binder content is therefore one of the reasons for the harshness of the wearing course mix. Gyratory compaction tests were done to investigate the compactibility of the laboratory mix in more detail.

To evaluate the influence of compaction temperature on compactibility of the laboratory mix, specimens were mixed at the design optimum binder content of 4.7 % and compacted at temperatures of 100 ºC and 160 ºC respectively. Two specimens were compacted at each of these temperatures.

To evaluate the influence of binder content on compactibility, two specimens were compacted at each of the four binder contents (4.5, 5.0, 5.5 and 6.0 %) at a compaction temperature of 135 ºC. A maximum of 288 gyrations were applied to the compacted specimens. This is a large number of gyrations and the density of the mix after this many gyrations therefore represents the refusal density of the mix. At refusal density, a mix will not densify (significantly) further. It is critical that a mix, at refusal density, has sufficient voids (at least 1 to 2 percent) to prevent the mix becoming unstable if the aggregate skeleton becomes overfilled with bitumen.

The gyratory compaction tests were done according to an American mix design procedure (Superpave) that relates number of gyrations (compactive effort) to four traffic levels (Blankenship *et al*., 1994). Superpave has three compaction parameters, which have the following relevance:

- N_{des} corresponds to the expected amount of traffic at the end of a 20-year design life.
- N_{ini} is a small number of gyrations that simulates mixture behaviour during breakdown rolling.
- N_{max} is a large number of gyrations that simulates mixture behaviour in an extreme stress situation.

Mechanical tests done on the laboratory mix indicate that the performance properties of the mix satisfy the respective criteria typically established for wearing course mixes. The low indirect tensile strength (ITS) obtained for the specimens at a binder content of 5 percent is contrary to what one would expect since tensile strength typically increases with an increase in binder content on the left of the optimum curve (where this would be expected to be). The dynamic creep tests were done at 40 ºC and the ITS and stiffness tests at 25 ºC. Table 2 shows the mean results for the different tests (two specimens tested for each test).

Table 2. Mechanical test results on laboratory mix

Test/Binder content	**4.7 %**	**5 %**
Dynamic Creep, MPa	20	46
ITS, kPa	1193	802
Stiffness, MPa	1097	1620

The influence of compaction temperature on compactibility of the laboratory mix was inconclusive, although the variability of the compaction results was lower at a compaction temperature of 160 ºC compared to that at 100 ºC.

5 PHASE 2 - ALTERNATIVE MIXES

Alternative wearing course mixes were established using the gradation equation shown below:

$$P = \frac{(100 - F)(d^n - 0.075^n)}{(D^n - 0.075^n)} + F \qquad \textbf{Eq. 1}$$

where:

P = Percentage passing a sieve size of d mm
D = Maximum aggregate size, mm
F = Filler content (sub 0.075 mm material)
n = a gradation exponent between 0 and 1

An inquiry into filler contents of wearing course mixes used in the Western Cape indicated that these were generally quite high, typically in the order of 7.5 percent, although a filler content in the order of 6.5 percent was possible. In theory, therefore, filler contents well below those currently used could be applied whilst remaining within the specifications. For this reason, a range of low filler contents of 6.5 and 4 percent were investigated in this study.

It should be noted that the bulk relative densities of the different aggregate gradations were not determined. A constant value of 2.709 (which was the bulk relative density of the plant mix gradation) was used for these gradations. In addition to the gradations developed using the different *n*-values, two other gradations (named Penn and Astec respectively) were analysed. These two gradations were not continuously graded as those developed using a specific *n*-value but had a semi-gap gradation. The gradation curves of these mixes are shown in Figure 3. The COLTO specification limits have been superimposed.

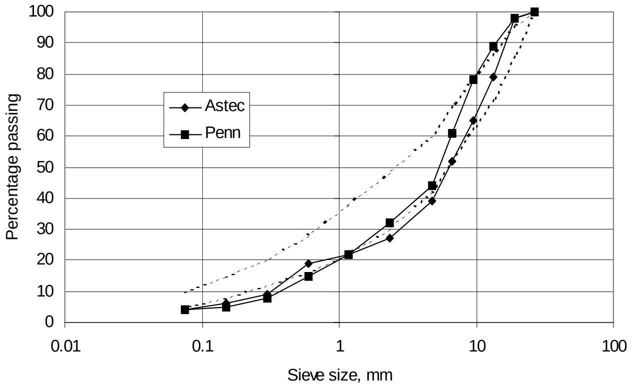

Figure 3. Gradation curves of Astec and Penn mixes

With regard to the influence of the gradation exponent, *n*, on the compactibility of the different mixes, it was found that the lowest VIM is achieved using gradation exponents less than 0.4. Above 0.4, the VIM of the mixes increases significantly.

It was also found that an increase in binder content facilitates compaction, as expected.

The gyratory compaction results indicate that design traffic has a significant influence on the optimum binder content. The higher the design traffic load, the lower the optimum binder content. Furthermore, for mixes having *n*-values greater than 0.4, the optimum binder content increases.

Also from the gyratory compaction results, an increase in filler content appears to improve the compactibility of the mixes slightly. The influence is not significant. It should be pointed out that the mix might tend to be stiffer at the higher filler content, which would counter compactibility.

Figure 4 compares the compactibilities of the different mixes investigated at binder contents of 4.5 and 6 percent. For both binder contents the ranking of compactibility was first the continuously graded mix with n=0.3, followed by the laboratory mix, then the Astec mix and last the Penn mix.

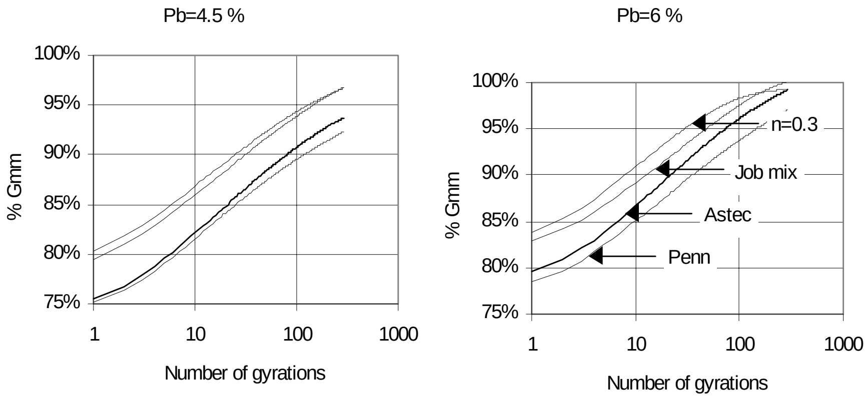

Figure 4. Comparison of mix compactibilities

6 PHASE 3 - EXPERIMENTAL MIXES

Based on the findings of the filler/binder characterisation study undertaken previously, a filler/binder ratio of between 1.3 and 1.5 (by mass) was selected as optimum for the Contermanskloof material and CALREF binder in question.

Figure 5 shows the gradation of the experimental mix compared to the job mix.

The gyratory compaction tests showed that at corresponding binder contents and traffic levels, the compactibility of the experimental mixes was less than that of the laboratory mix. This illustrates the complexity of asphalt mix design and indicates that the compactibility of a mix may be sensitive to even small deviations in gradation.
Based on these results, optimum binder contents of 5.2 and 5.0 percent were chosen for the experimental mixes at filler contents of 5.5 and 6 percent respectively. At these binder contents, the VIM at N_{max} was found to be greater than 2 percent.

The dynamic creep test results indicated that the mixes appear to have adequate stability at a temperature of 40 ºC. At 60 ºC, however, one of the specimens failed under repeated loading and the dynamic creep results of the other specimens tested at 60 ºC are well below the experimental limiting value of 10 MPa. The higher binder contents of these mixes have resulted in lower dynamic creep values compared with those of the laboratory mix.

	New mix	Job mix
26.5	100	100
19	86	86
13.2	84	84
9.5	70	71
6.7	62	64
4.75	54	58
2.36	38	40
1.18	23	25
0.6	15	18
0.3	11	13
0.15	8	10
0.075	5.5	7.5

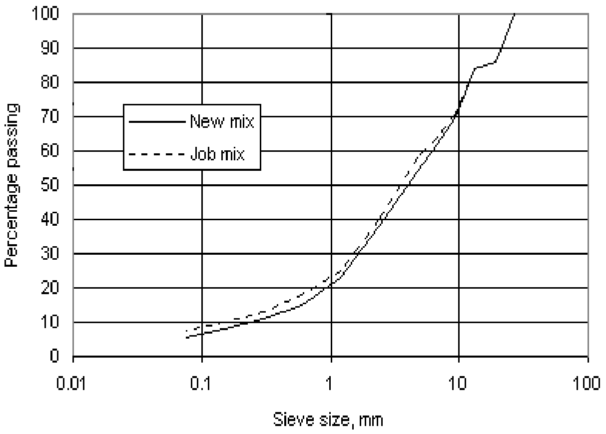

Figure 5. Gradation of the experimental mix

7 MMLS3 TESTING

Accelerated pavement testing (APT) under the MMLS3 was done on the different mixes with gradations shown in Figure 6.

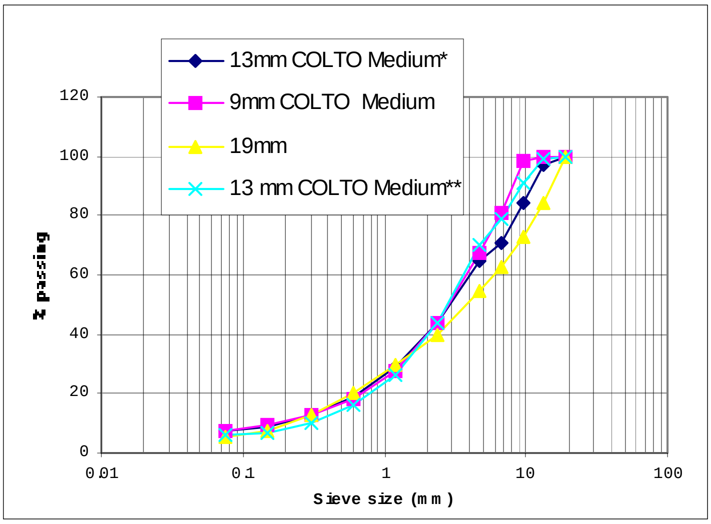

Figure 6: Gradation of mixes used for APT testing

For these tests, the MMLS wheel load was set to 2.5 kN and the tyre pressure to 690 kPa. No lateral wander was applied during testing and the rate of testing was maintained at 7200 axles per hour for both tests. Profile measurements were taken every 5 mm across the slabs after 0, 1000, 10 000, 25 000, 100 000, 150 000 axles.

The first test were done at an average asphalt temperature of 53 ºC and the second test at an average asphalt temperature of 50 ºC. The cumulative rutting curves are shown in Figure 7. Both the 19 mm and 13 mm* mixes showed better rut resistance than the 9 mm mix. From the first test the rut resistance of the 19 mm and 13 mm* mixes are comparable, although the 19 mm mix had a larger initial settlement.

From the second test, the rut progression of the 19 mm and 13 mm* mixes are comparable, with the 13 mm* mix showing larger deformation after 50 000 axles.
Also, the 13 mm** mix with the lower filler/binder ratio showed better rut resistance, than the reference mix after a higher rutting rate.

An important aspect between the two tests is the influence of the temperature. Inadvertently, test 1 was carried out at 53 ºC and test 2 at 50 ºC, but the results of the 19 mm and 13 mm* mixes are comparable.

Epps et. al (2001) conducted research to relate the rut depth under MMLS3 loading to a terminal rut depth under full-scale truck loading. The MMLS3 tyre pressure was 690 kPa (at 25 ºC) with a wheel load of 2.1 kN. For the full-scale truck, with dual wheels, the tyre pressure was 700 kPa (at 25 ºC) and the load 20 kN per single wheel. Epps et. al. found that at 100 000 load repetitions, an average rut depth of 3.5 mm under the MMLS3 relates to a 10 mm critical rut depth under full-scale trucks in the field. Compared to this critical 3.5 mm rut depth after 100 000 axles, all of the mixes tested in this investigation exceeded 3.5 mm after 100 000 axles. The actual rut depths were between 4mm and 5mm. Not withstanding this, except for the 9mm mix, all of the mixes with adjusted filler/binder ratios for better compactibilty, had equivalent or better rut resistance than the reference mix (13mm*) at 100 000 axles.

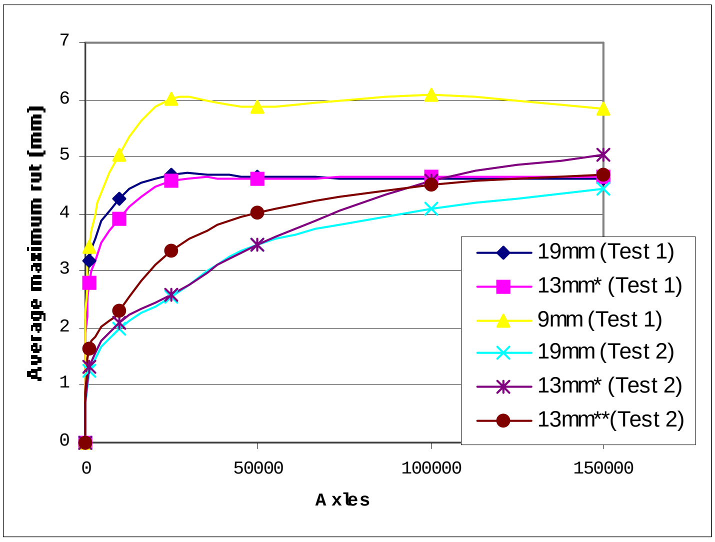

Figure 7: Cumulative rutting curves for Test 1 and Test 2

8 CONCLUSIONS & RECOMMENDATIONS

Based on the findings of this report, it is evident that one of the critical factors influencing the compactibility of wearing course mixes currently used in the Western Cape is the binder content of these mixes. Considering volumetric analysis of standard mix compositions, the binder contents are low. In contrast, the filler contents of these mixes are particularly high (in excess of 7 percent). This coupled with too low a binder content result in high filler/binder ratios, which can over stiffen the mastic of these mixes compromising the workability, durability and compactibility of these mixes. The findings of this research can be used to adjust mix design procedures so that harsh mixes can be addressed.

Reduction of the filler/binder ratios in order to improve compactability does not significantly increase rutting under APT. The 13 mm mix with the lower filler/binder ratio showed better rut resistance after a higher rate of deformation than the reference mix. The rut resistances of the 19mm and the 13mm reference mix were comparable.

It is recommended that softening point tests be done on filler/binder mastics at varying degrees of percent bulk volume of filler. An increase of 12 ºC in the softening of the mastic compared to that of the base bitumen should be used to establish the maximum filler/binder ratios to optimise the stiffening effect of the filler. Binder contents should be established based on these ratios. Gyratory compaction tests and mechanical tests should be done to validate the suitability of these binder contents.

For the MMLS3 tests, it is recommended that three slabs of the same mix be tested during one test to reduce the variability of the test results. For each mix of a specific maximum particle size, the filler/binder ratios can be selected as the variable between the slabs.

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