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INVESTIGATING THE INFLUENCE OF MINERAL FILLERS AT AUSTRALIAN ASPHALT MIXTURES

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Abstract

It is commonly known that mineral fillers significantly affect the asphalt mixture's performance. Superior flexible pavement performance can be ensured by gaining a deeper understanding of the function of filler. This research investigates the influence of three different fillers: granite dust, cement, and hydrated lime, at Australian asphalt mixtures. The testing program includes Marshall testing, moisture damage resistance, indirect tensile strength (ITS), and indirect tensile stiffness modulus (ITSM) tests of asphalt mixtures. Analysis of variance (ANOVA) was used to statistically assess the results obtained, besides damage analysis. The results indicate that using natural granite dust yields the highest resistance to moisture, while cement produces the highest stability, ITS, and ITSM. Unexpectedly, using hydrated lime filler decreases the stability/stiffness and moisture resistance of asphalt mixtures. ANOVA tests indicate that the type of filler affects ITS, TSR, and ITSM results (i.e., the p-value <0.05). The damage analysis shows that the design life of the asphalt mixture made with cement filler is higher than that of mixtures made with natural granite dust and hydrated lime fillers respectively. The findings indicate the important role of nontraditional fillers at the performance of Australian asphalt mixtures.

Keywords:

Mineral fillers;
Asphalt mixtures;
Moisture damage;
Stiffness modulus;
Damage analysis.

1 Introduction

According to Australian Standards, fillers are fine-grained particles that pass a sieve 0.075 mm. Fillers can play a crucial role in affecting workability [1], durability [2] [3] [4], and stiffness [5] [6] [3] [1] of asphalt mixtures. In the asphalt industry, fillers have two main roles. Fillers can fill the gaps between aggregates, and blend with asphalt to form asphalt mastics [7]. In Australia, various mineral fillers can be added to HMA such as hydrated lime, cement, slag, fly ash, ground limestone, and cement kiln dust. However, the most utilized filler in Australia for the production of asphalt mixtures is natural granite dust [8]. In this regard, few efforts are carried out to investigate the impact of using different fillers mentioned in the Australian Standards [9]. Although several researchers stated that different potentially available materials can be used efficiently to replace traditional fillers [10] and [11].

In this regard, there are two commonly used fillers in the pavement industry, i.e., Portland cement and hydrated lime fillers [12]. The advantages of using hydrated lime (HL) as a filler are incontrovertible. As revealed earlier, these two fillers (cement and hydrated lime) are both accepted to be used as fillers as mentioned in Australian standards [13]. HL has a significant contribution in improving the performance of mastic and asphalt mixtures on multilevel. [14] stated that using HL increases asphalt mixtures' durability and improves their mechanical properties. Moreover, [15] carried out an experimental study to evaluate the thermal resistance of asphalt mastic containing basalt and HL fillers. The results revealed that adding HL produces a better rutting behavior of asphalt mastic. Additionally, [4] evaluate the use of different waste fillers with RAP asphalt mixtures. The evaluation showed that the asphalt mixtures made with hydrated lime exhibited the highest ageing resistance among other prepared mixes. Another study showed that the use of HL produces better stability and strength index of asphalt mastic which leads to greater durability [9]. In addition, the use of cement filler is documented to be more beneficial than other traditional fillers. Cement filler can improve the high-temperature performance and durability of asphalt mastic and asphalt mixtures [16]. [17] studied the effects of cement filler on asphalt mixture performance. The results of their study showed that the replacement of hydrated lime filler with cement filler could improve the water stability of asphalt mixtures compared with that achieved with limestone filler. Another study by [18] showed that asphalt mixtures made with cement filler exhibit better stiffness than those made with calcium hydroxide filler.

Hence, an investigation of the mechanical properties of Australian asphalt mixtures incorporating fillers such as cement and hydrated lime is crucial. By doing this, the authors are opening a new window in the research area to explore the performance of Australian asphalt mixtures with two nontraditional fillers besides the natural granite dust filler.

The primary aim of this research is to study the effect of different fillers on volumetric properties, particularly the bitumen absorption, moisture damage, and stiffness of asphalt mixtures. The work here also aims to examine the damage analysis to investigate the effect of filler types on both permanent deformation and fatigue cracking of asphalt mixtures. Asphalt mixtures are made with the most traditional filler in Australia (i.e. natural granite dust) and alternative fillers (i.e. cement and hydrated lime). To achieve this aim, three asphalt mixtures with the same aggregate gradation and asphalt binder but with three different fillers have been prepared and evaluated as per Australian practices.

2 Materials and testing protocols

2.1 Aggregates

The natural granite aggregate (NGA) used in this work is sourced from a nearby quarry in Perth, Australia. It is confirmed that the NGA satisfies all requirements for use in the asphalt mixtures industry. The physical characteristics of fine and coarse NGA were evaluated, and Table 1 presents the fundamental properties of NGAs.

Table 1: Fundamental properties of NGAs.

Coarse aggregate			
Standard	**Property**	**NGA**	**Requirements**
Australian Standard 1141.6.1	Apparent density, gm/cm³	2.692	-
	Density of particle on a dry basis, gm/cm³	2.663	-
	Density of particle on a Saturated Surface Dry basis, gm/cm³	2.674	-
	Absorption, %	0.4	≤2
Australian Standard 1141.23	LA value, %	24.2	<35
Australian Standard 1141.21	Aggregates crushed value, ACV (%)	23.9	-
Fine aggregate			
Australian Standard 1141.5	Apparent density, gm/cm³	2.697	-
	Density of particle on a dry basis, gm/cm³	2.633	-
	Density of particle on a Saturated Surface Dry basis, gm/cm³	2.657	-
	Absorption, %	0.6	≤2

2.2 Minerals filler

Three kinds of mineral filler were utilized in this work: the granite dust, hereafter named Natural filler (NF), a byproduct produced during the cutting and polishing of granite stones in quarry industries. In addition, the ordinary Portland cement filler is hereafter referred to as (CF), and the hydrated lime filler is hereafter referred to as (LF). As suggested by the Main Roads standard, the hydrated lime was mixed with the conventional HMA at a dosage of 1.5% by weight of aggregates [19]. The laboratory tests to characterize the selected fillers are particle size distribution (PSD), apparent particle density, and Scanning Electron Microscopy (SEM).

2.3 Asphalt binder

In this work, Class 320 asphalt binder was utilized to make all asphalt mixture specimens. The evaluation of this binder affirmed its penetration value of 50 under standard testing conditions (i.e., 25 degrees Celsius, 100 grams, and 5 seconds) and a flash point exceeding 300°C. This type of binder is recommended for wearing pavement layers and base pavement layers with heavy loading constructed in hot areas [13]. The manufacturer confirmed that this binder satisfied all standard requirements according to Australian practices.

2.4 Marshall mix design

Marshall procedure was applied to find the optimum content of asphalt binder (OBC) following Australian Standard 2891.5 for the asphalt mixtures produced with various fillers.

The nominal maximum aggregate size (NMAS) of 14 mm was used to design and assess these asphalt mixtures [20]. The assessment was carried out based on the resistance to plastic deformation by measuring stability and flow values using the testing machine in Fig. 1. Density and measured volumetric properties were also used as criteria to determine the OBC.

Fig. 1: Set-up for stability and flow tests.

2.5 Indirect tensile strength (ITS) test

The ASTM D-6931 standard was followed to determine the indirect tensile strength (ITS) of asphalt mixtures containing NF, CF, and LF. [21]. ITS results can be used to assess rutting and cracking potential [21]. Three sets of asphalt mixture specimens were prepared with six specimens each to find the ITS values. A gyratory compactor was used to produce Marshall specimens that have a diameter of 100 ± 2 mm and a height of 65 ± 1 mm. The compaction of specimens was done at the OBC of each mix to a desired air void content of 8 ± 1 % and tested following the Austroads standard testing methods and specification, AG-PT/T232 [22]. The impact of different testing temperatures on the ITS values was evaluated by testing three specimens of each group at 25 °C, while the rest were tested at 40 °C. The ITS testing was conducted at a consistent loading rate of 50 mm/min. Fig. 2 shows the setup for the ITS test. Equation 1 was used to find the calculation of ITS as follows:

$$\mathrm{ITS} = (2\mathrm{P}_{\mathrm{ultimate}}/(\pi * \mathrm{T}_{\mathrm{s}} * \mathrm{D}_{\mathrm{s}})) * 10^{6} \tag{1}$$

where:
ITS – The Indirect tensile strength in [kPa],
$P_{ultimate}$ – The ultimate applied force in [kN],
Ts – The thickness of the specimen in [mm],
Ds – The diameter of the specimen in [mm].


Fig. 2: Set up for ITS test.

2.6 Water sensitivity test

One of the specific objectives of this work is to examine the effects of filler type on the asphalt stripping resistance made with NF, CF, and LF. To achieve this, three groups of six specimens each were produced for testing the tensile strength in both conditions, unconditioned (dry) and conditioned (wet). One group was prepared with NF, one with CF, and the last one was made with LF.

In accordance with the Australian standards AG-PT/T-232 (Austroads-2007), a gyratory compacter was used to compact Marshall specimens at the OBC of each mix to reach a target air void content of 8±1 %. The specimens have a diameter of 100 ± 2 mm and a height of 65 ± 1 mm. Each of the three mixtures consisted of two groups of samples: unconditioned (dry) and conditioned (wet). Conditioned samples experienced a freeze-thaw cycle at -18°C for 16 hours followed by thawing at 60°C for 24 hours. Next, a loading rate of 50 mm/min was applied to measure the ultimate applied force of the unconditioned and conditioned samples at the standard test temperature of 25 °C and the indirect tensile strength (TSD and TSW) was calculated according to Equation 1. Finally, the ratio of tensile strength of the conditioned to unconditioned samples (TSR) was calculated according to Equation (2). The TSR represents the Tensile Strength Ratio (%) and is calculated using the formula:

$$\mathrm{TSR} = (\mathrm{ITS_W}/\mathrm{ITS_D}) * 100 \quad (2)$$

where:
ITSW – the average tensile strength of the wet specimen set [kPa],
ITSD – the average tensile strength of the dry specimen set [kPa].

The specification 510 of Main Roads states that the ITSW and ITSD must be more than 750 kN and 850 kN respectively [19].

2.7 Indirect tensile stiffness modulus (ITSM) test

The resilient modulus of asphalt mixtures produced with NF, CF, and LF was determined using repeated loading by indirect tensile technique following the Australian Standards: AS/NZS-2891.13.1[23]. Performing this test by a universal testing machine (UTM) requires applying a repeated load to a cylinder-type specimen along the vertical diameter to measure the resulting displacement along the horizontal plane of the sample. Linear variable displacement transformers (LVDTs) have been used to measure deformation, which should not damage the sample because its behavior is still in the elastic range (Allan 2008). Thus, a horizontal strain of 50±20 $\mu\epsilon$ was applied to the samples conditioned at the test temperature of 25 °C. A haversine load pulse was applied with a rise time of 0.025 s to 0.1 s (± 0.005 s) by using the UTM 25 which can apply a peak load from 0.40 kN to 3.90 kN (±0.05 kN). Fig. 3 shows the setup for the indirect tensile stiffness modulus test. According to Australian standards, at least three samples should be tested. The average value of the measured stiffness modulus should not differ by more than ±15% from the average value, otherwise, the test should be repeated. The resilient modulus (E) in MPa was calculated based on Equation (3):

$$E = P * (v + 0.27)/(H * hc) \tag{3}$$

where:
P – the peak load [N],
v – the Poisson ratio (0.4 was used),
H – the recovered horizontal deformation [mm],
hc – the height of the specimen [mm].

Fig. 3: Set-up for indirect tensile stiffness modulus test.

2.8 Analysis of Variance ANOVA

ANOVA test, analysis of variance, was used to test the level of significance of the independent variable such as filler type, test temperatures, and state conditions (dry, and wet), on the dependent variables: ITSD, ITSW, TSR, and ITSM. The primary focus is on the main effect of the independent variable, whereas the interaction effect is attributed to the combined influence of the independent variables. A significance level of 0.05 was selected to assess the statistical significance. If the calculated probability value is less than 0.05, the results are significant, and thus the null hypothesis is consistently rejected. Fig. 4 outlines the steps followed in the current study.

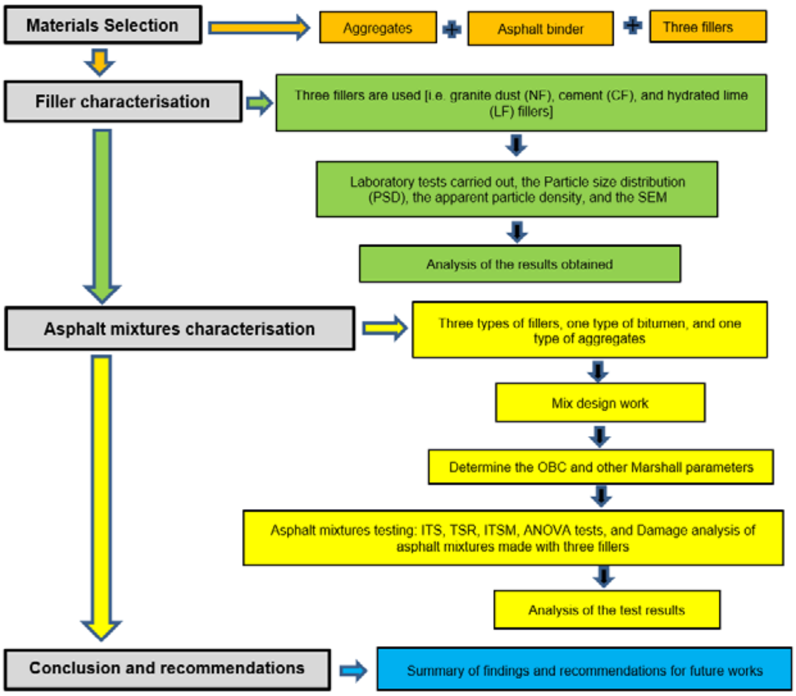

Fig. 4: Outlines of current work.

3 Results and discussions

3.1 Fillers testing results and discussion

Table 2 shows the results of the PSD and the apparent particle density tests of the three used fillers. Based on the PSD results, the NF is the finer filler followed by CF and then LF. In terms of apparent particle density, the CF has the highest apparent particle density (3.145 g/cm³) while the LF has the lowest (2.147 g/cm³). The lower apparent particle density can lead to a higher specific surface area, which, in turn, is expected to result in a higher bitumen absorption rate.

Furthermore, Figs. 5, 6, and 7 show the microscopic morphology of the NF, CF, and LF, respectively as determined by Scanning Electron Microscopy (SEM). The SEM revealed that the CF particles have a surface texture much rougher than NF particles while the latter particles are much bigger than LF particles. LF particles present an irregular surface texture which leads to more available surfaces. NF particles present a non-spherical shape with specific points of rough texture and high porosity. This in turn may lead to higher bitumen absorption of CF and LF particles if compared to NF particles. Without a doubt, the results obtained from PSD, SEM, and apparent particle density will affect the performance of asphalt binder and asphalt mixtures made with the fillers mentioned above.

Table 2: PSD, apparent particle density, and specific gravity of fillers.

Standard	Sieve size (mm)	NF	CF	LF	Limits
		Passing [%]			
ASTM D546 − 10	0.6	100	100	100	100
	0.3	100	99.4	98.6	95-100
	0.15	100	98.3	92.6	-
	0.075	98.4	96.7	86.6	75-100
AS/NZS 1141.7	Apparent particle density, gm/cm³	2.450	3.145	2.147	-
-	Specific gravity	-	3.2	2.2	-

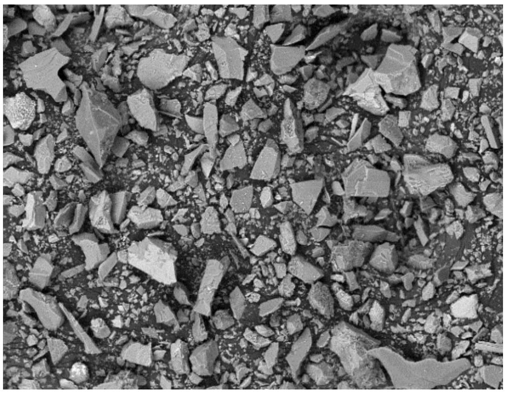

Fig. 5: SEM of NF.

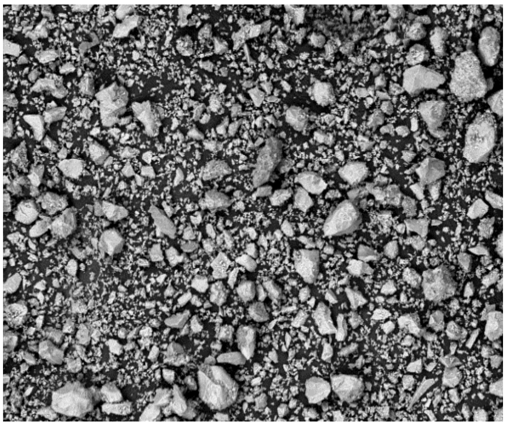

Fig. 6: SEM of CF.

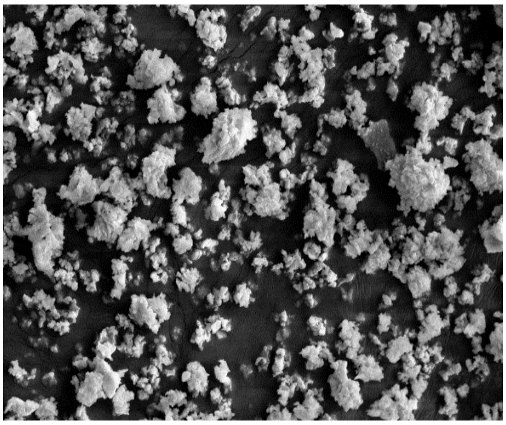

Fig. 7: SEM of LF.

In addition, the manufacturers provide the physical and chemical properties of cement and lime fillers, which are shown in Tables 3 and 4, respectively.

Table 3: Physical and chemical properties of CF.

Property	Comment/value (supplier)
Appearance	Grey powder
Odour	Odourless
pH	Alkaline
Boiling point	Not available
Specific gravity	3.0-3.4
Apparent particle density, g/cm³	3.145

Table 4: Physical and chemical properties of hydrated lime filler (LF).

Property	Comment/value (supplier)
Appearance	A white or off-white amorphous powder
Odour	Slight odour
pH	Approximately 12
Boiling point	Decomposes to calcium oxide and water at 580°C
Specific gravity	2.1-2.3
Apparent particle density, g/cm³	2.147

3.2 Asphalt mixtures testing results and discussion

3.2.1 Marshall mix design

The Marshall testing results at the Optimum Bitumen Content (OBC) are presented in Table 5. The findings indicate that mixes prepared with LF exhibited the lowest density values, whereas mixes made with CF recorded the highest densities. This disparity in apparent densities of the fillers can account for the observed differences in the Marshall parameters among the asphalt mixtures.

Where the higher the density of the filler, the higher the density of the mix produced. Furthermore, asphalt mixtures prepared with CF exhibited higher stability (S) among mixtures made with NF and LF. This could indicate that a better adhesion is developed between asphalt binder and aggregates when CF is used. Also, asphalt mixtures made with CF exhibit the lowest flow (F) values compared to those made with NF and LF. While the highest flow values were obtained for LF mixes. Therefore, Marshall Quotient (MQ) values, which are calculated by dividing the average stability of an asphalt mix by its average flow, for CF mixes were the highest among all mixes. The results revealed that the CF-asphalt mixture showed higher resistance to withstand deformation under loading.

It was found that the highest average values of Voids in Mineral Aggregates (VMA), and Voids Filled with Bitumen (VFB) were obtained for LF specimens. While the lowest values were obtained for NF specimens. These results may be explained by the fact that the LF had the highest bitumen absorption rate compared with other fillers, while the NF had the lowest. The results from SEM images and of OBC confirm this conclusion. Therefore, it is expected that any increase in the bitumen absorbed by filler produce an increase in the voids formed between aggregates particles and a reduction in the binder film thickness around them.

In terms of optimum bitumen content (OBC), it can be seen that the NF mix requires less bitumen (OBC = 4.23%) to reach the OBC than mixtures made with CF (OBC = 4.34%) and LF (4.97%) respectively. From an economic viewpoint, the use of NF was more effective if compared with CF and LF. The findings revealed that the LF mixes required the highest amount of bitumen to reach the OBC level in comparison to NF and CF mixes. This phenomenon can be attributed to the lower apparent particle density of LF, resulting in the highest specific surface area among the various fillers. This observation aligns with the outcomes derived from the scanning electron microscopy (SEM) images, confirming the influence of filler properties on bitumen absorption behavior.

Table 5: The results of Marshall tests and volumetric properties at OBC.

Mix type	Density (gm/cm³)	S (kN)	F (mm)	MQ (kN/mm)	VMA (%)	VFB (%)	Target VTM (%)	OBC (%)
NF	2.374	17.7	2.4	7.4	13.8	63.9	5	4.23
CF	2.384	18.7	2.3	8.1	14.58	66.04	5	4.34
LF	2.341	17.5	3.2	5.5	15.0	68.86	5	4.97

3.2.2 Indirect tensile strength (ITS) results

Fig. 8 shows the summary results of the ITS test of asphalt mixtures made with NF, CF, and LF at two test temperatures (25 °C and 40 °C). While the details of the results are presented in Table 6.

As shown in Fig. 8 and Table 6, the use of NF, CF, and LF produces a definite effect on the indirect tensile strength performance of asphalt mixtures. The results indicated that the CF-mix exhibited a higher ITS than other mixes. The order of ITS results was as follows: CF-mix > NF-mix > Lf-mix. This proves that using other fillers such as CF can produce higher ITS, while using LF produces the opposite. The outcomes demonstrated a significant influence of filler type on the indirect tensile strength of Australian asphalt mixtures. Furthermore, the results highlighted the remarkable sensitivity of mixtures'

ITS to variations in testing temperature. Notably, Fig. 8 portrays a clear trend wherein elevated testing temperatures correspond to diminished indirect tensile strength in asphalt mixtures. For example, the NF mix tested at 25 °C and 40 °C had ITS of 1150.84 kPa and 346.13 kPa respectively. This means that the NF mix lost 804.7 kPa of its tensile strength when the temperature increased by 15 °C. This phenomenon may be explained by the asphalt binder becoming softer at high temperatures, which in turn lowers the adhesion bonds between asphalt binder and aggregates. A higher ITS of CF-asphalt mixtures reflects better resistance to cracking and permanent deformation than that of mixes made with NF and LF respectively [21]. Furthermore, it should be stated that asphalt mixtures with LF did not satisfy the Main Roads Western Australia for minimum requirements of dry ITS tested at 25 °C which shall be greater than 850 kPa [19].

A two-way ANOVA was conducted to examine the impact of filler type and temperature on the indirect tensile strength of asphalt mixtures. The results of the analysis are presented in Table 7. According to the ANOVA results, both factors, i.e., the filler type (P value = 0.000823) and temperature (P value = 6.33E-13), were found to be statistically significant at a 95% confidence level. Notably, based on the obtained p-values, it can be deduced that the test temperature has a more substantial effect on the ITS compared to the filler type. Additionally, based on the ANOVA results, the interaction between the type of filler and temperature was insignificant. This is explained by a P-value of 0.415 which is higher than 0.05.

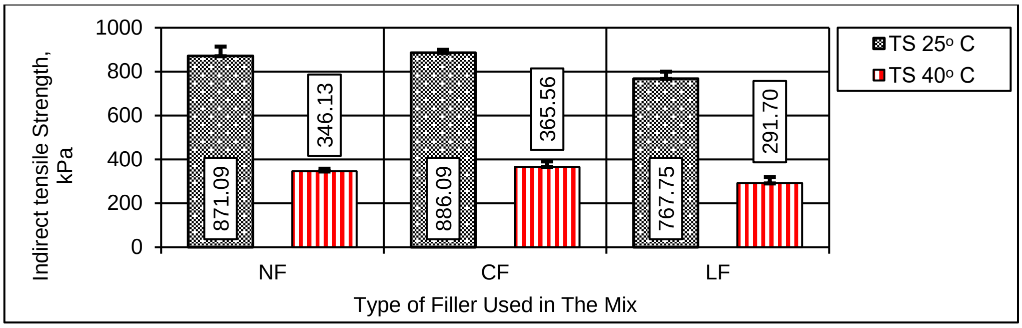

Fig. 8: ITS of asphalt mixtures at 25 °C and 40 °C.

Table 6: Details of indirect tensile strength of asphalt mixtures made with NF, CF, and LF.

Specimen #	Average H [mm]	Average D [mm]	P [kN] 40 °C	P [kN] 25 °C	TS 40 °C	TS 25 °C
NF 1	64.9	99.8	3.367	-	331.11	-
NF 2	65	100	3.545	-	347.38	-
NF 3	64.8	99.9	3.658	-	359.92	-
NF 4	64.9	99.8	-	8.341	-	820.24
NF 5	65.1	99.9	-	9.452	-	925.72
NF 6	64.9	100.2	-	8.855	-	867.31
Average					346.13	871.09
CF 1	64.9	99.7	3.678	-	362.05	-
CF 2	65	99.9	3.427	-	336.15	-
CF 3	64.9	99.9	4.056	-	398.46	-
CF 4	64.8	100	-	8.902	-	875.01
CF 5	64.9	99.9	-	8.941	-	878.37
CF 6	64.9	99.9	-	9.211	-	904.89
Average					365.56	886.09
LF 1	64.8	99.9	3.357	-	330.30	-
LF 2	64.9	99.9	2.719	-	267.12	-
LF 3	65	99.9	2.831	-	277.69	-
LF 4	64.8	99.9	-	8.263	-	813.01
LF 5	64.9	100.1	-	7.645	-	749.55
LF 6	64.9	99.8	-	7.532	-	740.69
Average					291.70	767.75

Table 7: Results of two-way ANOVA effect of type of filler and testing.

Source of Variation	SS	df	MS	F	P-value	F crit
Filler Type	31507.8	2	15753.9	13.60074	0.000823	3.885294
Test Temperature	1157538	1	1157538	999.3321	6.33E-13	4.747225
Interaction	2195.43	2	1097.715	0.947685	0.414827	3.885294
Within	13899.74	12	1158.312			
Total	1205141	17				

3.2.3 Tensile strength ratio (TSR) results

Fig. 9 shows the average indirect tensile strength of dry (unconditioned) and wet (conditioned) specimens made with three different types of fillers: NF, CF, and LF. It can be seen that the average dry tensile strength of asphalt mixtures prepared with cement filler was higher than those of corresponding asphalt mixtures made with natural and hydrated lime fillers. The results reveal the capability of asphalt mixture made with cement filler to mobilize higher resistance to indirect tensile forces than that of mixes made with NF, and LF respectively.

The data illustrates that the indirect tensile strength of conditioned specimens was generally lower than that of unconditioned specimens, with the exception of the result obtained for the NF-mix. These results have come in line with findings obtained previously [24]. The latter outcome may be explained by the addition of 1.5% hydrated lime by the weight of dry aggregates into NF-mix. The reduction in the tensile strength in the wet state explains the effect of water on the performance of the asphalt mixture against stripping. Furthermore, the average indirect tensile strength of dry and wet states of asphalt mixture made with LF was 767.75 kPa and 669.91 kPa respectively. Thus, the LF-mix did not satisfy the Main Roads Western Australia (MRWA) minimum requirements for Unconditioned (850 kPa) and conditioned ITS (750 kPa) (MRWA, 2017a). This proves that a mix that satisfies Marshall mix design limitations may not necessarily exhibit an acceptable performance. The latter conclusion corresponds to the results obtained by [25].

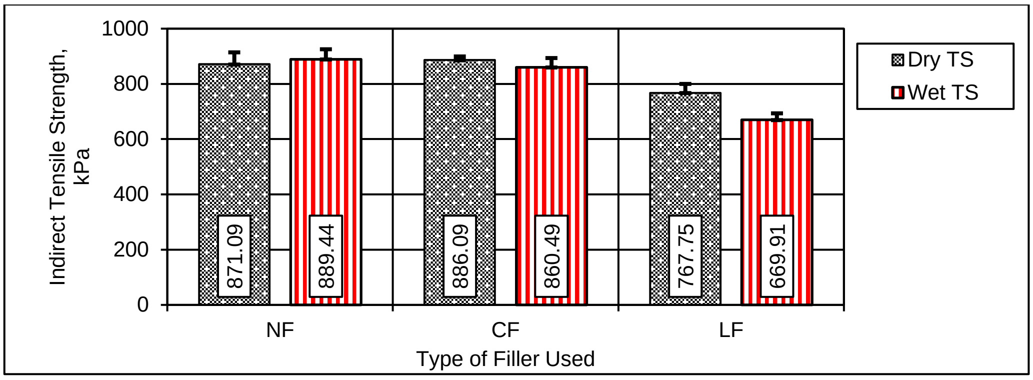

Fig. 9: Tensile strength of asphalt mixtures with various fillers.

Fig. 10 also shows the results of the TSR of the three designed mixes. It can be seen that the TSR of the LF-mix is noticeably lower than that of natural granite filler (NF) and hydrated lime filler respectively. This finding may be attributed to the lowest specific gravity of hydrated lime which may translate into the highest surface area among other fillers. As a result, the LF absorbs the highest asphalt binder as compared with NF and CF as shown in Table 5. Thus, insufficient asphalt binder film around aggregate particles of LF-mix is produced. The opposite story can be told by NF-mix where the TSR was the highest. It must be mentioned that all mixes are prepared with the same natural aggregates and asphalt binder and tested under the same conditions. Thus, the differences in the TSR are related to the type of filler used in the mix. The differences in TSR results can be explained by the difference between the capabilities of fillers to absorb asphalt binder. The more the absorbed asphalt binder, the thinner the film of the asphalt binder around aggregates. As a result, severe water damage is produced.

The most interesting observation is that the difference between dry and wet indirect tensile strength decreases as the filler type changes from lime to cement to natural filler. Consequently, it can be inferred that the asphalt mix made with LF is more susceptible to water invasion damage compared to mixes made with cement and natural granite dust fillers. The TSR results indicated that asphalt mixtures made with 100% hydrated lime filler tended to show more durability problems than mixtures made with Western Australian traditional filler (NF) and cement filler. A two-way ANOVA analysis was performed to investigate the effects of the type of filler and state conditions (dry and wet) on ITS. The result of the two-way ANOVA is presented in Table 8. The ANOVA indicated that the effect of filler type was significant (p-value = 1.29E-05) but the state conditions were not (p-value = 0.079626). In addition, the ANOVA results showed that the interaction effect of both individual factors on ITS was not significant at a 95% confidence level where the p-value was 0.066428. Another one-way ANOVA was carried out to examine the effect of filler type on the TSR of asphalt mixtures. The results of the one-way ANOVA are shown in Table 9. According to the ANOVA analysis, the type of filler used in asphalt mixtures can greatly affect the TSR produced. This is explained by the p-value of 0.003183 as shown.

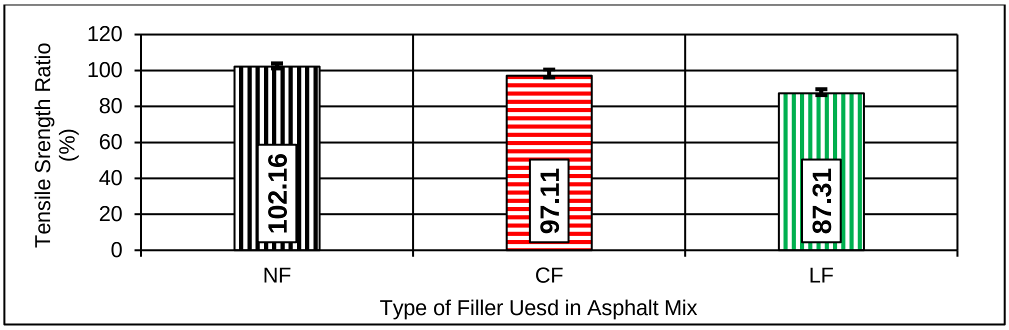

Fig. 10: TSR of asphalt mixtures made with various fillers.

Table 8: Two-way ANOVA effect of filler type and state conditions (dry and wet) on ITS.

Source of Variation	SS	df	MS	F	P-value	F crit
Filler Type	99937.25	2	49968.63	33.18034	1.29E-05	3.885294
State Conditions	5522.823	1	5522.823	3.667284	0.079626	4.747225
Interaction	10325.35	2	5162.673	3.428136	0.066428	3.885294
Within	18071.65	12	1505.971			
Total	133857.1	17				

Table 9: One Way ANOVA effect of filler type on TSR.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	342.3198	2	171.1599	17.39377	0.003183	5.143253
Within Groups	59.04178	6	9.840296			
Total	401.3616	8				

3.2.4 Indirect tensile stiffness modulus (ITSM) results

The resilient modulus results at 25 °C for asphalt mixtures made with NF, CF, and LF are presented in Fig. 11. The results reveal that the utilization of different traditional fillers in asphalt mixtures can greatly affect the mix's stiffness. It can be seen that the use of CF instead of traditional granite dust filler leads to an increase in resilient modulus up to 11.44%. However, adding LF instead of traditional granite filler (NF) produces a decrease in the mix's stiffness by up to 10.95%. This is expected to be related to the effect of the used filler on the properties of asphalt binder and asphalt mixtures as mentioned earlier. The results approve that the use of other fillers, i.e. some of these mentioned in Australian standards [13], can improve the performance of asphalt mixtures. The latter conclusion is true when cement filler is used as filler instead of natural granite dust filler (i.e. NF). Thus, it is recommended to conduct more research to investigate the field and laboratory performance of CF-asphalt mixtures in future studies. This is imperative to take a broad view of the performance of CF-mixes.

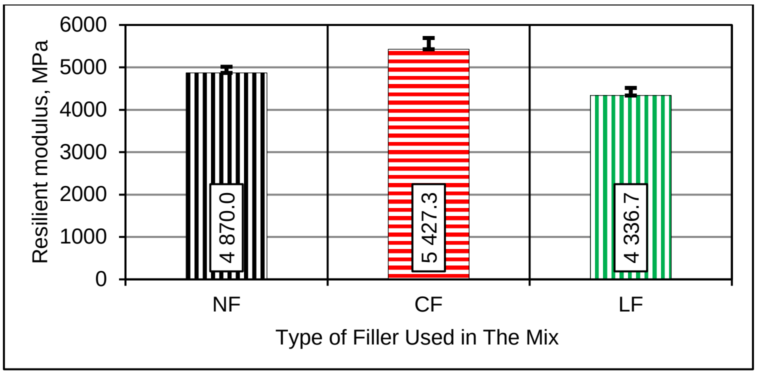

Fig. 11: Resilient modulus of asphalt mixtures made with various fillers.

A one-way ANOVA was carried out to examine the effect of the type of filler on the resilient modulus of asphalt mixtures. The results of ANOVA are presented in Table 10. As can be seen, the type of filler significantly affected the resilient modulus of the mix at a 95% confidence level where the p-value equals 0.004999 < 0.05.

Table 10: One-way ANOVA effect of type of filler on resilient modulus of asphalt mixtures.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1784619	2	892309.3	14.54554	0.004999	5.143253
Within Groups	368075.3	6	61345.89			
Total	2152694	8				

3.2.5 Damage analysis

In this part, damage analysis was carried out using the KENPAVE computer program to investigate the effect of filler types on both permanent deformation and fatigue cracking of asphalt mixtures. Table 11 shows the inputs required to perform this analysis by selecting a typical flexible pavement configuration with all necessary data: moduli, thickness, and Poisson's ratio of each layer. It should also be noted that the load applied to the proposed pavement section is the equivalent single axle load (ESAL) conforming to the guide of pavement technology, part 2: Pavement Structural Design [26]. The magnitude of load applied with dual tires is 80 kN, 20 kN applied to each of four uniformly loaded circular areas of radius 92.1 mm each at centre-to-centre spacings of 330 mm, 1470 mm, and 330 mm. The applied contact pressure per loaded area is 750 kPa.

The results presented in Table 12 show that the higher the stiffness modulus, the better the pavement performance. The asphalt mixture made with cement filler showed better resistance to both fatigue cracking and permanent deformation as it was found to have the largest values of N_f and N_c. The analysis also indicates that the asphalt-cement filler mixture had lower values of critical tensile and compressive strains than the other two mixtures. Using this mixture as a surface layer also results in the longest design life compared to two other mixtures. As shown in Table 12, the design life of the proposed pavement section is 22 years for the asphalt-cement filler mixture compared to 20 years for the asphalt-natural granite filler mixture and 18 years for the asphalt-hydrated lime filler mixture.

In this perspective, it was reported that the higher the modulus, the higher the pavement performance [27]. From an economic perspective, it was reported that the material with a lower stiffness modulus requires a thicker layer to reduce the stress produced at the underside to an acceptable level [28].

Table 11: Pavement layers and material properties.

Layer	Proposed Thickness, cm	Asphalt Mixtures with filler-type	E, MPa (Varied)	Poisson's ratio, υ
Asphalt	10	Naturel granite, NF	4870	0.40
		Cement, CF	5427.3	
		Hydrated lime, LF	4336.7	
Base	20	350		0.35
Surface	20	250		0.35
Subgrade	-	150		0.45

Table 12: Damage Analysis of a proposed pavement section.

Asphalt Mixtures with filler-type	Critical tensile strain (horizontal) at the bottom of asphalt, ε_t	Allowable number of load repetitions to prevent fatigue cracking, N_f	Critical compressive strain (vertical) at the top of subgrade, ε_c	Allowable number of load repetitions to limit permanent deformation, N_c	Design life in years
NF	$1.74*10^{-4}$	$9.809*10^{5}$	$2.02*10^{-4}$	$4.76*10^{7}$	20
CF	$-1.64*10^{-4}$	$1.074*10^{6}$	$1.98*10^{-4}$	$5.16*10^{7}$	22
LF	$-1.84*10^{-4}$	$8.951*10^{5}$	$2.06*10^{-4}$	$4.40*10^{7}$	18

4 Conclusion

This work aims to study the effect of mineral fillers on the moisture resistance and stiffness of Australian asphalt mixtures. While ordinary Portland cement and hydrated lime are widely used as fillers in road construction, the most traditional filler in Australia is natural granite dust. Therefore, these two fillers (cement and hydrated lime) were examined in addition to the granite filler to evaluate their effects on moisture resistance and stiffness modulus. ANOVA and damage analysis were also carried out to measure the effect of different fillers on mixture performance.

In view of the results and analysis, the following conclusion can be drawn:

1) Asphalt mixes made with CF showed the highest stability, indirect tensile strength, and stiffness. While those made with NF showed the highest moisture resistance.

2) Replacing 100% NF with LF can considerably affect the strength, moisture stability, stiffness, and bitumen absorption (i.e. cost) of asphalt mixes. The results showed that the LF asphalt mix required 17.5% and 14.5% more bitumen than the mixes made with NF and CF, respectively.

3) The results of the ITS test show that the difference between dry and wet indirect tensile strength decreased when the filler type changed from lime to cement to granite. This means that more durability issues can be expected when using LF in asphalt mixes. In addition, the ANOVA test shows that the type of filler can strongly affect the results of the ITS and TSR results (i.e. the p-value <0.05).

4) The results show that using CF instead of NF increased the resilient modulus of up to 11.44%, but using LF results in a reduction in the resilient modulus of up to 10.95%. This proves that the use of CF can improve the performance of Australian asphalt mixes.

5) The damage analysis indicated that the asphalt mixture produced using CF showed the longest design life compared to other asphalt mixtures produced using NF and LF by 10% and 22%, respectively. Also, the number of repetitions to prevent fatigue cracking, N_f for this mixture was greater than that of the two mixtures by 9.5% and 20%, respectively. Finally, the number of repetitions to limit permanent deformation, N_c of the asphalt-CF mixture was 8.4% and 17.3% higher than the other two mixtures.

Thus, the addition of CF as opposed to natural granite dust could improve the field and laboratory performance of asphalt mixes. Therefore, it is recommended that more research be done on CF asphalt mixes in future studies in Australia. This is essential to have a comprehensive idea of the performance of such mixes in this area of research.

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