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The Effect of Fine Aggregate Properties on the Fatigue Behavior of the Conventional and Polymer Modified Bituminous Mixtures Using Two Types of Sand as Fine Aggregate

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Abstract—Fatigue cracking continues to be the main challenges in improving the performance of bituminous mixture pavements. The purpose of this paper is to look at some aspects of the effects of fine aggregate properties on the fatigue behaviour of hot mixture asphalt. Two types of sand (quarry and mining sand) with two conventional bitumen (PEN 50/60 & PEN 80/100) and four polymers modified bitumen PMB (PM1_82, PM1_76, PM2_82 and PM2_76) were used. Physical, chemical and mechanical tests were performed on the sands to determine their effect when incorporated with a bituminous mixture. According to the beam fatigue results, quarry sand that has more angularity, rougher, higher shear strength and a higher percentage of Aluminium oxide presented higher resistance to fatigue. Also a PMB mixture gives better fatigue results than conventional mixtures, this is due to the PMB having better viscosity property than that of the conventional bitumen.

Keywords—Beam fatigue test, chemical property, mechanical property, physical property

I. Introduction

HOT mix asphalt (HMA) pavement has been found as an alternative, to prevent premature failure. However the use of HMA mixture in pavement construction has been associated with some performance problems which become the main focus of present day research.

The frequent problems associated with road pavements like rutting, abrasion, fatigue cracking, thermal cracking, aging and stripping cause the roads to wear away or fail [1], [2]. Among these road related problems, fatigue is considered to be the main problems in highway pavements [3]. Fatigue cracking is known as one of the primary reasons for failure of structural components of the pavement. When a bituminous pavement is loaded, tensile stresses and strains are induced at the underside of the bitumen bound layer. If the structure is inadequate for imposed loading or if the characteristics of the sub grade change through ingress of water, the tensile strength of the material will be exceeded and crack at the bottom of the bituminous layer will result. Repeated loads inducing tensile stresses above the tensile strength of the mix will cause the crack to propagate upwards towards the road surface [4], [5].

Fine aggregate is a primary constituent in asphalt mixtures. For that reason, the properties of fine aggregates namely its physical, chemical and mechanical properties played a significant role in determining the characteristics of the resulting bituminous mixtures. The advantage of using crushed rock as fine aggregate in HMA wearing course results in produce mixture with higher resistance to deformation, compared to the most natural sand fine aggregate [6].

Another study as in [7] investigated the effect of crushed fine aggregate. They found that the replacement of the rounded aggregate by crush fine aggregates improved mixture properties such as stability, rutting and water resistance.

The aggregate gradation (distribution of particles sizes) is one of the most important factors to resist pavement distress [8]. The effect of aggregate interlocking on the fatigue life is assessed by using control mixture and stone matrix asphalt. The results showed that, stone matrix asphalt mixture have lower fatigue life than control mixtures. This is referred to the lack of mechanical locking of the aggregate because stone matrix asphalt mixture is a gap graded asphalt mixture [9].

The chemical composition of aggregate has a significant effect on the stripping behavior, indirectly it effects on the cracking because one of the distresses that might be caused by stripping is cracking [10].

II. Methodology

In this study several tests were carried out to determine the following properties: specific gravity of coarse aggregate, fine aggregate and filler, physical, chemical and mechanical properties of fine aggregate, physical properties of polymer modified bitumen and conventional bitumen, Marshall Test and beam fatigue test.

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The conventional bitumen were PEN 50/60 and PEN 80/100, while the polymer modified bitumen were designated as PM1 (PM1_82& PM1_76) and PM2 (PM2_82& PM2_76). PM1 modified bitumen is made up by adding styrene butadiene styrene (SBS) to bitumen penetration 82 and bitumen penetration 76 to come up with PM1_82 and PM1_76. PM2 modified bitumen is made up by addition one of the plastomer polymer to bitumen penetration 82 and bitumen penetration 76 to come up with PM2_82 and PM2_76.

Both of the conventional bitumen are manufactured from refined crude oil and were obtained from Bellamy Precision and Berne Science respectively. Polymer modified bitumen was manufactured by adding polymers to the bitumen and were obtained from PPMS Technologies supplier in Malaysia.

Table I shows the physical properties of polymer modified bitumen and conventional bitumen. The consistency tests proved that bitumen PEN 50/60 has higher consistency (harder) than bitumen PEN 80/100. Because PEN 50/60 has lower penetration and ductility, and higher softening point compared to the PEN 80/100.

It can be also noticed that polymer modified bitumen has lower penetration and higher softening point compared to the conventional bitumen. This means the stiffness for polymer modified bitumen is higher than the conventional bitumen, thus exhibit better resistance to fatigue.

PM1 has lower penetration, higher softening point and lower density and higher ductility values as compared to PM2. This is because PM1 polymer modified bitumen consists of SBS polymer and the SBS which is considering one of the elastomer polymers consists of two elements: hard polystyrene end blocks and rubbery midblock. The hard polystyrene end blocks give high tensile strength and flow resistance at high temperature, whereas the rubbery midblocks are responsible for the elasticity, fatigue resistance and flexibility at low temperature [11].

TABLE I
PROPERTIES OF BINDERS

Type of bitumen	Penetration@ 25^0C (0.1mm) ASTM D5	Softening point ^{0}C ASTM D36	Ductility (cm) ASTM D113	Specific gravity at 25 ^{0}C ASTM D04
PEN 50/60	49	52	36	1.032
PEN80/100	90	49	125.6	1.030
PM1_82	39	70	59.1	1.028
PM1_76	47	67	56.4	1.027
PM2_82	48	65	35.5	1.032
PM2_76	48	53	29.6	1.035

Table II represents the specific gravity and source of coarse aggregate, fine aggregate and filler.

TABLE II
SPECIFIC GRAVITY OF AGGREGATE AND FILLER

Types of the aggregate	Source	Specific gravity(g/cm^3)
Coarse aggregate (granite)	Quarry	2.655
Fine aggregate (Mining sand)	Pond	2.695
Fine aggregate (Quarry sand)	Quarry	2.690
Filler (Portland cement)	Factory	3.135

A. Physical Property

The physical property of sand can be determined by using the fine aggregate angularity (FAA) test. Table III demonstrates the fine aggregate angularity results. The fine aggregate angularity is measured by determining the percentage of voids in the sand, the higher the percentage of voids the more angular the fine aggregate. It can be noticed from the table, that quarry sand has more angularity compared to the mining sand. It was found that fine aggregate with higher values of FAA produce more angular particles and greater rough surface texture, resulting in a larger interlock between the particles consequently resulting in higher shear strength, and this is enhanced the fatigue resistance [7].

TABLE III
FINE AGGREGATE ANGULARITY FOR THE SANDS USED

Types of the aggregate	Fine aggregate angularity (FAA) %
Fine aggregate (Quarry sand)	46.91
Fine aggregate (Mining sand)	42.58

B. Chemical Property

The chemical composition of sand can be determined by the X-ray fluorescence (XRF) test. The XRF test resulst in Table IV showed that mining sand has the higher percentage of SiO_2 (80%), compared to the quarry sand (66.1%). It was found that large amount of SiO_2 can cause stripping of HMA pavements because silica reduces the bond strength between the aggregate and binder [10]. Quarry sand has the higher total percentage of alumina (Al_2O_3) i.e. 12.6% compared to the mining sand which contains 8.98%. The Al_2O_3 content is related to the hardness of the material, this can be seen from Table V. Quarry sand also has the higher total percentage of hematite (Fe_2O_3) i.e. 5.30% compared to the mining sand which contains 2.2% of the hematite. The Fe_2O_3 content which has the smallest particle size compared to the other elements as shown in Table V increases the density of the bituminous mixture. The oil absorption property is needed to absorb the extensive oils in the bituminous mixture; this property could decrease the pavement distress behavior [12]. Al_2O_3 also has the highest oils absorption value (25-225 g/100g) followed by Fe_2O_3 and SiO_2 respectively. This indicates that quarry sand showed the highest ability to absorb the extensive oils in bituminous mixture, because it has got higher Al_2O_3 and Fe_2O_3 whilst mining sand exhibited the lower ability to absorb the extensive oils in bituminous mixture.

TABLE IV
CHEMICAL COMPOSITION RESULTS FOR FINE AGGREGATE

Fine aggregate type	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	K_2O (%)	Na_2O (%)
Quarry sand	7.19	66.1	12.6	5.30	10.5	1.95
Mining sand	3.6	80.0	8.98	2.2	2.2	0

TABLE V
CHARACTERISTICS OF COMPOUNDS [13]

Components	Solubility in Water	Hardness (Mohr)	Particle Size (µm)	Oil Absorption (g/100g)
CaO	Hydrophilic	-	-	-
SiO_2	Hydrophobic	7	2-19	17-20
Al_2O_3	Hydrophobic	9	0.8-10	25-225
Fe_2O_3	Hydrophobic	3.8-5.1	0.0130-105	10-35
K_2O	Hydrophilic	-	-	-

C. Mechanical Property

The mechanical Property of sand can be determined by using shear box test. The angle of internal friction (Ø) is an indication of particle interlocking and hence particle shape and surface texture. The direct shear test results in Fig. 1 showed that quarry sand has the higher Ø value (45^0) compare to the mining sand (34.9^0). It was found that rounded smooth textured aggregate particles tend to slide past one another producing a HMA mixture with relatively low shear strength [14]. These results explain why crushed aggregate like quarry sand has higher shear resistance compared to natural aggregate samples (mining sand). Because natural sand have more rounded particles with smooth surface textured resulting in less interlock between particles [7]. The high shear resistance is an indicator of resistance to mixture deformation or distress [14], [15]. Study confirmed that the higher internal friction angle of fine aggregate indicates better interlocking mechanism results in a more resistant granular structure [7].

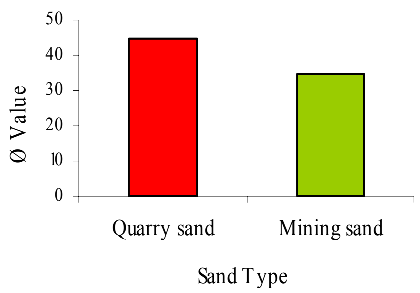


Fig. 1 Ø Values for different types of sand

D. Marshall Test

Marshall Test determination of optimum asphalt content by weight of total mix is done by using Marshall Mix design method [16]. The procedure involves 75 blows per face; three specimens of each asphalt cement contents (3.5 %, 4.0%, 4.5%, 5.0%, 5.5%, 6.0%, 6.5%, and 7%) are prepared. A total of 288 specimens have been tested with the stability, flow, air voids, unit weight, voids filled binder and voids in mineral aggregate [11], [17].

The optimum binder content is calculated as the average of asphalt contents that meet the maximum stability, maximum unit weight, minimum voids in mineral aggregate and 5.0% air voids. The results of optimum bitumen content (OBC) are tabulated in Table VI. It can be seen that mining sand has higher OBC compared to the quarry sand, this is because of the higher surface area of the mining sand which need higher amount of binder to cover the particles.

TABLE VI
OBC (%) FOR ALL TYPES OF BINDER & SANDS

Type of binder	Quarry sand	Mining sand
PM1_82	4.19	6.33
PM1_76	4.53	6.06
PM2_82	4.48	6.40
PM2_76	4.69	6.61
PEN 50/60	4.59	5.86
PEN 80/100	4.80	6.14

E. Beam Fatigue Test

The name of "fatigue" is based on the concept that a material becomes "tired" and fails at a stress level below the nominal strength of the material. Dynamic bending is the test used to assess the fatigue life on bituminous mix specimens [5].

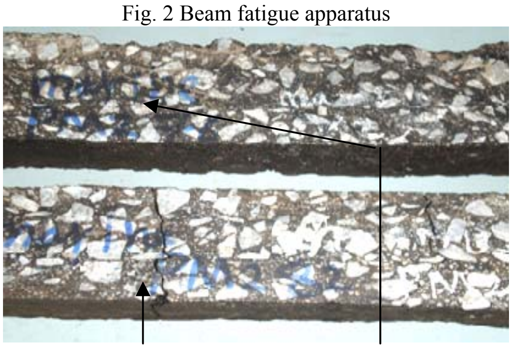
Rectangular specimens were prepared using rectangular metal mould. The mass of material used in the mixture is approximately 7700 g with a dimension of 100 mm x 100 mm x 500 mm. The materials used involving coarse aggregate, fine aggregate and filler were heated and mixed with bitumen at the optimum binder content at 160 ^{0}C using the electronic mixer. Grease was applied on the inside of the rectangular metal mould before the mixture was poured, for easy removal of the solidified specimen. The specimen was then compacted in two layers using the electric hand compactor. An electronic cutter was used to cut the sample into two specimens with the dimension of approximately 50 mm x 65 mm x 380 mm. Two specimens were prepared for each mixture variation (type of binder vs. type of sand).

Fatigue test was performed using the MATTA apparatus. All the specimens were kept at 20^0C for 2 hours before testing. The test temperature 20^0C was chosen since the effect of air void content on fatigue life is more pronounced than at lower temperatures [18].

The beam fatigue test was conducted by applying a repeated flexural bending to a bituminous beam specimen in control strain mode. A thin pavement with thickness of less than 60 mm is suggested for use in the control strain mode because failure will be more noticeable in this mode [19]. The applied force and the resulting beam deflection were measured using an on-specimen Linear Variable Displacement Transducers (LVDTs). The number of load repetitions at which the current stiffness decreases to 50% of the initial value is defined as the fatigue life of the specimen.

Fig. 2 shows the beam fatigue apparatus and Fig. 3 shows the different cracks on the bituminous specimens after the test performed.

Fig. 2 Beam fatigue apparatus



Heavy crakes Light crakes

Fig. 3 Different cracks on different tested specimens

The parameters used in beam fatigue test were as follows:

1) Default Poisson ratio: 0.4
2) Loading conditions:
   - Control mode: sinusoidal strain
   - Pulse width: 200 ms
   - Frequency: 5 Hz
   - Peak to peak: 100 micro strain
   - Conditioning: 50 cycles
3) Termination conditions:
   - Termination stiffness: 50% of the initial stiffness or
   - Stop test after 1,000,000 cycles

The tabulated test data of the load and deformation were updated every 10th cycle by the corresponding UTM 4-21 software of the apparatus.

III. Results And Discussion

Fatigue cracking is one of the primary damage mechanisms of structural components. It results from cyclic stresses that are below the ultimate tensile stress, or even the yield stress of the material. Any weak spot due to nonuniform materials properties will show up in the test results due to the existence of a constant bending movement over the middle third of the specimen [20]. By using beam fatigue test the failure can initiate in an area of uniform stress between the two centers loads [21]. Besides that, this method of loading is also said to be more sensitive to mixture variables such as binder type and aggregate grading. A total of 24 beams with 12 different combinations of mixes were tested using the Universal testing machine with 3 points loading method, under the constant strain loading to determine the bituminous mixture fatigue properties. The results of the beam fatigue test are presented in Table VII, which are expressed as the numbers of loading cycles required to initiate a fatigue crack as a function of both the constant load applied to the beam and the maximum initial tensile bending stress. In a plot relating tensile stress and number of cycles, a linear part of the curve which represents an initial period of large stress and a part of it represents a constant rate of stress amplitude were extrapolated. The stress value corresponding to the intersection point (×) of these two extrapolations is defined as the initial stress. The same principle was applied in determining the number of cycles to failure. Fig. 4 represents the procedure adopted to determine the initial stress and the number of cycles to failure on each beam.

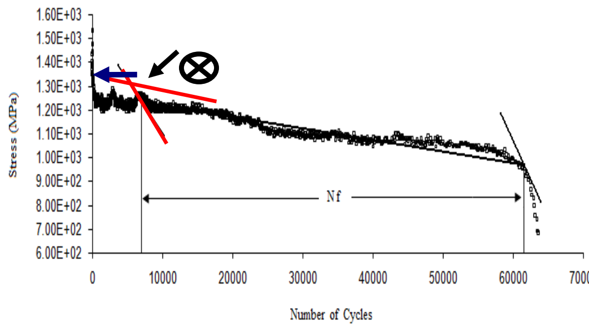


Fig. 4 Determination of initial stress and number of cycles to failure

In this study, the beam fatigue test results were analyzed based on the number of cycles (fatigue life) for binder and fine aggregate mixtures. From Table VII, it can be noted that the control mixtures consisting of the two types of sand with bitumen grade 80/100 are observed to have higher fatigue life (cycles) compared to the bitumen grade 50/60 mixtures. This demonstrates that bitumen grade 80/100 mixtures have a better fatigue resistance than bitumen grade 50/60 mixtures. The soft or low consistency bitumen (flexible binder) tends to absorb stress better than hard binder and relatively it shows

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much better fatigue resistant than the harder bitumen. This result is consistent with the physical properties results where the bitumen grade 80/100 has lower consistency (softer binder) than bitumen grade 50/60.

For the modified mixtures, PM1 has higher fatigue life (cycles) compared to PM2. This means PM1 mixtures have better fatigue resistance than PM2 mixtures. The reason behind that is the use of SBS polymer in PM1 which improved the flexibility of the binder at low temperature which lead to an increase resistance to the asphalt cracking at low temperature [2]. That means PM1 is more elastic and flexible than PM2, even though this result is not consistent with the physical properties results, where PM2 has lower consistency than PM1, but the presence of SBS in PM1 has given the binder more flexibility that contributes to improved resistance to fatigue cracking better than PM2 [11].

PM1_76 mixtures can resist fatigue cracking better than PM1_82 mixtures, because the PM1_76 mixtures have higher fatigue life compared to PM1_82 mixtures for the two type of sand. This result is consistent with the physical properties results where the PM1_76 has been found to have lower consistency (softer) than PM1_82. The same trend was observed for PM2_76 & PM2_82. This indicates that PM2_76 mixtures have longer fatigue life compared to PM2_82 mixtures. PM1_76 has the best fatigue resistance, followed by PM1_82, PM2_76, PM2_82, PEN 80/100 and PEN 50/60 respectively. An analysis of the results show that polymer modified mixtures has relatively longer fatigue life when compared to unmodified mixtures.

Based on the types of sand; quarry sand mixtures have the higher fatigue life compared to the mining sand mixture except with PM2_76 and PM2_82. This is due to the angularity of the quarry sand particles which provides a better interlocking property, as suggested in [9]. The rougher surface provides a greater bonding strength between the aggregate and binder, this leads to improve the frictional resistance between particles.

The distribution of large and small particles (gradation) varies from quarry sand to the mining sand as a result; the relative size of large and small particle in quarry sand is higher than in mining sand. The larger particles resist compressive stress better than the smaller particles. From the shear box test, mining sand which has smaller round particle showed the lower strength which result in lower fatigue life. Therefore the strength of material is the one possible way to resist the cracking. This agrees with an earlier study as in [22].

The aggregate gradation has important effects on the distress resistance [8]. Therefore to get better resistance to fatigue deformation good distribution of particles is required. This is because inhomogeneous distribution (like maximum aggregate size with smaller fines size) reduces adhesion by fines leading to less fatigue resistant. These incompatible materials form poor bonding that results in low crack resistance [10], [23].

This study also investigates the gradation or size distribution of sand type. The good shape, size, strength, and distribution of the particles could give better fatigue resistance as found in quarry sand.

TABLE VII
FATIGUE LIFE OF BINDERS AND FINE AGGREGATE MIXTURES VARIATIONS

Mixture Variations(Sand & binder)	Initial Stress (kPa)	Fatigue Life (No of cycle)
Quarry/PM1_76	3.08E+02	437610
Quarry/PM1_82	4.70E+02	328400
Quarry/PM2_76	8.80E+02	91580
Quarry/PM2_82	1.55E+03	73400
Quarry/PEN80/100	1.26E+03	88000
Quarry/PEN50/60	1.31E+03	51130
Mining/PM1_76	1.29E+03	122310
Mining/PM1_82	1.26E+03	111230
Mining/PM2_76	4.03E+02	104020
Mining/PM2_82	1.04E+03	100070
Mining/PEN80/100	8.36E+02	38930
Mining/PEN50/60	1.68E+03	11970

IV. Conclusion

Based on the experimental results the following conclusions can be drawn:

- The penetration and softening point results have demonstrated that the use of polymer modifier increased the stiffness of the binder at high pavement service temperature. This has the potential to improve the deformation resistance of the polymer modified bituminous mixture. At the same time, the stiffness of the binder at low pavement service temperatures is expected to decrease therefore reducing the mix potential to brittleness and cracking.
- A PM1 mixture, which consists of SBS polymer as a modifier, has better resistance to fatigue cracking compared to the PM2 mixtures. This is because SBS polymer is elastic in nature lead to increase the binder elasticity at high temperature and improves the flexibility at low temperature.
- The bituminous mixtures using bitumen PEN 80/100 has a better resistance to fatigue cracking compared to the bitumen PEN 50/60, because soft binder is more elastic and is better for absorption the stress compared to the hard binder.
- In general the quarry sand incorporated bituminous mixtures give a better fatigue performance. This is may be due to the effect of sand properties such as angularity, surface texture, shear strength, particle size and distribution and the content of alumina and hematite.
- The results obtained from beam fatigue test provide an insight view that physical, chemical and mechanical properties of fine aggregate could improve the mixture fatigue performance.

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