Effects of fillers and fine aggregates on the shear strength of fine aggregate matrix in hot mix asphalt

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Abstract: Fine aggregate matrix (FAM) or asphalt mortar consists of fine aggregate (d≤2.36mm), mineral filler and binder while mastic asphalt includes only mineral filler and binder. Both have been considered as a major component that impact mostly to mechanical behavior in general as well as shear strength of the hot asphalt mixtures in particular operation conditions. The paper introduces testing results of a major physical characteristic of mastic asphalt – softening point using Ring & Ball test and the one of mechanical property of shearing strength of FAM using triaxial compression test on the mixture with different types of mineral filler and fine aggregate. The results show impacts of the type of the filler on the softening point of mastic asphalt and impact of type of filler and fine aggregate on the shear strength of FAM.

Keywords: Fine Aggregate Matrix (FAM), Hot Mix Asphalt, Shear Strength, Filler, Fine Aggregate

1. INTRODUCTION

Hot mix asphalt (HMA) consists of coarse aggregates, fine aggregates, mineral filler and bitumen. The performances of hot mix asphalt depend on the properties of material constituents, volumetric of each fraction and their interaction. In another approach, HMA can be included by two basic components of coarse aggregate skeleton (d≥2.36 mm) and fine aggregate matrix (FAM) or asphalt mortar (Figure 1). FAM contains fine aggregates passing sieve No. 8 (mesh size of 2.36 mm), mineral filler and bitumen (Brown *et al.*, 1996) and plays a substantial role on the performance characteristics of asphalt mixtures. FAM performance considerably affects the mechanical characteristics of the entire asphalt concrete mixture especially the shear strength (Muraya, 2007; Underwood, 2015).

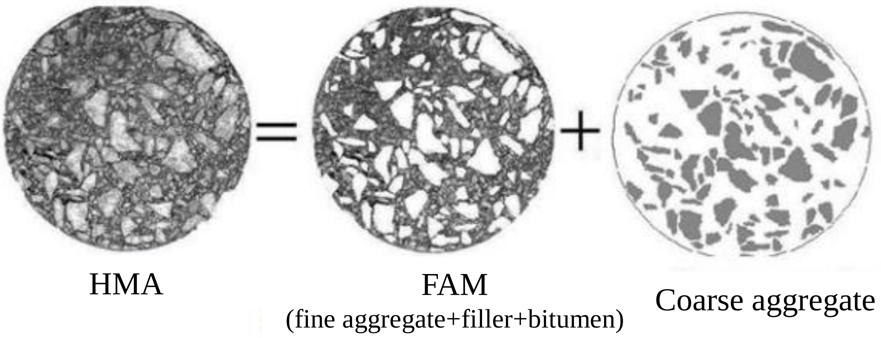


Figure 1. HMA and FAM illustrations

The FAM phase is important because it is one length scale below the hot mix asphalt and one phase closer to the location where most of the damage within the asphalt concrete structure occurs. Recently many researchers have studied about the properties of FAM and its relationships with HMA. Underwood and Kim (2013) investigated how changes in asphalt and air void content affect the dynamic shear modulus, |G*|, and tensile properties (strength and strain at failure) of FAM, and how FAM and AC mixture behaviors are related through analytical micromechanical modeling for |G*| and through correlation for damaged properties. The conclusions regarding fabrication of FAM for the purposes of experiment: when used as qualitative screening or in comparative studies it is not necessary to replicate FAM exactly as it exists in the mixture as long as consistent rules are followed in fabricating each study material, but when used for quantitative analysis and/or modeling purposes one must carefully consider the composition of the FAM as it exists within the asphalt concrete mixture. Im *et al.* (2014) characterized mode-I and mode-II fracture properties of a FAM mixture by using experimental and numerical efforts. The semicircular bending tests integrated with a digital image correlation system and extended finite element method were used in this study. Gudipudi and Underwood (2015) compared axial dynamic modulus and fatigue of FAM and asphalt concrete mixture and evaluated the mechanical linkages between the FAM and asphalt concrete mix by applying analytical upscaling methods with gross homogenization principles. Conclusion from this study is that the FAM scale may be accounting for most of the physicochemical interaction and aggregate stiffening, at least with respect to loads used to measure |E*| and in fatigue response. The upscaling of asphalt concrete modulus predictions showed an average of 10% variation from measured data, and damage response predictions using FAM properties show the variability that is normally seen in mixture tests with respect to fatigue prediction.

The shear strength is an important mechanical property of FAM and HMA. The shear strength of FAM depends on the type of the filler and the fine aggregate as well as binder types and binder content. The objective of this study is to determine the type the fillers and the fine aggregates that can create FAM with the high shear strength. To achieve this goal, the study was conducted in two stages. The first stage investigated softening point of bitumen and mastic asphalt using Ring and Ball test to find two fillers that have the highest delta of softening temperature between the mastic and the bitumen (within the permission range). These fillers are considered to be capable of producing FAM and HMA with the high shear strength. These fillers would be used to fabricate FAM in the second stage. The second stage investigated the shear strength of FAM made of different mineral fillers and fine aggregates using triaxial compression testing.

2. TEST PLAN

2.1 Materials

Experiment materials are popular materials used for HMA in the North of Vietnam:

1) Fine aggregate: Manufactured sand from Thong Nhat quarry, Hai Duong province; natural sand from Lo river – Viet Tri district – Phu Tho province. Fine aggregate angularity of manufactured sand and natural sand is 50.78 %, 44.29 % respectively (test method according to TCVN 8860-7:2011).
2) Mineral filler: Limestone dust (Hong Lac Company – Hai Duong province).
3) Hydrated lime: or calcium hydroxide ($Ca(OH)_2$) is produced by treating lime (CaO) with water (H_2O), wet sieving uses 0.075 mm sieve then drying in oven at 110±5^{o}C.
4) Cement: But Son cement – BCP30
5) Bitumen: Bitumen 60/70 from Petrolimex

2.2 Test plan

Testing plan has been developed with 2 stages. The first stage focuses on mastic asphalt which consist of 40% bitumen and 60% mineral filler by weight. A physical property of softening point of mastic are used for evaluating different types of filler to meeting with technical specification of filler for HMA in the Table III-2 in the Specification for HMA follows Vietnam 22TCN249-98 (the delta of softening temperature between the mastic and the bitumen within 10ºC to 20ºC). Different type of filler and number of specimens are in Table 1.

Table 1.Test plan for softening point of mastic asphalt

No	Mastic asphalt type	Number of specimens
1	Bitumen 60/70	2
2	Bitumen + Limestone dust	2
3	Bitumen + Cement	2
4	Bitumen + Filler (10% HL +90% LD)	2
5	Bitumen + Filler (20% HL +80% LD)	2
6	Bitumen + Filler (30% HL +70% LD)	2
7	Bitumen + Filler (40% HL +60% LD)	2
	Total number of specimens	14

Note : LD : Limestone Dust HL: Hydrated Lime

The second stage focuses on the shear strength of FAM determined by triaxial compression test. FAM specimens were fabricated from a bitumen 60/70, 2 fine aggregates (manufactured sand and natural sand), 3 mineral fillers including limestone dust and 2 fillers that could make the bitumen highest stiffness in the first stage. The detail of FAM type and number of specimens are presented in Table 2.

Table 2. Test plan for the shear strength of FAM specimens

FAM type		Number of specimens
Manufactured sand	Limestone dust	2x3=6
	MF 2	2x3=6
	MF 3	2x3=6
Natural sand	Limestone dust	2x3=6
	MF 2	2x3=6
	MF 3	2x3=6
Total number of specimens		36

Note: LD : Limestone Dust

MF2, MF3: 2 mineral fillers that could make the bitumen highest stiffness in the first stage

2.3 FAM Mix Design and prepare specimens

Ignoring the differences of bitumen absorption of fine aggregates and fillers, all FAM specimens were prepared with the same asphalt content. The aggregate gradation and the asphalt content of FAM was determined based on the mix design of a HMA 12.5 that was composed of the manufactured sand and the limestone dust. The HMA 12.5 was designed by the Marshall method and suitable to Vietnam specification for HMA (Decision

858/QĐ-BGTVT of Ministry of Transport of Vietnam). The aggregate gradation of the HMA 12.5 is presented in Table 3. The optimum bitumen content of HMA 12.5 was 4.6 % by weight and the absorbed bitumen content is 0.26 %. FAM specimens were produced from aggregates that pass sieve size 2.36 mm and the bitumen content was calculated by followed formula (Branco, 2008):

Bitumen content of FAM = Optimum bitumen content – (Absorbed bitumen content of coarse aggregate + Bitumen content bound on surface of coarse aggregate) (1)

Where:
Optimum bitumen content = 4.6 %;
Absorbed bitumen content of coarse aggregate=(Percentage of coarse aggregate)*(Absorbed bitumen content) = 72 % x 0.26 % = 0.187 %;
Bitumen content bound on surface of coarse aggregate = (Effective bitumen content)*(Percentage of aggregate specific surface of coarse aggregate) = (4.6 % - 0.26%) x 4.484% = 0.195 %.
Bitumen content of FAM = 4.6 – 0.187 – 0.195 ≈ 4.22 %.

The bitumen content of FAM was 4.22 % by total weight of HMA 12.5. Therefore, we could determine the bitumen content of FAM of 13.6 % by total weight of FAM. The aggregate gradation of FAM is presented in Table 3.

Table 3. The aggregate gradation of the HMA 12.5 and FAM

Sieve size (mm)	Aggregate (% Passing)			
	Decision 858		HMA 12.5	FAM
	Min	Max		
19	100	100	100.00	-
12.5	74	90	85.04	-
9.5	60	80	66.55	-
4.75	34	62	43.97	-
2.36	20	48	28.00	100.00
1.18	13	36	18.14	64.79
0.6	9	26	12.61	45.04
0.3	7	18	9.21	32.89
0.15	5	14	8.00	28.57
0.075	4	8	7.42	26.50

Prepare FAM specimens

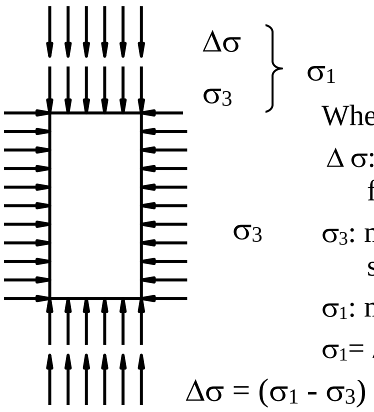
- The fine aggregates and fillers were sieved to separate size fractions of less than 0.075mm; from 0.075 to 0.15 mm, …, from 1.18 to 2.36 mm;
- Dry separately each size fraction in an oven at 110 ± 5°C to constant weight.
- Weight the separate size fraction according to the calculated rate (as in Table 3)
- Heat the fine aggregate and the filler to 170-180°C, the bitumen to 150-160°C and the mold to 105±5°C.
- Mix the FAM mixture of fine aggregate, filler and bitumen in 4 minutes. Put FAM mixture to the oven at 140-145°C in 30 minutes.
- Drop mixed FAM to the mold, tamp FAM with steel rod and tap around the mold by a small hammer.
- Cure FAM specimens in 12 hours.

Figure 2. FAM specimens for triaxial test

2.4 Determine the shear strength of FAM by the triaxial test

Cohesion (c) and internal friction angle (φ) of FAM specimens were determined using triaxial compression test. Cylinder specimens of FAM (height * diameter = 100 mm * 50 mm) (TCVN 8868:2011) were cured in environment tank at the given temperature for 3 hours before doing the triaxial test. Vertical loading rate was 0.05 mm/mm per minute (equivalent to 5 mm/min with specimen height of 100 mm) (T 0718 – 2011). The triaxial tests were conducted respectively at three levels of confining pressure of 0 kPa, 138 kPa, 276 kPa (Jun *et al*., 2009; T 0718 – 2011) at the given temperature. Data collected during the test were vertical stress, vertical strain, confining pressure and temperature. The apparatus and the stress state of specimen under triaxial test are shown in Figure 3a and 3b (Mulusa, 2009).

Figure 3a. Triaxial apparatus



Where,

$\Delta\sigma$: deviator stress (applied stress at failure)

σ_3: minor principal stress (confining stress)

σ_1: major principal stress

$\sigma_1 = \Delta\sigma + \sigma_3$

Figure 3b. The stress state in the triaxial test

The major principal stress (σ_1) and applied stress ($\Delta\sigma$) at failure are calculated by equation (2) and (3):

$$\sigma_1 = \Delta\sigma + \sigma_3 \qquad (2)$$

$$\Delta\sigma = \frac{P(1-\varepsilon)}{A_0} \times 10 \qquad (3)$$

Where, ε : vertical strain $\varepsilon = \Delta h / h_0$

A_0 : intersection area of the original specimen, cm^2;

Δh: vertical displacement of the specimen at failure, mm;

h_0 : height of the original specimen, mm.

Plot the Mohr circles and the Mohr-Coulomb failure envelope as shown in Figure 4 (Mulusa, 2009). Note from the Figure 4 that:

- The centre of Mohr circle must be on the abscissa and is given by (σ_1 + σ_3)/2;
- The radius of such circle is (σ_1 - σ_3)/2;
- Angle of internal friction is the angle of the Mohr-Coulomb failure envelope (failure line); and
- The failure line intersects with ordinate at the cohesion value

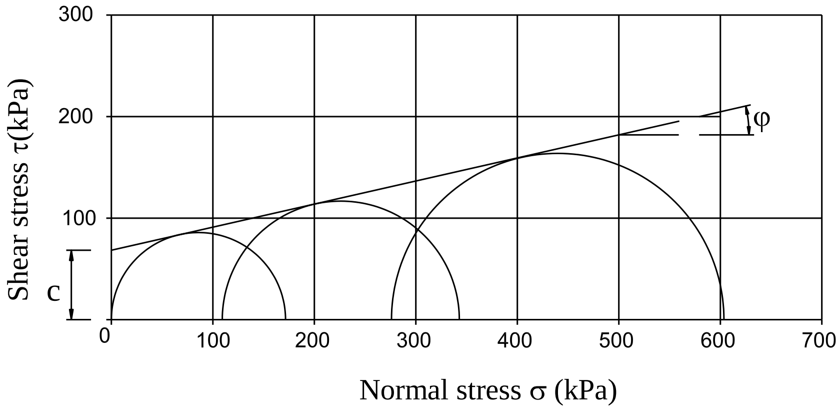


Figure 4. Mohr circles and Mohr-Coulomb failure envelope

Another way, the cohesion, the internal friction angle and the correlation coefficient can be calculated using the equations from (4) to (8) (T 0718 – 2011). The correlation coefficient r should be greater than 0.99.

$$\varphi = \arcsin m \tag{4}$$

$$c = \frac{b}{\cos\varphi} \tag{5}$$

$$m = \frac{\sum(p_i \times q_i) - \frac{1}{n}\times(\sum p_i)\times(\sum q_i)}{\sum(p_i)^2 - \frac{1}{n}\times(\sum p_i)^2} \tag{6}$$

$$b = \frac{1}{n}\times\sum q_i - \frac{m}{n}\times\sum p_i \tag{7}$$

$$r = \frac{\sum(p_i \times q_i) - \frac{1}{n}\times(\sum p_i)\times(\sum q_i)}{\sqrt{[\sum(p_i)^2 - \frac{1}{n}\times(\sum p_i)^2]\times[\sum(q_i)^2 - \frac{1}{n}\times(\sum q_i)^2]}} \tag{8}$$

Where,

p_i = (σ_{1i} + σ_{3i})/2 q_i = (σ_{1i} - σ_{3i})/2

n : number of levels of the confining pressure (n=3 in this study)

3. RESULTS AND DISCUSSION

3.1 The softening point of the bitumen and the mastic asphalt.

Experiment results for the softening point of the bitumen and the mastic asphalt are shown in Table 4 and Figure 5. Some pictures of the ring and ball test for softening point of the bitumen and the mastic asphalt are shown in Figure 6.

Table 4. Softening point of bitumen and mastic asphalt

Mastic asphalt type	Softening point (ºC)		
	Specimen No 1	Specimen No 2	Average
Bitumen 60/70	47,2	47,4	47,3
Bitumen+Limestone dust	59,4	60,2	59,8
Bitumen + Cement	59,2	62,4	60,8
Bitumen + Filler (10%HL+90%LD)	59,2	60,4	59,8
Bitumen + Filler (20%HL+80%LD)	64,6	64,6	64,6
Bitumen + Filler (30%HL+70%LD)	67,0	67,4	67,2
Bitumen+ Filler (40%HL+60%LD)	The mastic asphalt was too dry to mix		

Note : *LD : Limestone Dust* *HL : Hydrated Lime*

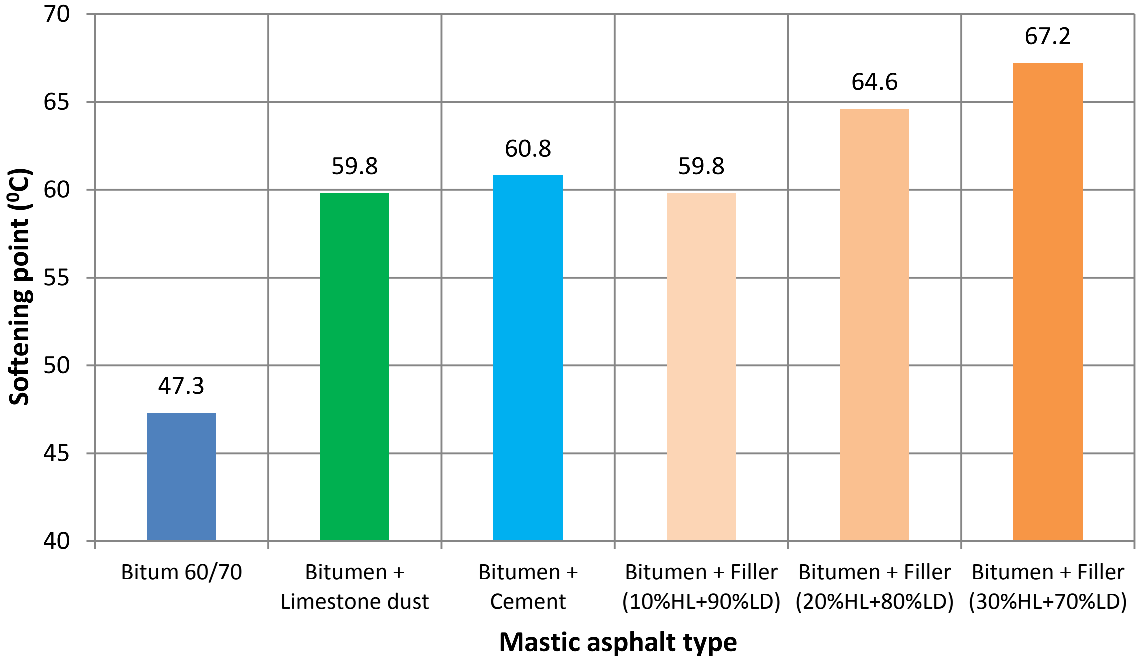


Figure 5. The softening point of the bitumen and the mastic asphalt types

Discussion:

- The delta of the softening temperature of all mastic asphalt types and the bitumen were in a range from 10ºC to 20ºC. Therefore, these fillers satisfy the recommendation for fillers using in the HMA according to 22TCN249-98 HMA specifications in Vietnam.
- The softening temperatures of the mastic asphalt types using the cement and the filler (10% HL + 90% LD) were almost the same softening temperature of the mastic asphalt using the limestone dust.
- The softening temperatures of the mastic asphalt types using the filler (20% HL + 80% LD) and the filler (30% HL + 70% LD) significantly increased compared to the softening point of the mastic using 100% limestone dust of 8.03% and 12.37% respectively. These two fillers should be used for FAM used in the second stage of testing plan with the expectation of these FAM would have the high shear strength.

Figure 6. The ring and ball test for softening point of the bitumen and the mastic asphalt

3.2. Triaxial test result of FAM

The triaxial compression test for shear strength of FAM was carried out at 30^{o}C. The internal friction angle and cohesion of FAM at 30^{o}C are shown in Figure 7 and Figure 8 respectively. Figure 9 provides some pictures of triaxial testing for FAM specimens. Details of testing data are presented in Table 5

Some conclusions were withdrawn from triaxial testing results:

- The internal friction angle of the FAM mainly depends on the type of fine aggregate and hardly depends on the type of mineral filler. Internal friction angles of FAM using manufactured sand are higher about 45 % than the one using natural sand in all three types of filler. It can be due to the angularity of the manufactured sand (50.78%) is higher than that of the natural sand (44.28%).
- The cohesion of the FAM depends on both type of fillers and the type of fine aggregates. When using the limestone dust as filler, the cohesion of the FAM specimens using the manufactured sand was significantly higher than that of the FAM specimens using the natural sand (20.20%). However, when using the hydrated lime as a part of filler (20% and 30% total weight of aggregate particles pass 0.075 mm sieve size), the cohesion of the FAM specimens using the manufactured sand or natural sand was almost similar. It is due to the hydrated lime improves the adhesion between the bitumen and the natural sand more than the bitumen and the manufactured sand.

Table 5: Triaxial test result of the FAM specimens

Mastic asphalt type		Specimen No.	σ_3 (kPa)	$\Delta\sigma$ (kPa)	σ_1 (kPa)	φ (^{0})	c (kPa)	r
Manufactured sand	LD (1)	BT11.1	0	325.41	325.41	26.48	107.74	0.9931
		BT11.2	138	624.46	762.46			
		BT11.3	276	760.64	1,036.64			
	LD (2)	BT21.1	0	329.42	329.42	26.78	108.40	0.9933
		BT21.2	138	633.13	771.13			
		BT21.3	276	772.96	1,048.96			
	Average					26.63	108.07	
	Filler (20% HL + 80% LD) (1)	BT12.1	0	363.69	363.69	26.74	117.41	0.9964
		BT12.2	138	647.01	785.01			
		BT12.3	276	810.48	1,086.48			
	Filler (20% HL + 80% LD) (2)	BT22.1	0	360.30	360.30	26.95	117.43	0.9937
		BT22.2	138	665.44	803.44			
		BT22.3	276	809.10	1,085.10			
	Average					26.85	117.42	
	Filler (30% HL + 70% LD) (1)	BT13.1	0	417.12	417.12	26.65	122.99	0.9974
		BT13.2	138	589.63	727.63			
		BT13.3	276	862.76	1,138.76			
	Filler (30% HL + 70% LD) (2)	BT23.1	0	391.78	391.78	26.46	120.22	0.9999
		BT23.2	138	603.20	741.20			
		BT23.3	276	835.29	1,111.29			
	Average					26.56	121.60	
Natural sand	LD (1)	BT14.1	0	251.38	251.38	18.36	91.88	0.9995
		BT14.2	138	388.12	526.12			
		BT14.3	276	505.02	781.02			
	LD (2)	BT24.1	0	234.88	234.88	18.50	87.93	0.9956
		BT24.2	138	392.84	530.84			
		BT24.3	276	489.83	765.83			
	Average					18.43	89.91	
	Filler (20% HL + 80% LD) (1)	BT15.1	0	320.65	320.65	18.59	115.68	0.9999
		BT15.2	138	453.74	591.74			
		BT15.3	276	579.04	855.04			
	Filler (20% HL + 80% LD) (2)	BT25.1	0	310.51	310.51	18.89	115.40	0.9926
		BT25.2	138	482.55	620.55			
		BT25.3	276	571.90	847.90			
	Average					18.74	115.54	
	Filler (30% HL + 70% LD) (1)	BT16.1	0	320.05	320.05	18.28	118.93	0.9958
		BT16.2	13	474.68	612.68			
		BT16.3	276	570.91	846.91			
	Filler (30% HL + 70% LD) (2)	BT26.1	0	331.92	331.92	18.57	122.12	0.9971
		BT26.2	138	485.17	623.17			
		BT26.3	276	588.76	864.76			
			Average			18.42	120.53	

Note: LD : Limestone Dust HL Hydrated Lime

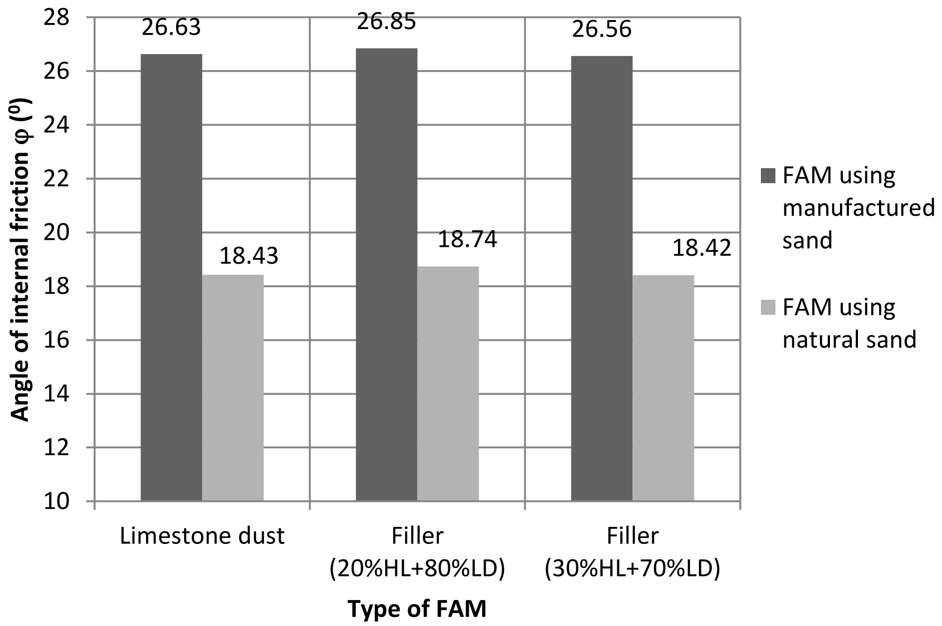


Figure 7. The internal friction angle of FAM at 30ºC

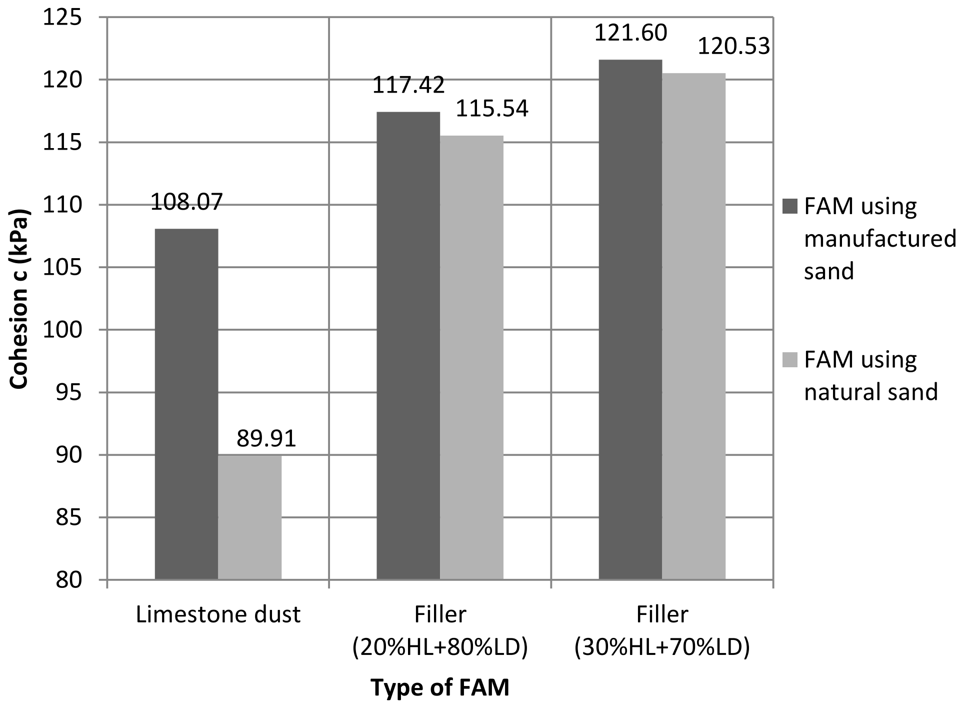


Figure 8. Cohesion of FAM at 30ºC

Figure 9. Triaxial test for FAM

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

- The softening temperature of the mastic asphalt using the cement was hardly higher than that of the mastic asphalt using the limestone dust. In other words, the ability of increasing the bitumen stiffness of the cement and the limestone dust was almost similar.
- The softening temperature of the mastic asphalt has a relationship with the cohesion of the FAM. The higher softening temperature the mastic asphalt has the higher cohesion the FAM has.
- The softening point of the mastic asphalt and the cohesion of the FAM using the hydrated lime replacing a suitable percentage of the limestone dust (20% and 30% in this research) are higher significantly than that of the mastic asphalt and the FAM using 100% limestone dust.
- The internal friction angle of the FAM mainly depends on the type of fine aggregate. The internal friction angles of the FAM using manufactured sand are higher significantly than that of FAM using natural sand.

Recommendations:

- The bitumen content was used in this study may be not as correct as the FAM content in HMA. Research of optimum bitumen content for FAM and FAM specimen preparation should be focused in the coming time for further research on impacts of FAM properties on HMA performance.

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