THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

ISSN 1822-427X print / ISSN 1822-4288 online
2014 Volume 9(3): 191–199

MECHANICAL PROPERTIES OF CEMENT-BITUMEN COMPOSITES FOR SEMI-FLEXIBLE PAVEMENT SURFACING

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Abstract. Semi-flexible pavement surfacing is a composite pavement that utilizes the porous pavement structure of the flexible bituminous pavement, which is grouted with an appropriate cementitious material. The main objective of this study is to investigate the mechanical properties of cement-bitumen composites as an alternative semi-flexible pavement surfacing material. This involves the selection of acceptable proportions of cementitious grouts as well as the development of cement-bitumen composites. The findings showed that by replacing 5% of the cement with silica fume (with adequate amount of superplasticizer) there is improvement in compressive strength and tensile stiffness modulus. In addition, resistance to abrasion is improved.

Keywords: cementitious grouts, superplasticizer, open-graded asphalt skeletons, cement-bitumen composites, workability, compressive strength, semi-flexible pavement.

1. Introduction

Road pavement plays an important role in the development of rural and urban area. It is essential as a link to new places for the purpose of trade and economic activities. The purpose of road pavement is to carry traffic safely, conveniently and economically over its design life by protecting subgrade from the effects of traffic and climate by ensuring that no materials used in the pavement suffer any unacceptable deterioration (Wright, Paquette 1979). Road pavements are generally grouped into two types as flexible and rigid pavement. The flexible pavement is defined as a pavement with a bituminous surfacing and with a base layer with or without a hydrocarbon binder in *PIARC Road Dictionary of World Road Association,* 2011. The rigid pavement is defined as a pavement substantially constructed of cement concrete in *PIARC Road Dictionary*. In short, flexible pavement contains aggregates bound by bituminous binders while rigid pavement comprises a variety of cement concrete types with or without reinforcements.

In Malaysia, the choice of road surfacing is normally a conventional (flexible) pavement whilst the application of concrete (rigid) road pavement is not widely used because of slow setting time during the construction process, poor riding quality, noise problems during usage and higher costs, although they do have longer durability compared to flexible pavement. In addition, due to their viscoelastic nature, asphalt pavements are also sensitive to both loading and temperature. Therefore, the distresses typically seen in asphalt pavements are often attributed to extreme temperatures and loading, or combinations of these two factors (Thodesen *et al.* 2012). The conventional mixes used in flexible pavement tend to exhibit relatively poor resistance to high traffic stresses and are not able to meet the demands of heavy traffic load, which cause deterioration of its structure. Rutting and cracking are the major problems that occur in conventional flexible pavement. This is because of the load bearing and durability problems due to the heavy traffic load and its resistance to diesel spillage issue. Thus, in order to overcome the above weaknesses and improve the performance of pavements, an alternative semi-flexible pavement is proposed.

2. Experiences of using semi-flexible pavement

The principles and applications of semi-flexible pavement have gained acceptance in many European countries since it offers a number of important advantages. For example, the semi-flexible pavement is accessible to the public 6 h to 8 h after the laying process. The fieldwork application is simple, rapid installation and minimum maintenance costs are required for this type of pavement. Therefore, it is a preferable solution due to the low installation costs and shorter construction process compared to conventional pavement. It also offers a solution for pavement area that demands higher strength, durability and

doi:10.3846/bjrbe.2014.24

chemical resistance. Research conducted by Hassan *et al.* (2002) showed that impregnation between selected grout mixtures resulted at higher workability while maintaining higher strength at 28 days. Based on the research findings in Europe, semi-flexible pavements have been utilised in airport areas, industrial applications, ports and at bus terminals. The laid semi-flexible pavements have not demonstrated major deformations and are still in good condition. Road authorities in the US, Germany and Netherlands have applied semi-flexible pavement in their airport areas and ports. This showed that the concept of semi-flexible pavement has already gained acceptance because of its successful applications. In Malaysia, semi-flexible pavement is implemented on public road and heavily trafficked surfaces, located in metropolitan area such as Kuala Lumpur. In addition, semi-flexible pavement was implemented on bus lanes in city area. The Kuala Lumpur City Hall is responsible for maintenance and upgrading projects on road pavement by using semi-flexible pavement materials since 2001. The current design of semi-flexible pavement is the imported cementitious material and modified polymer bitumen. By using these imported materials, the production cost of semi-flexible pavement very much depends on the currency exchange. If the Euro gains the cost of imported raw materials also increases. Thus, in order to avoid this fluctuation in cost, alternative indigenous products are used. By using indigenous materials, the production and maintenance costs will be much lower, economical and competitive than the imported ones. The authors focused on redesigning the existing semi-flexible pavement surfacing to be more applicable to local conditions.

The main objective of this study is to investigate the mechanical properties of cement-bitumen composites as an alternative semi-flexible pavement surfacing material. The study covers two main aspects, which involves binder selection and acceptable cementitious grouts as well as investigating the properties of the cement-bitumen composites.

3. Experimental programme and materials

The first phase in the manufacture of the semi-flexible pavement surfacing is to develop acceptable proportions of cementitious grouts. The second phase is to produce an open-graded asphalt skeleton and finally the production of the cement-bitumen composites. Sufficient and ideal proportions for these three types of specimens are discussed in this section.

3.1. Cementitious grout mixtures

The aim is to produce highly workable grout slurries to penetrate easily into the open-graded asphalt skeletons. Cementitious binders used in this study are Ordinary Portland Cement (OPC), White Cement (WC) and Silica Fume (SF). The specific gravity of OPC was 3.10 and the surface area was 335 m^2/kg. In order to produce sufficient strength and highly workable grout, mineral admixtures of 5% and 10% SF was used as cement replacement. The specific gravity of SF was 2.2 and the surface area was 20 000 m^2/kg. To enhance the workability of the mix, a superplasticizer (SP) (polycarboxylic ether polymer chemical base) was used. This type of superplasticizer (SP) used conformed to *ASTM C494/C494M-13 Standard Specification for Chemical Admixtures for Concrete, Type F-Water-Reducing High Range Admixtures*. The cementitious grout mixtures were design in three main groups, defined as CG1, CG2 and CG3. The first cementitious grout group (CG1) contains 100% OPC, the second cementitious grout group (CG2) contains WC as a replacement to OPC and the third cementitious grout group (CG3) contains 5% and 10% of SF as replacement of OPC. The mix details of cementitious grout mixtures are presented in Table 1.

Table 1. Mix details of cementitious grout mixtures

Cementitious grout design	Percentage of cementitious binder, %			Water/binder ratio	Percentage of superplasticizer (SP), %	Type of superplasticizer (SP)
	OPC	WC	SF			
CG1	100	0	0	0.24, 0.26	0.5, 1.0	Polycarboxylic Ether Polymer
				0.30, 0.32	1.5, 2.0	
				0.34, 0.36	2.5	
				0.40		
CG2	90	10	0	0.28, 0.30	1.5, 2.0, 2.5	Polycarboxylic Ether Polymer
	80	20	0	0.35, 0.40		
	70	30	0			
	60	40	0			
	50	50	0			
	40	60	0			
	30	70	0			
	20	80	0			
	10	90	0			
CG3	95	0	5	0.30, 0.32, 0.35, 0.40, 0.50	1.0, 1.5	Polycarboxylic Ether Polymer
	90	0	10		2.0, 2.5	

Cementitious grouts were produced using a mechanical mixer with varying speed in accordance to the *ASTM C 305–99 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*. A modified method to that practiced by Hassan *et al.* (2002) and as suggested by the supplier of the admixtures was adopted. After mixing, the grout mixtures were placed in 50×50×50 mm moulds for compressive strength test.

3.2. Open-graded asphalt skeleton

Open-graded asphalt skeleton was composed of crushed aggregates (granite), 3.0% filler and 3.62% of 80/100 penetration grade bitumen. The open-graded asphalt skeleton was designed to achieve high void content of 25% to 30% while maintaining a thick binder coating on the aggregates. High percentage of coarse aggregates was used and the amount of compaction was decreased in order to attain high air void content and to ensure there is no unnecessary aggregate crushing. The *Public Works Department, Kuala Lumpur City Hall, Malaysia*, provided the aggregate gradation. Fig. 1 shows the gradation limits for open-graded asphalt mixture. In tropical countries such as Malaysia, where the average monthly precipitation can be as high as 314 mm, (Wong *et al.* 2009) the use of open-graded pavement system can be extremely beneficial (Ibrahim *et al.* 2014).

3.3. Cement-bitumen composites

The cement-bitumen composites were produced by impregnating open-graded asphalt skeletons with selected proportions of cementitious grout mixture. The open-graded asphalt skeletons were weighed in order to determine its porosity or air voids content. After porosity test, the open-graded asphalt skeletons were fixed in the moulds that have been specially fabricated for grouting process. Cement grout is poured onto the surface of the open-graded asphalt skeletons and spread using a rubber applicator. Adequate and constant supply of the cement grout was prepared to ensure that the bituminous matrix (open-graded asphalt skeleton) was completely filled. Wet hessian and polythene plastic sheets were used to cover the freshly prepared cement-bitumen composites for 24 h in a room at 25 °C and 70% relative humidity until testing day. This curing method is adapted from Hassan *et al.* (2002). The cement-bitumen composites were tested at 1 day and 28 days.

3.4. Laboratory testing

The fresh cementitious grouts were tested for density and flow time which were conducted to measure the fluidity of various cementitious grout compositions and to ensure that the grouts have the correct consistency to infiltrate easily into the open-graded asphalt skeletons. The test was carried out in accordance to *ASTM C 939 1997 Test Method of Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)* and Kuala Lumpur City Hall (2003) was adopted in order to examine the workability of cementitious grout mixtures under Malaysian condition. The hardened grout cubes were tested for compressive strength performance at the ages of 1, 3, 7 and 28 days. The compressive strength test was carried out in accordance to *BS 1881: Part 116:1983 Testing Concrete. Method for Determination of Compressive Strength of Concrete Cubes*. The open-graded asphalt skeletons were tested for binder drainage, air void or porosity, compressive strength, indirect tensile stiffness modulus and air abrasion test. The binder drainage test was carried out in order to determine the binder content that an asphalt mixture holds without excessive binder drainage. This test was conducted by following closely the Transportation Research Laboratory (TRL), United Kingdom procedure as described by Daines (1992). The compacted open-graded asphalt skeletons were tested for porosity, bulk density and specific gravity to determine the air void or porosity content. Density and air void analysis was implemented according to the *ASTM D 2726-96a Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures*. The indirect tensile stiffness modulus test was implemented in accordance to *ASTM D4123-82 (Reapproved* (1995*) Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures*. The procedure of compressive strength test for cement-bitumen composites was referred from *Densiphalt Handbook* (2000) and *ASTM C-39-03 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. Instron testing machine with maximum 100 kN capacity was used to investigate the compressive strength of open-graded asphalt skeletons at 1 and 28 days. The measurement of open-graded asphalt skeleton resistance to the particle loss was evaluated by the Cantabro test. The Cantabro test on air cured samples was carried out in the Los Angeles Machine (*ASTM C131-96 Standard Test method for Resistance to Degradation of Small Size Coarse Aggregate by Abrasion and Impact*). In order to investigate the strength and performance properties of the cement-bitumen composites, similar tests were carried out. These tests are air void or porosity test, compressive strength test, indirect tensile stiffness modulus test and abrasion test.

4. Results and discussion of experimental results

The properties of cementitious grout mixtures, open-graded asphalt skeletons and cement-bitumen composites are discussed in this section. The results of the analysis using

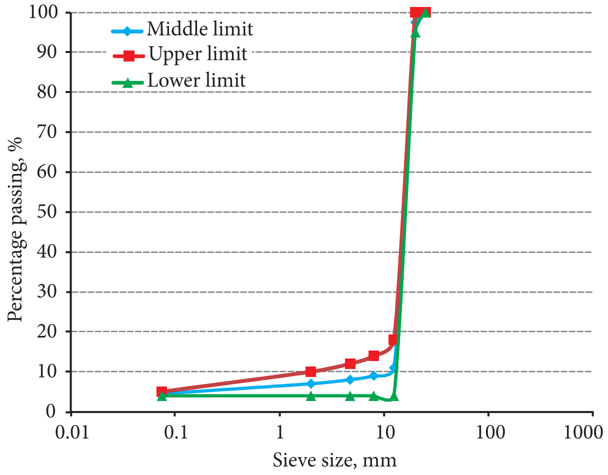

Fig. 1. Open-graded asphalt gradation limits

SPSS statistical software were presented by using paired-sample *t*-test.

4.1. Workability of cementitious grout mixtures

The workability performance was measured through flow time test. From findings, it is found that the workability of cementitious grouts was influenced by various factors such as the water/binder ratio, dosage of SP, type of SP used, different brand of SP, different types of cement and use of supplementary cementitious material. The workability of fresh grouts containing different cementitious materials is presented in Table 2.

There were four main designs discussed in this table, which were 100% OPC mixtures and 5% to 10% SF mixtures. The water/binder ratio for all the designs was 0.30 and the superplasticizer (SP) percentages were 1.5% and 2.0% of the grout content. The type of SP used was polycarboxylic ether polymer.

The main purpose of adding SP into the grout mixture is to enhance the flow ability of the cement slurries. According to Baltazar *et al.* (2012), the fresh grout properties were improved with the use of dispersant additives such as superplasticizers (SP), which cause an important improvement in the grout fluidity and stability through inter-particle repulsive forces. From Table 2, flow ability values for different cementitious grout designs were in the range of 54.0–15.0 s. The results show that the highest flow ability value was 54.0 s produced by cementitious grout mixture containing 100% WC, 0.30 w/c ratio and 1.5% SP. The lowest flow ability value was 15.0 s produced by cementitious grouts mixture containing 95% OPC, 5% SF, 0.30 w/c ratio and 2.0% SP. The increasing trend for workability (flow ability values decreasing) was showed at higher SP percentages. Dosage of SP significantly influences workability, the increase in the amount of SP produce higher workability of the cementitious grout, irrespective of water/binder ratio (Koting *et al.*

Table 2. Workability and compressive strength test results for different cementitious binders

Cementitious grout design	Percentage of cementitious binder, %			Water/binder ratio	Percentage of SP, %	Flow ability, s	Compressive strength, N/mm^2	
	OPC	WC	SF				1 day	28 days
CG1	100	0	0	0.30	1.5	23.4	57.6	85.5
					2.0	19.3	59.3	87.2
CG2a	95	5	0	0.30	1.5	17.2	48.2	76.4
	90	10	0			19.4	51.3	78.5
	80	20	0			21.0	57.9	93.8
	70	30	0			28.0	55.6	70.8
	60	40	0			32.0	53.1	68.4
	50	50	0			38.5	50.2	67.3
	40	60	0			44.2	48.5	66.7
	30	70	0			46.0	46.4	65.2
	20	80	0			47.0	43.6	64.8
	10	90	0			49.0	38.3	63.4
	0	100	0			54.0	32.4	62.5
CG2b	95	5	0	0.30	2.0	15.1	50.4	78.0
	90	10	0			16.2	52.4	80.3
	80	20	0			17.5	58.3	95.2
	70	30	0			23.3	56.1	72.3
	60	40	0			26.7	54.2	70.8
	50	50	0			32.1	53.4	68.3
	40	60	0			36.8	50.5	67.2
	30	70	0			38.3	47.1	66.1
	20	80	0			39.2	44.6	65.4
	10	90	0			40.8	40.3	64.3
	0	100	0			45.0	35.6	63.4
CG3a	95	0	5	0.30	1.5	18.0	55.4	91.7
					2.0	15.0	57.5	92.5
CG3b	90	0	10	0.30	1.5	22.5	57.5	90.2
					2.0	18.3	59.7	92.8

2007). For all mixtures, the maximum dosage of SP, which is sufficient for workability requirement, was 2.0%. This is because at 2.5% SP dosage, samples tend to bleed. "Bleeding" or "water gain" is the tendency for water to rise to the surface of freshly placed concrete (Neville 1995). It results from the inability of the constituent materials to hold all the mixing water dispersed throughout the mix (Neville 1995). However, according to Neville (1995), it is observed that the effectiveness of SP is enhanced by the existence of silica fume, SF. The use of SF affects significantly the properties of fresh concrete. The mix is strongly cohesive and, in consequence, there is very little bleeding or even none. Based on the discussion in *Scancem Materials,* 2005, SP shows a greater effect in SF due to its very fine nature and greater surface area, which increase the water demand. The large surface area of the particles of silica fume, which have to be wetted, increases the water demand, thus, in mixes with a low w/c ratio, it is necessary to use a superplasticizer. This condition allows the use of high dosage of SP for very low w/c ratio without bleeding or segregation problems encountered with normal OPC concrete. In addition, flowable slurries without segregation and very high strength grouts are produced by using appropriate dosage of SP (Neville 1995).

The paired sample *t*-test on the workability performance between 100% OPC mixture and 95% OPC, 5% SF, 0.30 w/c ratio with different SP content was carried out. Replacing the cementitious grout mixtures with 5% SF influence workability performance by 1.5%. However, replacing cementitious grout with 5% SF and 2.0% of SP did not influence workability performance. This test yielded a *t* value of 4.347 for 1.5% SP that was significant ($p < 0.05$) and yielded a *t* value of 3.263 for 2.0% SP which was not significant ($p > 0.05$). From the analysis, it could be concluded that there is no significant difference on workability performance by using 5% replacement of SF with different SP content.

4.2. Compressive strength of cementitious grout mixtures

The compressive strength was determined at 1, 3, 7 and 28 days. From findings, the compressive strength of cementitious grouts are influenced by several factors such as water/cement ratio, type and amount of SP used, cement types and its content, different composition of grout mixtures and inclusion of supplementary cementitious material. From Table 2, the compressive strength performance varies between 32 N/mm^2 to 60 N/mm^2 at 1 day and 62 N/mm^2 to 95 N/mm^2 at 28 days. The compressive strength performance of cementitious grout containing SF was higher as compared to 100% OPC mixture with same SP percentages. Silica fume also contributes to the progress of hydration of the latter material (Davraz, Gunduz 2005). This contribution arises from the extreme fineness of the silica fume particles, which provide nucleation sites for calcium hydroxide. Thus, early strength development takes place (Davraz, Gunduz 2005). The contribution of silica fume to the early strength development (up to about 7 days) was probably through improvement in packing, that is, action as a filler and improvement of the interface zone with the aggregate (Neville 1995). In *Scancem Materials,* 2005, it was discussed that the micro-filler effect from silica fume allows the silica to react rapidly and provide high early age strength and durability. The efficiency of silica fume was 3–5 times that of OPC and consequently vastly improved concrete performance. The effect of 5% SF replacement on compressive strength performance at 28 days is more significant as compared to 5% WC replacement with 2.0% SP. The highest compressive strength value at 1 and 28 days was produced by 20% WC, 80% OPC, 0.30 w/c ratio and 2.0% SP. According to a study by Hamad (1995) the compressive strength of the white cement concrete cylinders was greater at 1 day and 28 days than the companion gray cement cylinders regardless of the nominal concrete strength and of whether superplasticizers (SP) were used or not (Hamad 1995). However, the compressive strength value was lower for 30% WC replacement and above. This was due to incompatibility of WC and OPC for those percentages of mixture proportions. In addition, there is increment in compressive strength performance, which is parallel to increase in SP percentages for all cementitious grout mixtures. Increasing dosage of SP accompanied by a corresponding reduction of w/b ratio does appear to significantly affect the compressive strength performance (Neville 1995). The use of polycarboxylic based SP do not alter fundamentally the structure of hydrated cement paste, but the main effect is being a better distribution of cement particles and consequently, better hydration (Mohammed, Fang 2011). This condition would explain why, in some cases, the use of SPs increase the strength of concrete at a constant w/b ratio. Values of a 10% increase at 24 h and 20% increase at 28 days have been quoted, but this behaviour has not been universally confirmed (Neville 1995). The use of polycarboxylic ether polymer also affects compressive strength performance especially at 28 days. Through this study, the use of naphthalene formaldehyde sulphonate based superplasticizer (SP) produced lower strength performance as compared to polycarboxylic based SP, due to the long lateral chains of the polycarboxylic ether polymer, which reduces water demands but provide better cement dispersion (Koting *et al.* 2014). In addition, Hommer and Wutz (2005), Li *et al.* (2004), Skripkiūnas *et al.* (2012) have noted in their research papers that superplasticizers of new generation not only disperse the material and actively influence cement hydration process but also improve the structure of cementations materials due to nano dispersion particles present in their composition. The effect of the long molecules in the superplasticizer is to wrap themselves around cement particles and provide negative charge so that they can repel each other (Neville 1995). This will result in deflocculation and releasing of trapped water from cement flocks (Neville 1995). The paired sample *t*-test was carried out on the compressive strength performance at 1 and 28 days between 100% OPC mixture and 95% OPC, 5% SF, 0.30 w/c ratio with different SP content. Replacing the cementitious grout mixtures with 5% SF influenced compressive performance at 1 and 28 days only for 2.0% of SP. This test yielded a *t* value of –15.254 at 1 day and 6.250 at

28 days for 2.0% SP which was significant at the 0.05 level (p = 0.004 (1 day) and p = 0.025 (28 days)). Based on the statistical analysis, there is significant difference on compressive strength performance at 1 and 28 days by using 5% replacement of SF for 2.0% of SP.

4.3. Properties of open-graded asphalt skeletons

The open-graded asphalt skeletons were tested for density and void analysis in accordance to *ASTM D2726-96 Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures*, indirect tensile stiffness modulus in accordance to *ASTM D4123-82 (Reapproved* (1995) *Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures*, compressive strength test in accordance to *ASTM C-39-03 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* and air abrasion loss test in accordance to *ASTM C131-96 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*. The list of important formula and the properties of an open-graded asphalt skeleton is presented in Table 3.

The average void in total mix (*VIM*) which refers to the porosity of the mix was 27.4%. According to *Densiphalt Handbook* (2000), if the porosity or air voids is less than 25%, it will be difficult for selected cementitious grouts to completely fill the bituminous skeletons. If the porosity or air voids is higher than 30%, the open-graded asphalt skeletons surface will not have the necessary flexibility, which means cracks will occur in the finished surface. The compressive strength of the open-graded skeleton was 1.39 N/mm^2 after 1 day of curing which was slightly lower as compared to porous asphalt skeleton (1.69 N/mm^2) by Hassan *et al.* (2002). The average stiffness modulus value of the open-graded asphalt skeleton exhibited slightly higher elastic modulus of 2380 N/mm^2 as compared to the value of 1530 N/mm^2 porous asphalt skeleton conducted by Hassan *et al.* (2002). The resistance of the open-graded asphalt skeleton to particle

Table 3. List of important formula and the properties of an open-graded asphalt skeleton

Measured properties	Notations	Values
Bulk density, d, g/cm^3 $d = G_{mb}\rho_w$	d – bulk density; G_{mb} – bulk specific gravity of the mix; ρ_w – density of water, = 1g/mm^3	1.81 g/cm^3
Bulk specific gravity of the mix, G_{mb} $G_{mb} = \left[\dfrac{W_D}{W_{SSD-W_{SUB}}}\right]$	W_D – mass of specimen in air, g; W_{SUB} – mass of specimen in water, g; W_{SSD} – saturated surface dry mass, g; G_{mm} – maximum theoretical specific gravity of the mix; TMD – maximum theoretical density, g/mm^3; P_b – asphalt content, percent by weight of the mix; G_{se} – effective specific gravity of the mix; G_b - specific gravity of asphalt cement; G_{sb} – bulk specific gravity of the aggregate	2.52 g/ml
Voids in mixture (VIM), % $VIM = \left[1-\left(\dfrac{d}{TMD}\right)\right]100,$ $TMD = G_{mm}\rho_w,$ $G_{mm} = \left\{\dfrac{1}{\left[\left(\dfrac{1-P_b}{G_{se}}\right)+\dfrac{P_b}{G_b}\right]}\right\}$		27.4%
Voids in mineral aggregate (VMA), % $VMA = 100\left\{1-\left[\dfrac{G_{mb}(1-P_b)}{G_{sb}}\right]\right\}$		33.9%
Voids filled with bitumen (VFB), % $VFB = \left[\dfrac{VMA-VIM}{VMA}\right]100$		19.2%
Compressive strength, $f'c$, N/mm^2 $f'c = \dfrac{P}{A}$	P – maximum load, N; A – cross-sectional area of specimen, mm^2	1.39 N/mm^2
Resilient modulus, E, N/mm^2 $E = F\dfrac{\mu+0.27}{LH}$	E – resilient modulus; F – maximum applied load, N; μ – poisson's ratio; L – length of specimen, mm; H – total horizontal deformation, mm	2380 N/mm^2
Abrasion Loss (AL), % $AL = \left[\dfrac{Mi-Mf}{Mi}\right]100$	M_i – initial mass of specimen, g; M_f – final mass of specimen, g	14.9%

loss as evaluated by the Cantabro test was 14.9%. The abrasion loss required by Kuala Lumpur City Hall (2003) is a maximum of 15% from the initial mass of the specimen.

4.4. Air void analysis of cement-bitumen composites

In order to determine the porosity of the cement-bitumen composites, air void analysis was carried out. It was calculated by subtracting the sum of the volumes of the bitumen mixture volume and dry grout volume from the bulk volume of the grouted specimen. Table 4 shows air void results for different cement-bitumen composite prototypes.

The cementitious grout designs in Table 4 were selected because they produced sufficient workability and compressive strength performance. The cement-bitumen composite containing 95% OPC, 5% SF, 2.0% SP and 0.30 w/c ratio shows the lowest air void value, which is 3.0%. The cement-bitumen-composite containing 100% OPC, 2.0% SP and 0.30 w/c ratio shows the highest air void value, which is 5.8%. The air void values were lower for cement-bitumen composites designs containing SF. It is because of higher workability performance of cementitious grout design for those particular proportions. The higher percentages of SP produced lower air void values. This result is expected as the presence of higher percentage of SP fills the voids between the aggregates, thus reducing the air voids in the mix. This is an agreement with the workability performance of cementitious grout mixtures using the same proportions. However, according to Neville, the influence of SP is not straightforward and SP generally decreases bleeding except at a very high slump (Neville 1995). The schematic drawing of particles interaction with air voids between binder, aggregate and cement grout is presented in Fig. 2. The aggregate was initially coated with asphalt cement binder. The binder acts as an adhesive agent that binds aggregate particles into a cohesive, interconnected mass. When bound by asphalt cement binder, aggregate acts as a stone framework, which provides strength and toughness to the structure of cement-bitumen composite. The cement grout was then poured gradually on the open-graded asphalt surface. The slurry will then infiltrate into air voids under influence of gravitational flow. From Fig. 2, it is seen that air voids were partially filled with cement grout. The fluidity of cement grout is important criterion to ensure the air voids is completely filled in order to provide a solid, homogeneous grouted cement-bitumen composite structure. The effect of SF and WC replacement was seen from air voids result. Both replacements are found to refine the pore structure of the cement-bitumen composites and hence improve the performance properties.

4.5. Compressive strength of cement-bitumen composites

The cement-bitumen prototypes were prepared and tested at 1 and 28 days. Fig. 3 shows the compressive strength performance for different cement-bitumen composite designs at 1 and 28 days for 0.30 w/b ratio and 2.0% SP.

Referring to Fig. 3, different cementitious grout designs are a major factor influencing the strength of cement-bitumen composites. The study showed that the highest compressive strength of cement-bitumen composites was 5.3 N/mm^2 at 1 day and 10.3 N/mm2 at 28 days. This result was produced by 95% OPC, 5% SF replacement. This is not in agreement with compressive strength value of cementitious grout mixtures as shown in Table 2. Although 80% OPC, 20% WC showed the highest compressive strength value (Table 2) of cementitious grout, the cement-bitumen composites for this proportion produced the lowest value in compressive strength performance. The cement-bitumen composites containing 20% WC shows the lowest compressive strength performance at 1 day (2.4 N/mm^2) and 28 days (3.4 N/mm^2) as compared to other designs. For the cement-bitumen composites containing WC, it is difficult for the grout mixture to infiltrate into unfilled skeleton surface because the grout was dense and sticky. This condition leads to high porosity values of cement-bitumen composites containing WC, which influenced the compressive strength performance. As such, the use of WC

Table 4. Air void values of cement-bitumen composites

Cement-bitumen composite design	SP percentages, %	W/b ratio	Air void values, %
100% OPC	2.0	0.30	5.8
95% OPC + 5% SF	2.0	0.30	3.0
90% OPC + 10% SF	2.0	0.30	4.2
95% OPC + 5% WC	2.0	0.30	3.9
90% OPC + 10% WC	2.0	0.30	4.1
80% OPC + 20% WC	2.0	0.30	5.2

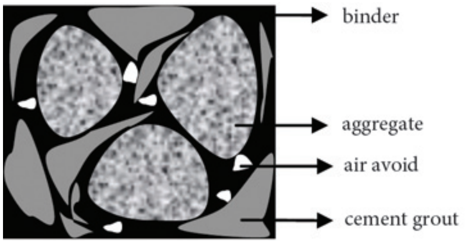

Fig. 2. Particle interaction with air voids of cement-bitumen composite (schematic drawing by the author)

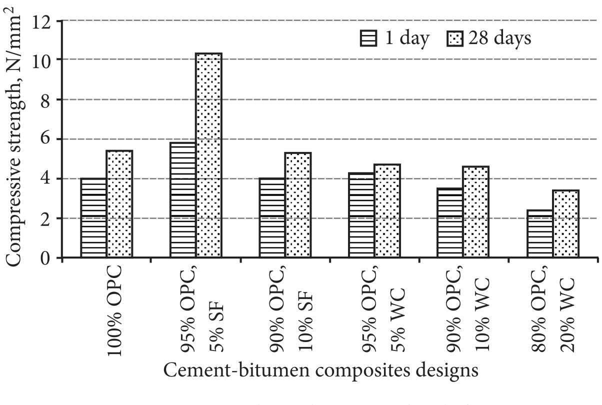

Fig. 3. Compressive strength performance for different cement-bitumen composite designs

in development of cement-bitumen composites for semi-flexible pavement surfacing does not have significantly increase in compressive strength at 28 days. The beneficial effect of 5% SF as a replacement material is significantly illustrated at 28 days. Silica fume particles enhanced particle packing and ultimately higher compressive strengths and enhanced durability was achieved because of the extremely small shape of the material. For further verification, statistical analysis was performed on the influence of replacing 5% SF on the compressive strength performance at 1 and 28 days. The *t*-test analysis at 1 day between 100% OPC, 2.0% SP, 0.30 w/c ratio and 95% OPC, 5% SF with 2.0% SP, 0.30 w/c ratio yielded a *t* value of 13.67 which was significant at the 0.05 level ($p = 0.0465$). At 28 days, this test yielded a *t* value of 18.14 which was significant at the 0.05 level ($p = 0.0351$). Thus, replacing 5% silica fume in grout mixtures significantly influenced the compressive strength performance of cement-bitumen composites at 1 and 28 days. From the results obtained, the use of SF as a replacement (5%) in a small proportion of OPC has influence grout strength performance. This is because of the microfiller effect from SF allow the silica to react rapidly and providing high early age strength and durability (Neville 1995). The efficiency of SF is 3–5 times that of OPC and consequently vastly improved concrete performance can be obtained (Neville 1995). However, it is found that increment of SF from 5% to 10% did not significantly influenced the compressive strength performance of cementitious grout mixtures. According to Neville (1995), the replacement with adequate amount of SF improves the interface zone with the aggregate. In this case, the replacement of 5% silica fume is sufficient in order to increase the grout mixtures performance. This is agreeable to findings of this study that the contribution of SF to strength increases with an increment in the content of SF in the mix (up to a certain limit).

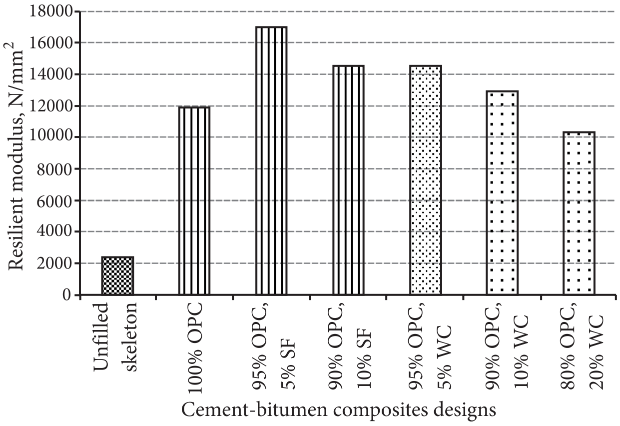

Fig. 4. Indirect tensile stiffness modulus performance of cement-bitumen composites designs

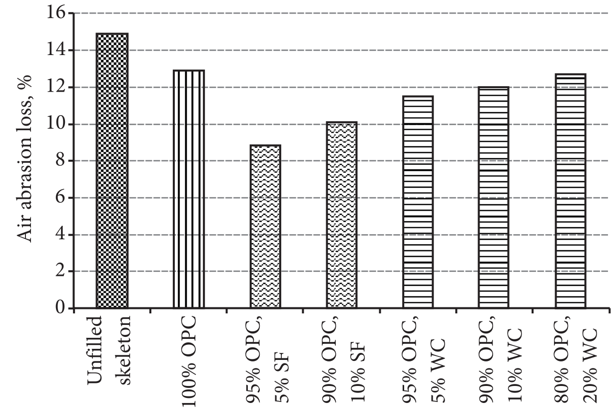

Fig. 5. Resistance to abrasion performance for different cement-bitumen composites designs

4.6. Indirect tensile stiffness modulus of cement-bitumen composites

The indirect tensile stiffness modulus test on the cement-bitumen composites was carried out after 28 days of curing at 20 °C. Fig. 4 shows the results of resilient modulus for different designs of cement-bitumen composites with 0.30 w/c ratio and 2.0% SP.

From Fig. 4, the different cementitious materials do influence the resilient modulus. The highest resilient modulus value was 16516 N/mm^2, produced by 95% OPC, 5% SF and the lowest resilient modulus value was 2380 N/mm^2, produced by unfilled skeleton samples. This is in agreement with compressive strength performance of cement-bitumen composites. The value for cement-bitumen composites containing 5% SF increased 6 to 10 times as compared to unfilled skeleton performance. Mixes containing 20% WC replacement produced slightly lower value as compared to 100% OPC mixtures, apparently due to the stickiness and rapid hardening effect of WC. The cement-bitumen composites containing 5% and 10% SF produced higher resilient modulus as compared to OPC mixture and WC mixtures.

4.7. Resistance to abrasion

The Cantabro test was carried out to measure the resistance to ravelling of the mix. The result of this test is presented in Fig. 5.

From Fig. 5, it was noticed that inclusion of 5% SF lowers the air abrasion loss of cement-bitumen composites as compared to unfilled skeleton and mixes containing 100% OPC and different percentages of WC. The highest air abrasion loss value was 14.9% produced by unfilled skeleton. The replacement of 5% to 20% WC in the grout mixtures exhibited slightly higher values as compared to cement-bitumen composites containing SF and lower values as compared to cement-bitumen composites containing OPC and unfilled skeleton. This is in agreement with the compressive strength performance and air void analysis of cement-bitumen composites. Inclusion of silica fume increases the strength of the grouted composites and hence increases its abrasion resistance.

5. Conclusions

Based on the results of the laboratory investigation, the following conclusions were made.

1. High workability and high strength cementitious grouts that were infiltrated into open-graded asphalt

skeletons were produced. The properties of cementitious grout mixtures are influenced by water/cement ratio, dosage of superplasticizer, types of cement and inclusion of silica fume as replacement cementitious material.

2. Open-graded asphalt skeleton of 25% to 30% voids content was recommended. Although the skeleton has high voids content, it is able to maintain a thick binder coating on the aggregates at the same time.

3. The prototype of cement-bitumen composites (semi-flexible pavement surfacing) was produced by using appropriate proportions of cementitious grout mixtures and open-graded asphalt skeletons.

4. The higher percentages of superplasticizer produced lower air void values for cement-bitumen composites. It indicated a close relationship between air void and workability performance of cementitious grout mixtures. Higher workability performance allows more grouts to fill voids between the aggregate and finally reducing the air voids content in the cement-bitumen composites.

5. The cement-bitumen composites containing 5% silica fume replacement showed the highest compressive strength performance at 1 and 28 days. This indicated that the cementitious grout mixtures with highest compressive strength performance at 1 and 28 days will not necessarily produce the highest compressive strength performance of cement-bitumen composites.

6. The cement-bitumen composites with 5% replacement of silica fume showed the highest resilient modulus and resistance to ravelling as compared to other mixture proportions.

7. The replacement of 5% silica fume with adequate amount of superplasticizer was considered in developing cementitious grout mixtures in order to produce sufficient performance of cement-bitumen composites (semi-flexible pavement surfacing) as a final product.

Acknowledgement

This investigation was supported by Scientific Research Fund provided by Malaysian Ministry of Higher Education (Project number FP021-2011A).

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Received 10 February 2012; accepted 7 September 2012