Development of Cement-Bitumen Composites for Semi-Flexible Pavement Surfacing

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Abstract: Cement-bitumen composites are produced by pouring selected cementitious grout slurries onto the surface of open graded asphalt skeletons, which subsequently filled the voids under the influence of gravitational action. 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 satisfied grouted pavement mixes. The cementitious grout mixtures, open graded asphalt skeletons and grouted pavement mixes were tested for physical, strength and deformation performances.

Key Words: *semi-flexible pavement, cementitious grouts, cement-bitumen composites*

1. INTRODUCTION

Researches and studies are carried out continuously in order to explore and investigate the most appropriate and susceptible ways to fulfil the demands of enhanced and better performance in the design of highway constructions. Quality of the road, cost effectiveness and performances of the pavement are some of the important criteria that have been taken into consideration in order to find the right choice in the design of pavements. Generally, road pavements are categorized into two broad classes of rigid and flexible pavements. Concrete surfaces and bases are frequently classed as “rigid” pavements, the term “rigid” implying that pavements constructed of this material possesses a certain degree of “beam strength” that permits them to span or “bridge over” some minor irregularities in the subgrade or subbase upon which they rest. The concrete base which supports a block or brick layer is also classified as rigid pavement. On the other hand, a flexible pavement is a structure that maintains intimate contact with and distributes loads to subgrade and depends on aggregate interlock, particle friction and cohesion for stability (Wright and Paquette, 1979). Flexible pavement contains aggregates that are bound by bituminous binders while rigid pavement comprise of 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. 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. Thus, in order to overcome the above weaknesses and improve the performance of pavements, an alternative semi-rigid or semi-flexible pavement is proposed. Semi-flexible pavement surfacing is a composite pavement that utilizes the open graded asphalt skeleton structure of the flexible bituminous pavement which is subsequently grouted with an appropriate cementitious material. The pavement combines the best qualities of cementitious grout rigidity and the flexibility of the bituminous material. The technology of semi-flexible pavement has been applied in the road maintenance and rehabilitation projects since 2001. The Kuala Lumpur City Council or Dewan Bandaraya Kuala Lumpur (DBKL) has awarded maintenance and upgrading projects of public roads and heavy trafficked surfaces by using imported cementitious material and polymer modified bitumen. DBKL published a guideline on the workmanship and materials to be used in semi-rigid pavement for contractors in producing this material (Dewan Bandaraya Kuala Lumpur, 2003). Since semi-flexible pavement is manufactured using imported material, the production cost of semi-flexible pavement very much depends on currency exchange. Thus, in order to avoid this fluctuation in cost, alternative local products are explored to replace the costly imported cementitious material. As a cost-effective solution in heavily trafficked roads and other pavement areas, semi-flexible pavement will substantially contribute to alleviating severe deformation problems faced by conventional pavement design. In Malaysia, semi-flexible pavements have been introduced on public roads especially in areas with heavy traffic (bus lanes, bus and car terminals, heavily trafficked roads etc.) in order to enhance the road performance and effectiveness, thus offering joint-free and high friction pavements. The semi-flexible pavement is designed to withstand the stresses from the wear and tear from heavy continuous traffic, rutting from continual driving along the same routes and sudden braking (Dewan Bandaraya Kuala Lumpur, 2003).

The development of semi-rigid or semi-flexible pavement, especially in European countries has shown increased acceptance in recent years. Research done by the Danish Road Institute, Denmark, showed that the application of semi-flexible pavement offers high strength and remarkable durability while avoiding some of the drawbacks of rigid and flexible pavement such as cracking, surface deterioration, rutting problem and deformation, which make it difficult to maintain the pavement. The principles and applications of semi-flexible pavement have gained recognition in many European countries since it offers a number of important advantages. In other countries, this type of pavement was also adapted for industrial surfaces to ensure safe working area and to minimize the wear on machine and vehicles. The floor must be able to resist stress, wear and tear from traffic by forklift, trucks and other vehicles. It must also be able to resist high point loads from racking system, stacked goods and machinery, rutting from continual driving along the same routes, impact from the handling of goods and static loads from stacked goods, vibration from machineries, resistance to chemical and high temperature attack (Euco Densit LLC, 2000). Based on the research findings in Europe, semi-flexible pavements have been utilised in airport areas, industrial applications, ports and at bus terminals. Semi-flexible pavements have not demonstrated major deformations and are still in good condition. In addition, road authorities in the US, Germany and Netherlands have applied semi-flexible pavement in their airport areas and ports. This shows that the concept of semi-flexible pavement has already gained wide acceptance.

2. RESEARCH OBJECTIVE

The main objective of this study is to investigate the mechanical properties of cement-bitumen composites as an alternative semi-flexible pavement surfacing material. It involves the selection of acceptable proportions of cementitious grouts and open graded asphalt skeletons as well as the development of satisfied grouted pavement mixes. The study covers two main scopes which involves binder selection and acceptable cementitious grouts as well as investigating the properties of the grouted pavement mixes.

3. MIX DESIGN AND EXPERIMENTAL WORKS

This section discusses the mixture proportions and preparation of cementitious grout mixtures, open graded asphalt skeletons and grouted pavement mixes (cement-bitumen composites). The first phase in the manufacture of the semi-flexible pavement surfacing is to develop acceptable proportions of cementitious grouts. The second stage is to produce an open graded asphalt skeleton and finally the production of the grouted pavement mixes (cement-bitumen composites). Several prototypes of the grouted pavement mixes were designed in order to determine the most acceptable product that fulfill the requirements needed in the manufacture of semi-flexible pavement.

3.1 Cementitious Grout Mixture

The main requirement of the cementitious grout is to develop sufficient strength and workability so that they can penetrate easily into open graded asphalt skeletons and when cured will improve the strength of the cement-bitumen composites. Studies done by Zoorob et al. (2002) produced higher workability cementitious grouts while maintaining higher strength at 28 days. In order to fulfill these requirements, different cementitious grout mixes were prepared, produced and analyzed. The cementitious grout mix design included the selection of different grout composition, variation in water/cement ratios as well as type and dosages of superplasticizer (SP).

The cementitious grout mixtures were produced by using ordinary Portland cement (OPC), 5% silica fume (SF), which is a locally available pozzolanic material. The potential of using white cement as a replacement to OPC was also investigated. 5% silica fume (SF) implies weight of the supplementary cementitious material to that of total grout. In order to produce flowable cementitious grout mixtures, two superplasticizing (SP) admixtures were used, a polycarboxylic ether polymer (SP D) and a naphthalene formaldehyde sulphonated chemical based (SP E). Percentages of SP used were between 0.5% to 2.5% by weight of the cement grout. The water/cement ratio was varied between 0.24 to 0.50. Cementitious grouts were mixed 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 Zoorob *et al*. (2002) as suggested by the supplier of the admixtures was adopted. After mixing, the grout mixtures were placed in 50 x 50 x 50 mm moulds.

3.2 Open Graded Asphalt Skeleton

Grouted pavement mixes comprise of open graded asphalt skeleton and cementitious grout. Open graded asphalt skeleton is composed of crushed aggregates (granite), 3.0% filler and 3.62% bitumen 80/100. 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 number of compaction was decreased in order to attain high air void content and to ensure there is no unnecessary aggregate crushing. The aggregate gradation was provided by 'Jabatan Kerja Raya Malaysia (JKR)'. Based on the DBKL specification and Marshall Mix Design Method, an open graded asphalt skeleton was prepared. After mixing and remoulding, all the specimens were left to cool for 24 hours. The sample was demoulded after 24 hours and cured at 25ºC and 75% relative humidity before testing or impregnation later with cementitious grout mixtures.

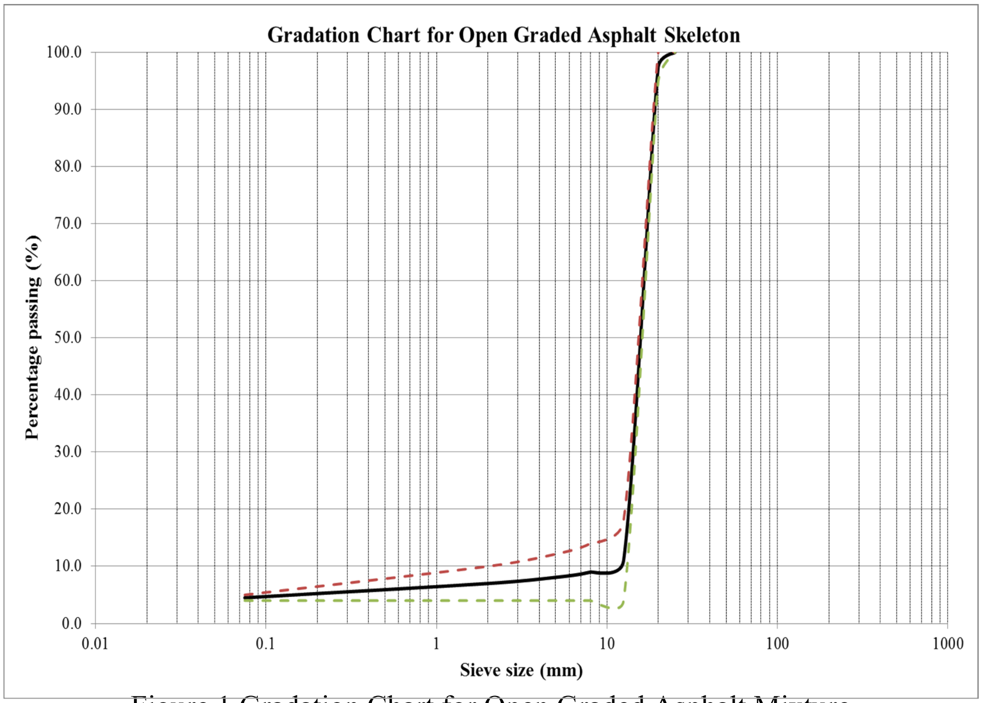

Figure 1 Gradation Chart for Open Graded Asphalt Mixture

3.3 Grouted Pavement Mixes (Cement-Bitumen Composites)

The grouted pavement mixes were produced by impregnating open graded asphalt skeletons with selected proportions of cementitious grout mixture. Different proportions of grout mixtures were poured onto the surface of open graded asphalt skeletons in order to produce grouted pavement mixes. Adequate and constant supply of the cement grout was prepared to ensure that the bituminous/asphalt matrix was completely filled. The grouted pavement mixes were cured in a room at 25°C and 75% relative humidity (Zoorob *et al*. 2002).

4. PROPERTIES OF SEMI-FLEXIBLE PAVEMENT SURFACING

Mechanical properties of semi-flexible surfacing were carried out to determine the characteristics of cementitious grout mixtures, open graded asphalt skeletons and grouted pavement mixes (cement-bitumen composites).

4.1 Properties of Cementitious Grout Mixtures

Fresh and hardened characteristic of cementitious grout mixtures were determined. Workability test was conducted on fresh mixture while cube compressive strength tests on 50 x 50 x 50 mm specimens and flexural strength test on 50 x 50 x 330 mm samples were carried out on hardened grout.

4.1.1 Workability Performance

The workability performance was measured through flow time test. This test was conducted to measure the fluidity of various cementitious grout compositions and to ensure that the grouts have the correct consistency to infiltrate easily into an open graded asphalt skeleton using the Malaysian Mortar Flow cone method. The flowability was measured for every l litre of wet cementitious grout.

The results show that flowability value varied from the highest at 136 seconds (using naphthalene formaldehyde sulphonated based, SP E) to the lowest at 6.3 seconds (using polycarboxylic ether polymer based, SP D). Use of polycarboxylic based SP produced better flowability compared to naphthalene formaldehyde sulphonated based SP. The polycarboxylic ether polymer SP is different from conventional SP since its cement dispersion action can be greatly improved and thereby producing grouts with higher fluidity. Dosage of SP significantly influences the workability, increasing the amount of SP produce higher workability of the cementitious grout, irrespective of w/c ratio. At higher w/c ratios, dosage of SP can be decreased up to 0.50% of the cementitious material. For all mixtures, the maximum dosage of SP which is sufficient for workability requirement was 2.0%. This is because for 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). Influence of using supplementary cementitious material (SCM) on flowability properties of grouts was also investigated. The supplementary cementitious material was silica fume as partial replacement of OPC. The highest workability performance of using silica fume was 8.6s which is produced by 5% silica fume, 0.35 w/c ratio and 2.5% SP. This is because pozzolanic reactions take place when silica fume is added to the concrete mixture (Neville, 1995).

The workability performance of cementitious grouts is influenced by various factors such as water/cement ratio, dosage, types of SPs, different brand of SPs, types of cement and incorporation of supplementary cementitious material.

4.1.2 Compressive Strength

Compressive strength was performed to ascertain an overall quality of the hardened grout as strength is directly related to the structure of the hydrated cement paste (Neville, 1995). The compressive strength was conducted at 1, 3, 7 and 28 days. The compressive strength of cementitious grouts are influenced by several factors such as water/cement ratio, type and amount of SPs used, cement types and its content, different composition of grout mixtures and inclusion of supplementary cementitious material.

In this study, it was found that the w/c ratio influenced the strength performance of cementitious grouts. Compressive strength performance gradually decreased as the w/c ratio was increased from 0.24 to 0.50 for 100% OPC mixtures and 1.5% of SP. For these mixtures, the highest strength was 59.1N/mm^2 at 1 day and 92.0N/mm^2 at 28 days, which was produced at 0.24 w/c ratio. The lowest strength was produced at 0.50 w/c ratio, 34.0 N/mm^2 at 1 day and 64.5 N/mm^2 at 28 days were achieved. This trend is similar for compressive strength performance of the grout mixtures containing white cement and 5% silica fume. It can be seen that there is increment in compressive strength performance which is parallel to decrease in w/c ratio. The highest compressive strength for the grout mixtures containing 5% silica fume was 55.4N/mm^2 at 1 day and 91.7N/mm^2 at 28 days which was produced by grout mixture containing 95% OPC, 5% silica fume, 0.30 w/c ratio and 1.5% SP of polycarboxylic ether polymer type. The lowest compressive strength performance was 42.7N/mm^2 at day 1 and 71.0N/mm^2 at 28 days for the same grout mixture composition containing silica fume but at a w/c ratio of 0.50. This is due to the higher value of the w/c ratio, which allows the grout mixture to become more flowable. The influence of different w/c ratio (0.24-0.50) on 100% OPC mixtures using 1.5% SP D (polycarboxylic ether polymer chemical based) is shown in Figure 2.

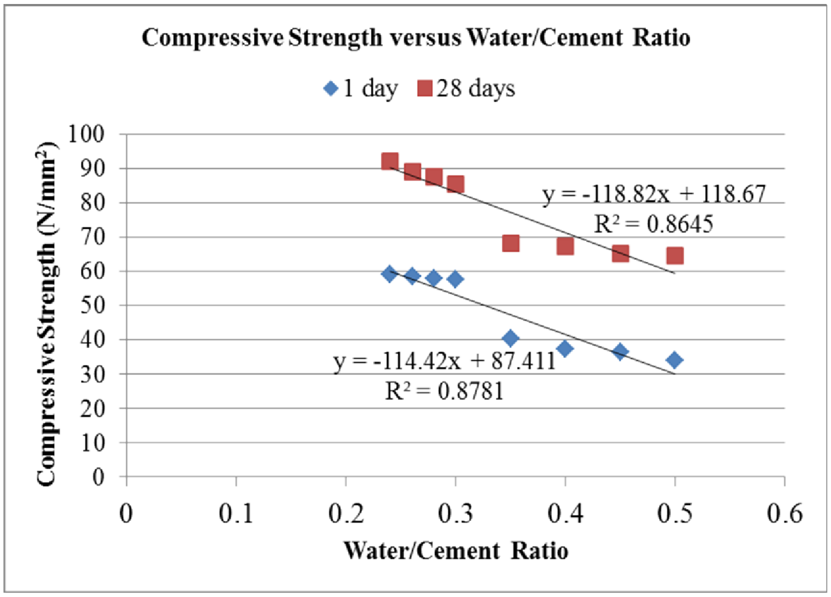

Figure 2 Influence of W/C Ratio on the Compressive Strength of 100% OPC Mixture

The figure shows that 87.8% of the variation in 1 day compressive strength and 86.5% of the variation in 28 days compressive strength is influenced by variation in water/cement ratio.

Types of SP were also found to affect compressive strength performance especially at 28 days. Naphthalene formaldehyde sulphonate based SP produced lower strength performance compared to polycarboxylic based SP, due to the long lateral chains of the polycarboxylic ether polymer which can reduce water demands but provide better cement dispersion. 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. This will result in deflocculation and releasing of trapped water from cement flocks (Neville, 1995).

In addition, it is observed that the use of silica fume as cement replacement (5%) has an influence on grout strength performance. This effect can be seen by comparing cementitious grout containing OPC with the one containing silica fume. The highly reactive and finer particles of the silica fume speeds up the reaction with calcium hydroxide produced from hydration of Portland cement (Scancem Materials, 2005). The finer particles of silica fume enter the space between the particles of cement and thus improve packing. In addition, silica fume also contributes to the progress of hydration of the latter material. 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. 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 addition, the microfiller 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 can be obtained.

4.1.3 Flexural Strength Performance

Flexural strength test was carried out to determine the tensile strength of cementitious grout. According to Neville, (1995), the theoretical maximum tensile stress reached at the bottom fibre of a test beam is known as the modulus of rupture, which is relevant to the design of highway and airfield pavement. Three samples of beams were tested and an average result was calculated and the results are shown in Figure 3.

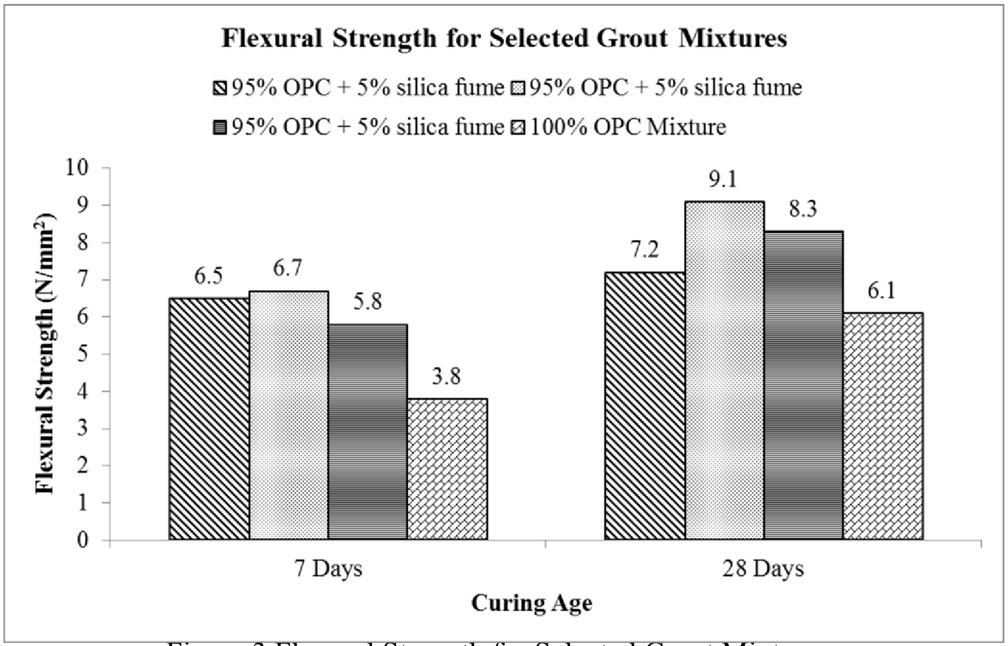

Figure 3 Flexural Strength for Selected Grout Mixtures

The flexural strength performance was investigated at 7 and 28 days. The use of 5% silica fume influences the flexural strength performance at 7 and 28 days. Additionally, the grout mixture containing 95% OPC, 5% silica fume, 2% SP and 0.30 water/cement ratio produced the highest flexural strength at 7 and 28 days. Use of adequate dosage of SP will enhance the ability of the grout mixtures to infiltrate into the open graded asphalt skeletons under gravitational action. This means, the addition of superplasticizer will improve the cement dispersion action and thereby producing grouts with higher fluidity. The presence of the long lateral chains which linked to the polymer backbone generates a steric hindrance, which stabilises the cement particles capacity to separate and disperse. This characteristic provides flowable grout with greatly reduced water demand. Instead of controlling the water-cement ratio, the cement dispersion will encourage the development of grout mixture with higher strength (Zoorob *et al*. 2002).

4.2 Properties of Open Graded Asphalt Skeletons

In this study, different strength and performance tests were carried out. The open graded asphalt skeletons were tested for density and void analysis (ASTM D2726), indirect tensile stiffness modulus (ASTM D4123) compressive strength test (ASTM C39) and air abrasion loss test (ASTM C131). The properties of an open graded asphalt skeleton are summarized in Table 1.

Table 1 Properties of Open Graded Asphalt Skeleton

Measured Properties	**Value of Open Graded Asphalt Skeleton**
Bulk density(g/cm^3)	1.81
Specific gravity (g/ml)	2.52
Voids in total mix (VIM)	27.4
Voids in mineral aggregate (VMA)	33.9
Voids filled with bitumen (VFB)	19.2
Compressive Strength (N/mm^2) at 20°C	1.39
Resilient Modulus (N/mm^2) at 20°C	2380
Abrasion Loss (%)	14.9

The average void in total mix (VIM) which refers to the porosity of the mix was 27.4%. According to Euco Densit LLC, (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 aphalt 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 1.39N/mm^2 after 1 day of curing. The average stiffness modulus value of the open graded asphalt skeleton exhibited appreciably higher elastic modulus of 2380N/mm^2 as compared to the value of 1530N/mm^2 porous asphalt skeleton conducted by Zoorob *et al*. (2002). The resistance of the open graded asphalt skeleton to particle loss as evaluated by the Cantabro test was 14.9%.

4.3 Properties of Grouted Pavement Mixes (Cement-Bitumen Composites)

The properties of grouted pavement mixes (cement-bitumen composites) are discussed through air void analysis, compressive strength test, resilient modulus test and air abrasion loss test.

4.3.1 Air Void Analysis

In order to determine the porosity of the grouted pavement mixes, 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

A decrease in air voids or porosity of grouted pavement mixes containing 100% OPC and 0.30 w/c ratio was found when the SP content was increased from 1.5% to 2.5%. Average porosity of grouted pavement mixes for 1.5% SP was 8.0%, followed by 5.8% for 2.0% SP and 3.9% for 2.5% SP. 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. Increasing the SP percentage from 1.5% to 2.0% did not influence the porosity performance of grouted pavement mix containing 100% OPC and 0.30 w/c ratio. However, it is found that increasing the SP percentage from 2.0% to 2.5% influenced this property. It was observed that grouted pavement samples tend to bleed at 2.5% SP content due to higher SP content. Lower strength values were also associated with the use of this higher SP content.

4.3.2 Compressive Strength

The influence of different composition of cementitious grout mixtures on compressive strength performance of grouted pavement mixes is shown in Table 2.

Table 2 Influence of SP Dosages on Strength of Grouted Pavement Mixes

Composition of Grouted Pavement Mixes	**Percentage of SP**	**Average Compressive Strength at 1 day (N/mm^2)**	**Average Compressive Strength at 28 days (N/mm^2)**
100% OPC 0.30 w/c ratio Polycarboxylic Ether Polymer SP	1.5 2.0 2.5	3.5 3.9 2.8	3.9 5.4 3.8
95% OPC, 5% silica fume 0.30 w/c ratio Polycarboxylic Ether Polymer SP	1.5 2.0 2.5	5.2 5.8 5.3	6.0 10.3 6.4
100% WC 0.30 w/c ratio Polycarboxylic Ether Polymer SP	2.0	2.4	3.4
70% WC, 30% OPC 0.30 w/c ratio Polycarboxylic Ether Polymer SP	2.0	3.5	4.6

The compressive strength of grouted pavement mixes containing 100% OPC mixture increased with increasing SP from 1.5% to 2.0%. The same trend is also true for grouted pavement mixes containing 95% OPC and 5% silica fume. The highest strength of grouted pavement mixes was produced by 95% OPC, 5% silica fume, which is $5.8N/mm^2$ at 1 day and $10.3N/mm^2$ at 28 days. SP addition did not influence the compressive strength performance of grouted pavement mixes at 1 day. Increasing the SP content from 2.0% to 2.5% decreased the compressive strength performance significantly at 1 and 28 days, due to bleeding problems. Grout mix containing 95% OPC with 5% silica fume replacement with 0.30 w/c ratio and 2.0% SP gave the highest strength at 1 and 28 days respectively. The beneficial effect of silica fume as a replacement material is clearly shown at 28 days. This is because silica fume is 100 to 150 times finer than cement particle, which can fill the voids, created by free water in the matrix. Silica fume particles enhanced particle packing and ultimately higher compressive strengths and enhanced durability can be obtained because of the extremely small shape of the material (Fatimah, 2007). For the grout mixture containing 100% white cement (WC), it is difficult for the grout mixture to infiltrate into unfilled skeleton surface because the grout was dense and sticky. Mixing 70% WC with 30% OPC, 0.30 w/c ratio and 2.0% SP, increased the 1 day strength and 28 days strength. However, the resulting strengths are lower than the samples containing 5% silica fume.

4.3.3 Resilient Modulus Performance

Stiffness modulus test on the grouted pavement mixes was carried out after 28 days of curing at 20°C, in accordance to ASTM D4123-82 (Reapproved 1995): Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. The resilient modulus of unfilled grouted pavement mixes (skeleton samples) was also determined before impregnation on selected proportions of cementitious grout mixtures. The resilient modulus performance is influenced by SP content and use of different cementitious binder.

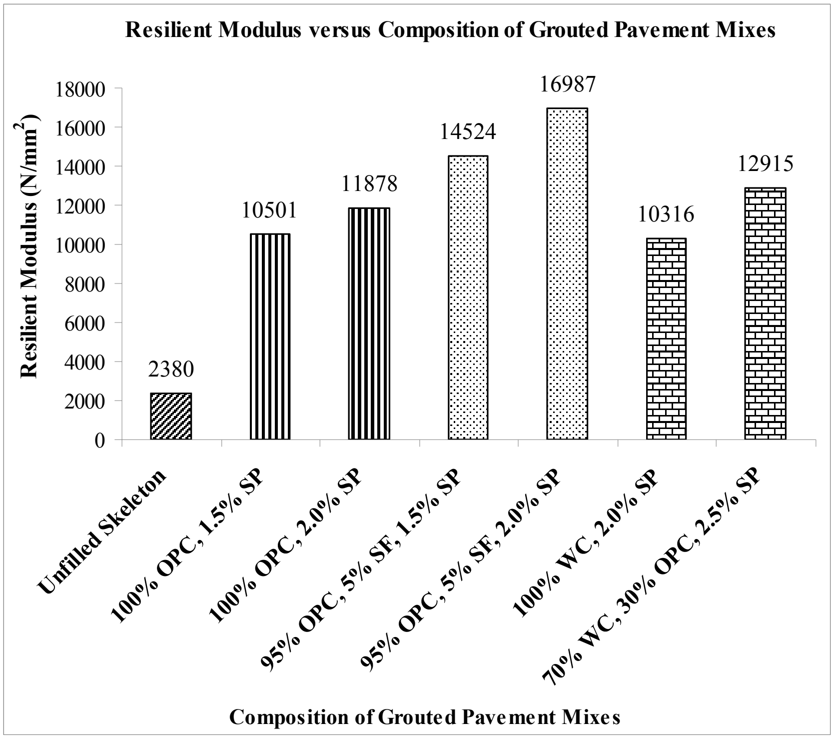

Figure 4 Influence of SP Content and Type of Cementitious Binder on Resilient Modulus Performance

From Figure 4, it can be seen that the resilient modulus increased with increasing SP content for 100% OPC and mixes containing 95% OPC with 5% silica fume. Higher SP dosage produces more workable slurry and allows more grout to penetrate into the voids of unfilled skeletons. It can also be seen that the resilient modulus also increased by incorporation of supplementary cementing materials. The value for mixes containing OPC and silica fume increased 6 to 10 times as compared to unfilled skeleton performance.

Mixes containing 100% white cement produced slightly lower value as compared to 100% OPC mixtures, apparently due to the stickiness and rapid hardening effect of white cement. Partially replacing the white cement with 30% OPC increased the resilient modulus value possible due to compatibility of the OPC with white cement.

4.3.4 Air Abrasion Loss Performance

Preliminary investigation using the Cantabro test was also carried out to measure the resistance to ravelling of the mix. The mean value of air abrasion loss achieved by unfilled skeletons and different composition of grouted pavement mixes were compared. The maximum permissible air abrasion loss is normally taken as 25%, which is a typical value used by the other researchers (Katman, 2006). The result of this test is shown in Figure 5.

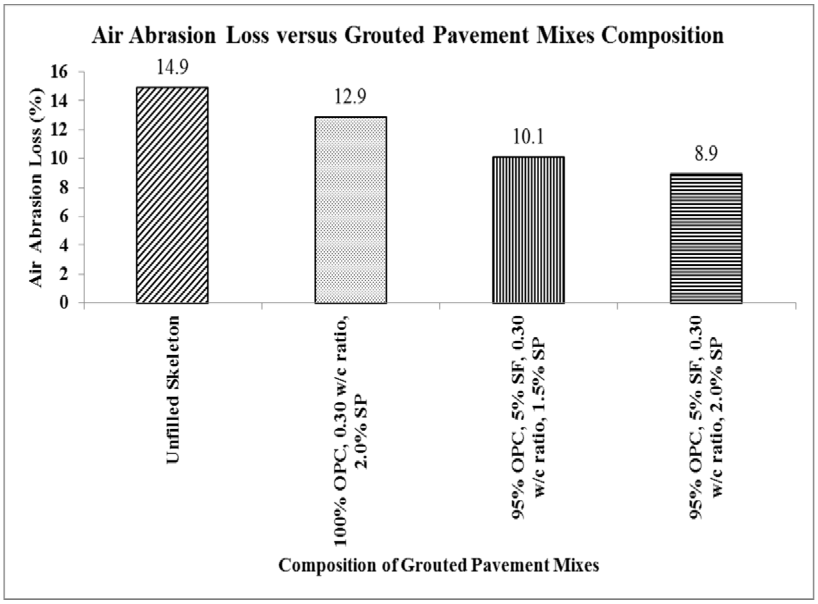

Figure 5 Air Abrasion Loss of Grouted Pavement Mixes

From Figure 5, it was noticed that inclusion of silica fume lowers the air abrasion loss of grouted pavement mixes compared to unfilled skeleton or mix containing 100% OPC. Inclusion of silica fume increases the strength of the grouted mix and hence increases its abrasion resistance. Increasing SP content from 1.5% to 2.0% also improved this property.

Prototype grouted pavement mixes (cement-bitumen composite) have been produced successfully in the laboratory. By proper selection of cementitious binder, type and dosage of SP as well as w/c ratio, cementitious grouts having high workability and high strength can be routinely designed. Produced grouted pavement samples exhibited superior mechanical properties.

5. CONCLUDING REMARKS

Based on the results of the laboratory investigation on cementitious grout mixtures, open graded asphalt skeletons and grouted pavement mixes, the following conclusions can be drawn.

1. High workability and high strength cementitious grouts that can infiltrate into open graded asphalt skeletons can be produced. The properties of cementitious grout mixtures are influenced by water/cement ratio, dosage and type of SPs used, types of cement and inclusion of supplementary cementitious material.
2. Open graded asphalt skeleton of 25% to 30% voids content is 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 properties of grouted pavement mixes are influenced by water/cement ratio, type and content of SPs and type of cementitious binder in the grout mixtures.
4. The impregnation of cementitious grout mixtures into open graded asphalt skeletons improved the compressive strength, resilient modulus and resistance to ravelling performance of open graded asphalt skeletons.

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