Chapter

Cementitious Grouts Containing Irradiated Waste Polyethylene Terephthalate

Muhammad Imran Khan, Muslich Hartadi Sutanto, Madzlan Bin Napiah and Salah E. Zoorob

Abstract

This chapter describes a review of the design and formulation of various cementitious grouts for semi-flexible pavement surfaces. Additionally, the authors also conducted extensive experimental work on the possibility of using a most effective and innovative way of recycling waste polyethylene terephthalate (PET) by exposing to gamma radiation and using as a replacement of Ordinary portland cement in the formulation of cement grouts for semi-flexible pavement surfaces. In the current study, cement in the grouts was replaced with PET (regular and irradiated), fly ash and silica fume and was evaluated for flowability and strength properties. The study concludes that normal PET causes a significant reduction in compressive strength, however, some of the strength is restored when irradiated PET was used. The recycling of waste PET, as a cement replacement in the cementitious grouts for semi-flexible pavement surfaces, with the irradiation process can be doubled as compared to utilizing normal/regular PET.

Keywords: cementitious grout, irradiated waste polyethylene terephthalate, fly ash, silica fume, compressive strength

1. Introduction

Generally, pavements are classified into two types: flexible pavements and rigid pavements. Conventional flexible pavements are constructed from bituminous materials and are widely used as a highway, expressway/freeway, and airport pavements due to their satisfactory performance against distresses and better riding quality, good serviceability, high skid resistance, low cost and easy maintenance [1–3]. However, due to recent exponential increase in traffic load and extreme adverse environmental conditions, the flexible pavements are exposed to many distresses (such as rutting, cracking, corrugation, shoving, stripping etc.) which can badly affect its service life and performance [4, 5]. On the other hand, rigid pavements are constructed from cement concrete with or without reinforcement. Rigid pavements have better durability, high compressive strength but have some disadvantages such as; provision of joints, rough-riding quality, slow setting time, high susceptibility to thermal stresses, high initial cost and maintenance efforts, cannot simply be ignored [6–8]. Taking into consideration the disadvantages of both flexible and rigid pavements there was a need for an alternative pavement design that can combine the positive attributes of conventional flexible and rigid pavements with a view of the improvement in serviceability and performance. One such alternative is the design of semi-flexible pavement surfaces (SFPS) [9–13].

2. Semi-flexible pavement surfaces

Semi-flexible pavement surface (SFPS) material (also known as grouted macadam) is designed as an open-graded asphalt mixture (OGAM) with 25–35% air voids and then cement grout is infused into the voids [2, 7, 14–17]. However, few researchers advised the range of air voids to be 20–35% [18, 19]. It is a well-known fact that the major demerits of rigid pavements are extended construction time and provision of joints to allow thermal expansion as compared to flexible pavements. Therefore, the semi-flexible pavements are gaining popularity from last few decades and are devised as a jointless pavement with reduced time of construction, easy to repair and construct as well as offers good serviceability and riding quality as compared to rigid pavements [18, 20, 21]. This new type of pavements possesses both flexibility and rigidity which depends on characteristics of the bituminous mixture and cement grout, respectively. Moreover, SFPS provides superior resistance to rutting and are not susceptible to permanent deformation [18]. Semi-flexible pavements have been constructed in various countries as a highway intersection, bus lanes in urban areas, tunnels roads, the pavement in industrial area for the movement of heavy machinery, airport taxiways and aprons as fuel and spillage resistance [15, 16, 21–27].

3. History of the construction of semi-flexible pavement

The first construction of SFPS was carried out in the 1950s, in France and was given the name as Salviacim. It was proposed to provide resistance against oil and fuel attack on the surface and was constructed as a protective layer over conventional asphalt concrete pavement [28]. However, further development of Salviacim was processed by Lefebvre Enterprises, a French construction company, as a replacement to rigid pavements to provide cost-effective construction [29, 30]. Later, this type of pavement construction spread in different countries including South Africa, Saudi Arabia, Australia, UK and Japan as a heavy-duty surface construction [31]. Some other brand names also become popular in Europe based on the type of designed materials such as Hardicrete Heavy-duty surfacing, Densiphalt (or confalt) and Worthycim Heavy-duty surfacing [32–35]. In the USA the semi-flexible pavement is called as Resin Modified Pavement (RMP) and in Japan, it was given name as Rut-proof Pavement (RP-Pavement) [20, 29]. Moreover, the construction of SFPS spread throughout Europe, Various states of Africa, North America, South Pacific and Far East [36].

4. Composition of semi-flexible pavement surfaces

The construction of semi-flexible pavement surfaces (SFPS) is performed in two stages. In the first stage, the open-graded asphalt mixture (OGAM) is prepared, laid, and compacted to achieve the target air voids of 25–35%. The compaction is accomplished by a light application of roller compactor without vibration to avoid disintegration of course aggregates and tracks in the mixture. In the second stage, the cementitious grouts are prepared and poured on the surface of OGAM and allowed to infiltrate into the voids. The construction is normally carried out in two consecutive days, the reason is to allow the OGAM to cool down before applying the cement grouts. Rubber scraper can be used to spread the grout on the surface [18, 20]. The schematic representation of this process is demonstrated in **Figure 1**. Hence the major constitutes of semi-flexible surfaces are a selection of open-graded asphalt mixture and formulation of cement grouts.

4.1 Selection of open graded asphalt mixture

The major constituent in constructing semi-flexible pavement surfaces are the aggregates. Consequently, it needs careful attention while selecting gradation of aggregate for mix designing of semi-flexible mixtures. Typically, semi-flexible pavement surfaces comprise of open-graded asphalt skeleton with air voids ranging from 25 to 35% above which highly flowable cementitious grouts are spread and allowed to penetrate [35, 37, 38]. The key parameters for the selection and design of OGAM for semi-flexible pavements are the consideration of air voids and binder drainage. The air voids of final compacted OGAM shall be in the range of 25 to 35%. In case if air voids are less than 25%, the mixture may not have interconnected voids and would be difficult for the cement grout to penetrate through the depth of OGAM [39]. As a result, adequate strength and homogeneous properties will not be attained to withstand traffic load and environmental stresses as shown in **Figure 2** [18]. On the other hand, if air voids are more than 35%, a large amount of cement grout will be required, and the final mix will more be likely a rigid pavement and may lead to fatigue failure. Similarly, binder drainage (or draindown) of bitumen in the final mixture shall not be more than 0.3% as per AASHTO T 305 or ASTM D6390 standards [40, 41].

Therefore, few studies have been conducted for the selection of suitable aggregate gradation that fulfills the requirement of air voids and binder drainage. Recently, a detailed study has been conducted by Saboo N. et al., (2019) on

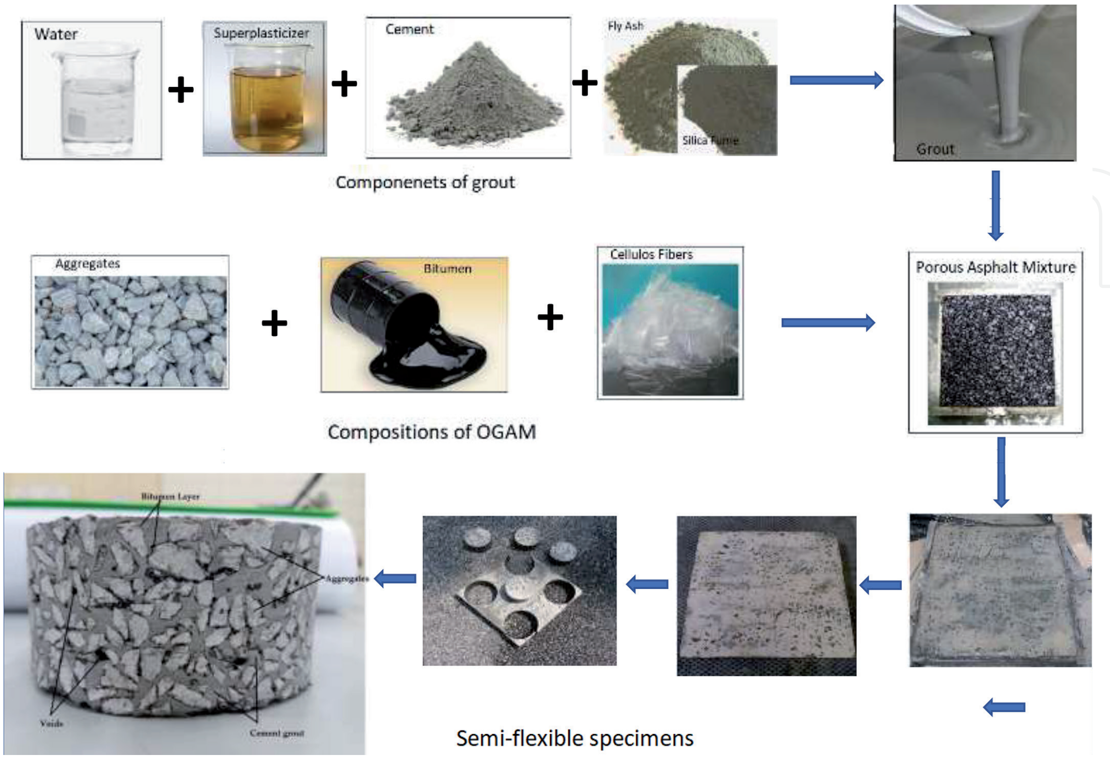

Figure 1.
Schematic representation of the process of preparing semi-flexible surfaces.

Figure 2.
Disconnectivity of internal voids due to low air-voids [18].

evaluating different types of porous aggregate gradations for semi-flexible pavement surfaces. The hierarchical ranking approach was used to reject/select and finally to choose the most desirable gradation system [26]. In this study, seven different porous asphalt mix skeletons were prepared with bitumen contents ranging from 2–5%. The gradations were selected from the previous research that has already been used in various studies and is presented in **Figure 3**.

During the initial elimination process, draindown test, air voids in the compacted mix, voids in the coarse aggregate (VCA), permeability and cantabro loss tests were used. The selected mixtures were further evaluated for Indirect Tensile test (ITS) to rank the gradation system accordingly. It was finally suggested three mixes including BSI with 4% bitumen, Densiphalt-12 with 4% and Densiphalt-12 with 4.5% bitumen were chosen as most desirable porous asphalt mix skeleton to be considered for semi-flexible pavement surfaces as shown in **Table 1** [26].

Similarly, another study was conducted by Hou et al., on the random selection of 22 aggregate gradations by varying percentages of coarse aggregates, fine aggregates, and fillers. The effect of grouting on these gradations was evaluated by volumetric analysis, cantabro and binder drainage test as well as wheel tracking and bending tests [42]. It was revealed that grouting ability of OGAM is not only influenced by initial air voids but also on void interconnectivity, morphological characteristics, and size of pores. The comparison of air voids before and after grouting is demonstrated in **Figure 4** and can be seen that grouting ability is not

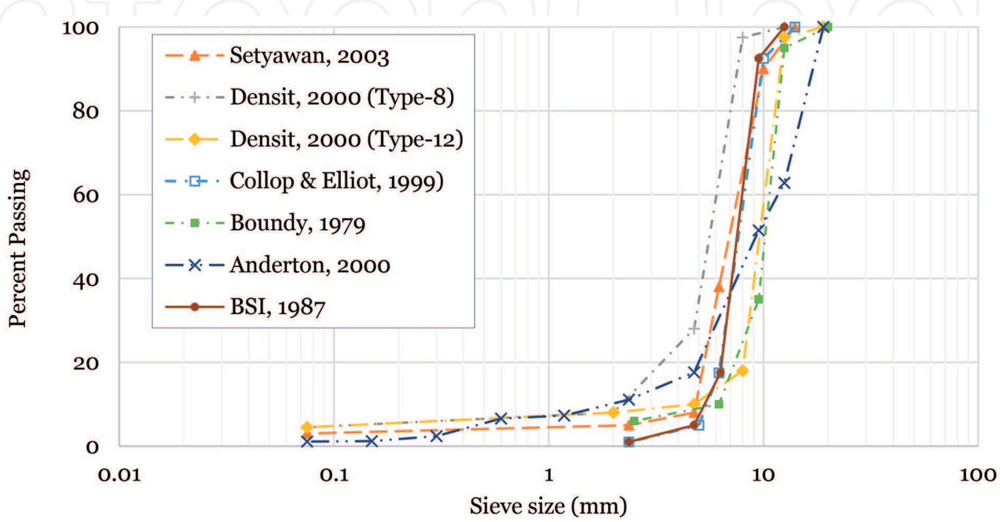

Figure 3.
Porous asphalt gradation curves.

Gradation	Draindown (%) <0.30	Air voids (%) >25%	VCA ratio < 1	Permeability (m/day) >100 m/day	Cantabro loss (%) <50%	ITS(kPa)
BSI with 4% bitumen	0.30	33.05	0.95	362.90	33.20	113.35
Densiphalt-12 with 4%	0.19	33.56	0.93	332.90	34.91	114.42
Densiphalt-12 with 4.5%	0.30	32.08	0.91	247.69	34.91	136.80

Table 1.
Final selection criteria for porous aggregate gradation.

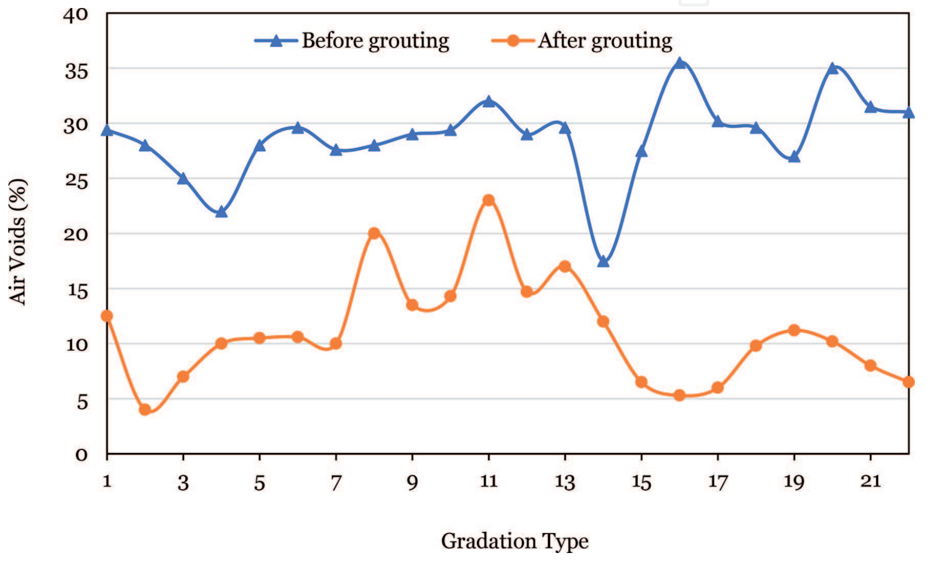

Figure 4.
Air voids before and after grouting [42].

only influenced by initial air voids. The grouting ability can also be enhanced by increasing the percentage of coarse aggregates and reducing binder content (3.8% in this study was used) which can improve the interconnectivity of voids.

4.2 Cement grouts

Cement grout or cement slurry is an essential part of semi-flexible pavement surfaces, which contributes to the rigidity of pavement. The design and formulation of grouts for semi-flexible pavement surfaces differ from traditional cement past and cement mortars used in the concrete industry. The constituents of the grouts are formulated in such a way that can easily be penetrated the voids of OGAM. Additionally, the grouts should have enough strength to withstand the stresses induced due to traffic and the environment. Therefore, the flowability (fluidity), workability, and strength of cement grouts play a key role in the performance of semi-flexible pavement surfaces. In a scenario, if the fluidity of cement grout in insufficient it would not fill properly the air voids of OGAM and as a result, the designed SFP mixtures would not provide sufficient strength and durability. The fluidity of grouts is usually determined by flow-cone, however, the flow-out time depends on the geometry of the cone. Ordinary Portland cement (OPC), water (different ratios), and/or sand, fillers, and other supplementary cementing materials (such as fly ash and silica fume) are normally used to formulate the compositions of cement grouts. Furthermore, superplasticizer can be used to improve the fluidity at a relatively low w/c ratio. Various studies have been conducted on designing the constituents of cement grouts for semi-flexible pavements surfaces and are listed in the following section.

5. Design parameters of cement grouts for SFPS

5.1 Flowability of the cement grouts

One of the primary considerations to formulate the compositions of cementitious grouts for semi-flexible pavement surfaces is the flow or fluidity of grouts. The grouts are required to be sufficiently flowable that can easily penetrate the voids of the porous asphalt skeleton. The flowability/fluidity of grouts highly depends on w/c ratio, superplasticizer as well as other additives and supplementary cementing materials. Traditionally, the flowability/fluidity is measured by flow-cone apparatus in which the desired quantity of grout is poured and the flow-out time of grout from the flow-cone is measured in seconds. Higher the time of flow, lower is the fluidity and hence less workability. On the other hand, a lower time taken by grout to flow-out indicates high flowability and higher workability.

However, the standard requirement of flow-out time of cement grout depends on the geometry and size of the flow-cone, as three different flow-cones are being frequently used in literature. Which are; (a) Malaysian flow-cone, (b) Marsh flow-cone and (c) ASTM flow-cone and their schematic representation are shown in **Figure 5(a-c)**. According to the Malaysian standards, the flow-out time of 1000 mL of grout using Malaysian flow-cone (**Figure 5(a)**) shall be in the range of 11 sec to 16 sec [43, 44]. The cement grouts with the flow of 11–16 sec will have sufficient fluidity and suitable for grouting SFP surfaces. Similarly, the quantity of grout required for Marsh flow-cone (**Figure 5(c)**) is also 1000 mL, however, due to change in geometry the time of flow-out shall be in the range of 8 to 10 sec [38]. Nevertheless, the flow-cone used in ASTM C939 have different geometry as shown in **Figure 5(b)** and hence the requirement of flow-out time. According to the standard, recommended fluidity of cement grout is 10 to 14 sec while allowing a grout quantity of 1725 mL to flow-off the funnel.

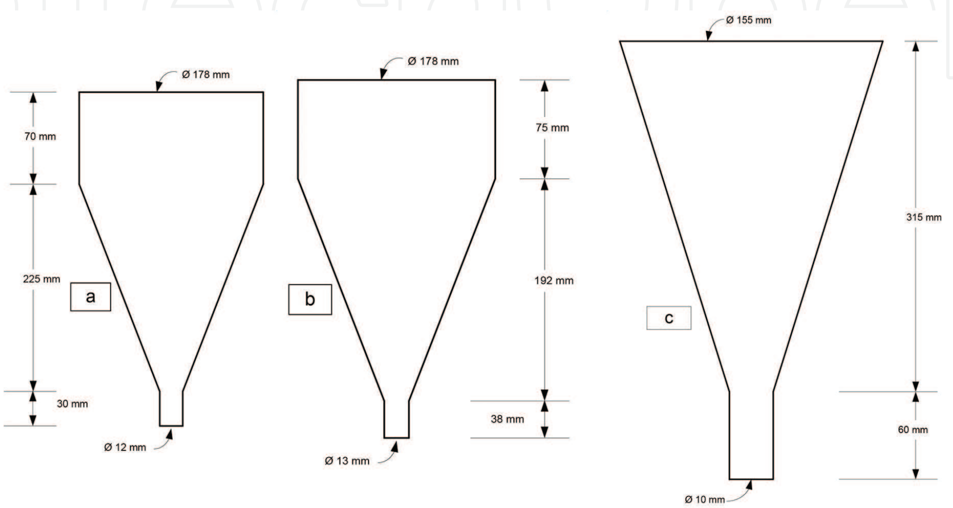

Figure 5.
Flow cones used in literature to measure the fluidity of grouts: (a) Malaysian flow-cone, (b) ASTM flow-cone and (c) marsh flow-cone (dimensions not-to-scale).

Various studies have been conducted on evaluating the fluidity of cement grout by varying water content as well as inclusion superplasticizer, other additives and supplementary cementing materials. However, increasing w/c ratio causes a reduction in strength properties of grout and therefore it shall be carefully selected. To overcome the issues related to high w/c ratio, superplasticizer plays a key role in improving the fluidity of grouts at relatively low w/c ratio. It is always recommended to use superplasticizer in designing cement grouts for SFP surfaces at low w/c ratio in order to achieve the desired strength properties at high flowability of grouts [15, 45]. A study concluded that increasing w/c ratio causes a significant increase in fluidity with a considerable reduction in compressive strength. However, the addition of superplasticizer up to 1% (by weight of cement) causes improvement in fluidity as well as compressive strength. Moreover, increasing superplasticizer beyond 1.5% can cause a bleeding problem in grouts [46].

The incorporation of high w/c ratio and plasticizing action of styrene-butadiene admixtures produces highly flowable cement grout however with low strength properties and gives weaker grouts [15]. On the other hand, stronger grouts with desired fluidity can be achieved by the addition of milled glass and polycarboxylate superplasticizer at relatively low w/c ratio [15]. The highest fluidity presented by the weaker grout group could be explained by their higher water/cement ratio and the styrene-butadiene admixture plasticizing action. In the stronger grouts group, increasing the content of milled glass significantly reduces the flow time values. Incorporating milled glass particles with their impermeable and low specific surface areas indicates that at the same water/cement ratio water is available to fluidize the grouts.

Similarly, in a study different w/c ratio (0.48–0.63), fly ash content (0–20%) and mineral powder (0–20%) were used to design cement paste and to analyze the fluidity of grouts using flow-cone shown in **Figure 5(b)**. Increasing w/c ratio causes a significant increase in the fluidity of cement paste. Similarly, the increase in fluidity was also observed with increase in the dose of fly ash. However, the addition of mineral powder initially causes a reduction in fluidity and then increased was witnessed. Based on fluidity, drying shrinkage and strength properties, 0.56–0.58 w/c ratio, 10% fly ash and 10% mineral powder were recommended as a suitable combination of grouts for SFP mixtures [47].

5.2 Strength properties of grouts

The second most important parameter for selection of cement grout for SFP surfaces is the compressive strength of grouts. The compressive strength largely depends on w/c ratio and other supplementary cementing materials and additives. Various materials have been used so far including, fly ash, silica fume, ground granulated blast furnace slag (GGBS), gypsum and mineral powders for designing cement grouts suitable for SFP surfaces requirements. A study has shown that increase in w/c ratio from 0.48 to 0.63 causes a significant reduction in 7 and 28-days compressive strength, however, flexural strength was slightly reduced [47]. Therefore, there is need to introduce the addition of other admixtures and supplementary cementing materials, such as superplasticizer, fly ash, silica fume which can contribute in improving the strength properties at relatively low w/c ratio while achieving the desired flowability.

The combination of silica fume additionally with superplasticizer can produce grouts with sufficient fluidity and strength properties that can be recommended for semi-flexible pavement surfaces. Hence, silica fume with 5% replacement of OPC and 2.0% polycarboxylate based superplasticizer at 0.30 w/c ratio gives fluidity of 15 sec (as determined by Malaysian flow-cone) and 28-days compressive strength of 92.5 MPa [48]. Therefore, this grout can be recommended to produce high-strength cement grouts for semi-flexible pavement surfaces that can be used in heavy-loaded pavements.

6. Formulation of cement grouts for SFPS

It is necessary to optimize the constituents of cement grouts that can be used as a grouting material for semi-flexible surfaces. The constituents are but not limited to water, cement, superplasticizer, sand, and/or other supplementary cementing materials (SCM). The optimization is normally evaluated based on fluidity and compressive strength (at different curing period). The Authors also conducted a related study to optimize the constituents of cement grout using a statistical tool known as response surface methodology (RSM). In this study, w/c ratio (0.25 to 0.45) and Polycarboxylate-ether type superplasticizer (0 to 2%) were selected as factors (dependent variables) whereas flow-value and compressive strength (1-day, 7-days, and 28-days) were considered as responses (dependent) variables to conduct statistical analysis and optimization in RSM. The ANOVA and multi-objective optimization techniques were utilized to formulate the optimum combination of w/c ratio and dosage of superplasticizer [46].

A study conducted by [49] utilizing latex modified cement mortar to investigate the performance SFPS. The composition of cement grouts was selected as; 0.70 w/c ratio, 20% sand, 10% limestone filler, and latex with 0, 1.2, and 2.4%. The results indicate that an increasing percentage of latex improved the compressive and flexural strength, however, a negative effect on fluidity. Moreover, SFP mixtures with latex-modified grout showed better moisture resistivity, rutting resistance, and fatigue life as compared to conventional asphalt mixture [49]. In another study, three different interface optimizers (silane coupling agent, carboxyl styrene-butadiene latex, and cationic emulsified asphalt) were used with various percentages in cement grouts to improve the interfacial connection between the cement grout and asphalt in SFP mixtures. The results indicate that interface optimizers despite causing a reduction in strength properties of grout, greatly improves the interfacial connection of cement grout with asphalt as observed from microstructural analysis of mixtures as shown in **Figure 6** [50]. These interface optimizers also show a positive effect in terms of crack resistance at low temperature, stability at high temperature, and moisture stability, particularly by cationic emulsified asphalt.

A similar study was conducted to evaluate the adhesion of cement grout with porous asphalt mixture and the mechanical properties of SFP mixtures. In this study a modified cement grout containing; cement, w/c ratio (0.40), silica fume (10%), superplasticizer (2%), aluminum powder (0.04%), viscosity modifying agent (0.2%), and asphalt emulsion (20%, 40% and 60%) were used to produce SFP mixtures. The results indicate that asphalt emulsion modified grouts have better adhesion with porous asphalt mixture as compared to control grouts. This phenomenon may overcome fatigue problems in semi-flexible pavements. The overall performance of semi-flexible pavement mixtures using asphalt emulsion modified grouts showed better performance in terms of rutting resistance, moisture damage resistance, and low-temperature crack resistance as compared to control grout and conventional HMA [1].

An analytical approach using mathematical programming was used to optimize the constituents of cement grouts. Various combinations of grouts were prepared using w/c (0.40, 0.50, 0.60), naphthalene based superplasticizer (0%, 2%, 4%, 6%),

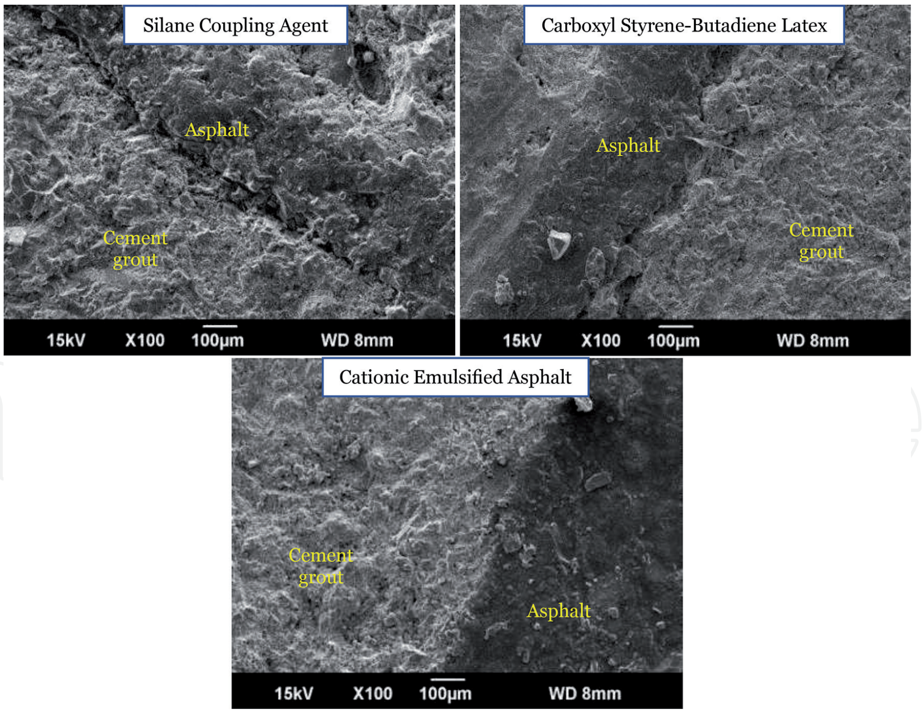

Figure 6.
Microstructure of cement-asphalt interface modified with a silane coupling agent, carboxyl styrene-butadiene latex, and cationic emulsified asphalt [50].

sand with 23% by weight of cement (size <2.36 mm, <1.18 mm, <0.6 mm) to optimize the composition of grouts by evaluating flow and compressive strength properties. The results indicate that flow was significantly improved by increasing the dose of naphthalene superplasticizer from 0 to 6% and the w/c ratio from 0.40 to 0.60. The optimal combination of grouts obtained using mathematical programming was 0.54 w/c ratio, 2% superplasticizer, and 1.66 mm sand size. The flow time and compressive strength at this combination are 14 sec and 24.25 MPa respectively. Similarly, another group of grouts was prepared using polycarboxylate superplasticizer. The compositions were w/c ratio (0.40, 0.45, 0.50), polycarboxylate superplasticizer (0%, 0.5%, 1.0%, 1.5%, 2.0%), sand with 23% by weight of cement (size <2.36 mm, <1.18 mm, <0.6 mm). Interestingly, the compressive strength of grouts increased with an increasing dose of SP from 0 to 1.0% and then starts decreasing again. Moreover, the flow time was significantly decreased with increasing SP and w/c ratio. The optimal doses of ingredients using the analytical approach were 0.48 w/c ratio, 1.0% SP and 0.6 mm sand particle size with flow time of 14 sec and compressive strength of 23.46 MPa [27].

Latex powder (0%, 1.2% and 2.4% by weight of cement) was used to modify cement grout with 0.72 w/c ratio, 20% sand, and 10% filler and to use for semi-flexible pavement mixtures. The addition of latex powder showed improved compressive and flexural strength of cement grout, while causes reduction in fluidity. The latex powder with 1.2% was considered as optimum based on strength and fluidity and was used to produce SFP mixtures. SFP mixtures with 1.2% latex-modified grout showed better resistance to high-temperature performance while higher moisture susceptibility, while weaker fatigue resistance and low-temperature performance. However, the moisture damage and low-temperature behavior of SFP mixtures were still in good agreement [51]. Similarly, cement grout was formulated using 0.63 w/c ratio, 10% mineral filler, 20% sand and 0–12% Carboxyl Latex. The substation of carboxyl latex to grout causes a reduction in compressive strength both at 7-days and 28-days curing.

However, flexural strength was increased with increasing dose of carboxyl latex. Hence, 8% of carboxyl latex was considered as optimum dosage. The performance of SFP mixtures filled with carboxyl latex-modified grout was improved in terms of rutting resistance, low-temperature crack resistance, moisture damage and fatigue resistance [52]. Moreover, various studies have been conducted on the selection of compositions of cement grouts for semi-flexible pavement surfaces as described in **Table 2**.

Composition of grouts	Strength Properties of grouts	Concluding remarks	References
w/c ratio = 0.50, fly-ash = 23%, superplasticizer = 2%	Not determined	SFP mixtures demonstrate higher resistance against rutting and moisture damage as compared to HMA mixtures. SFP mixtures showed lower fatigue life as compared to HMA mixtures. SFP mixtures showed better thermal cracking resistance at low temperatures than HMA mixture using fracture work property.	[53]
w/c ratio = 0.31 Cement grouting was JGM-301 (factory produced)	Compressive Strength: 3-days = 34.5 MPa 28-dyas = 42.3 MPa	It was recommended that semi-flexible pavement surfaces with this grout can be used for heavily loaded pavements.	[19, 54]
Water: cement: sand: filler = 720:1000:497:249 Means: w/c ratio = 0.72, sand =20%, filler = 10% Latex = 0, 1.2%, 2.4%	Compressive Strength: 7-days = 21.6 MPa to 24.1 MPa Flexural Strength: 7-days = 1.65 MPa to 3.54 MPa	Latex in cement mortar has a positive effect on compressive and flexural strength while negative impact on fluidity. SFP mixtures show better moisture resistance, high rutting resistance, and better fatigue life as compared to dense asphalt mixtures. However, SFP mixtures showed poor performance in terms of brittle cracking resistance as compared to dense asphalt mixtures.	[49]

Composition of grouts	Strength Properties of grouts	Concluding remarks	References
Three interface optimizers were used 1. Control grout (OPC) 2. Silane coupling agent (0.25%, 0.50%, 0.75%) 3. Carboxyl styrene-butadiene latex (5%, 10%, 15%) 4. Cationic emulsified asphalt (5%, 10%, 15%) w/c ration = not known	7-days compressive Strength: 1. 42.98 MPa for OPC 2. 34.65 MPa, 36.85 MPa, 33.61 MPa for Silane coupling agent 3. 25.70 MPa, 29.70 MPa, 26.15 MPa for Carboxyl styrene-butadiene latex 4. 37.79 MPa, 33.82 MPa, 31.53 MPa for Cationic emulsified asphalt	The interface optimizers improve the drying shrinkage resistance but cause a reduction in strength properties. The interfacial connection of cationic emulsified asphalt modified grout with bitumen was proved to be best whereas worst for silane coupling agent. These interface optimizers also deliver satisfactory results in terms of crack resistance at low temperature, stability at high temperature, and moisture stability.	[50]
w/c ratio = 0.40 silica fume = 10% SP = 2% aluminite powder (AP) = 0.04% viscosity modifying agent (VMA) = > VMA/C = 0.2% Asphalt Emulsion (AE)/cement binder AE/C = 20%, 40%, 60%	7-days compressive Strength: CP = 26 MPa CAEP20% = 13 MPa CAEP40% = 11.3 MPa CAEP60% = 10.5 MPa 28-days compressive Strength: CP = 28.5 MPa CAEP20% = 19 MPa CAEP40% = 17.8 MPa CAEP60% = 17 MPa	The compressive strength of grout reduces with the addition of asphalt emulsion. The asphalt emulsion improves the adhesion between cement grout and porous asphalt mixture. SFP with asphalt emulsion-based grouts has better rutting resistance as compared to conventional HMA. However, the rutting resistance decrease with increasing percentages of asphalt emulsion in the grouts. The overall performance of SFP mixtures based on asphalt emulsion modified grouts have better performance in terms of rutting resistance, moisture damage resistance, and low-temperature crack resistance as compared to control grout and conventional HMA.	[1]

Composition of grouts	Strength Properties of grouts	Concluding remarks	References
Naphthalene based superplasticizer = 0, 2%, 4%, 6% w/c ratio = 0.4, 0.5, 0.6 Sand = 23% by weight of cement	7-days compressive Strength: 10.22 MPa to 31.65 MPa (for sand size <0.6 mm) 13.15 MPa to 33.75 MPA ((for sand size <1.18 mm) 16.48 MPa to 36.69 MPA ((for sand size <2.36 mm)	An analytical approach was used for optimization using mathematical programming. The optimal composition of grout: w/c ratio = 0.54, SP = 2% with compressive strength of grout = 24.25 MPa	[27]
Polycarboxylate superplasticizer = 0, 0.5%, 1%, 1.5%, 2% w/c ratio = 0.4, 0.45, 0.50 Sand = 23% by weight of cement	7-days compressive Strength: 13.15 MPa to 29.10 MPa (for sand size <0.6 mm) 16.38 MPa to 30.39 MPA ((for sand size <1.18 mm) 18.45 MPa to 31.20 MPA ((for sand size <2.36 mm)	An analytical approach was used for optimization using mathematical programming. The optimal composition of grout: w/c ratio = 0.48, SP = 1% with compressive strength of grout = 23.46 MPa	[27]
w/c ratio = 0.72, sand =20%, filler = 10% Latex powder (LP) = 0, 1.2%, 2.4%	7-days Compressive Strength: 23.5 MPA (0% LP), 24.1 MPa (1.2% LP), 21.6 MPa (2.4% LP) 7-days Flexural Strength: 1.65 MPa (0% LP), 2.81 MPa (1.2% LP), 3.54 MPa (2.4% LP)	Fluidity decreases with increasing latex powder. The cement grout with 1.2% latex powder has higher compressive strength as compared to control and 2.4% latex powder. However, the flexural strength of grouts increased with increasing latex powder. SFP mixtures with latex-modified grout showed better resistance to high-temperature performance and moisture susceptibility, while weaker fatigue resistance and low-temperature performance.	[51]

Composition of grouts	Strength Properties of grouts	Concluding remarks	References
w/c ratio = 0.63, mineral filler = 10% and sand = 20% Carboxyl Latex = 0–12%	7-days Compressive Strength: 20.76 MPa to 11.20 MPa 28-days Compressive Strength: 31.43 MPa to 18.56 MPa 7-days Flexural Strength: 1. MPa to 4.95 MPa 28-days Flexural Strength: 5.74 MPa to 6.49 MPA	The substation of carboxyl latex to grout causes a reduction in compressive strength both at 7-days and 28-days curing. However, flexural strength was increased with increasing dose of carboxyl latex. 8% carboxyl latex was considered as optimum dosage. The performance of SFP mixtures filled with carboxyl latex-modified grout was improved in terms of rutting resistance, low-temperature crack resistance, moisture damage and fatigue resistance.	[52]
w/c ratio = 0.60 cement: sand = 1: 0.5	3-days compressive strength = 10.4 MPa 28-dyas compressive strength = 30.7 MPa 3-days Flexural Strength = 3.3 MPa 28-days Flexural Strength = 7.3 MPa	The semi-flexible mixtures show better high-temperature performance while maintaining its flexibility. It also demonstrates better results of low-temperature cracking resistance as compared to conventional HMA. However, the split tensile strength was lowered. The SFP mixtures showed significant improvement in moisture resistance and present great advantages over conventional HMA.	[55]

Composition of grouts	Strength Properties of grouts	Concluding remarks	References
Cement paste: w/c ratio = 0.48, 0.53, 0.58, 0.63 fly ash = 0%, 10%, 20% mineral powder (ground granulated blast furnace slag) = 0%, 10%, 20% **Cement mortar:** w/c ratio = 0.55, 0.60, 0.65 fly ash = 0%, 10%, 20% mineral powder (ground granulated blast furnace slag) = 0%, 10%, 20% Sand = 10%, 15%, 20%	**Optimal Combinations:** Cement paste: 0.56–0.58 w/c ratio, 10% fly ash and 10% mineral powder Cement mortar: 0.61–063 w/c ratio, 10% fly ash and 15% mineral powder	The overall performance of cement paste was observed to be better than cement mortar in terms of fluidity and strength and recommended more suitable for grouting semi-flexible pavement surfaces with the following combinations; w/c ratio = 0.58, fly ash = 10 and mineral powder = 10%	[47]
w/c ratio = 0.30, 0.35, 0.40, 0.45, 0.50 SP (Polycarboxylate) = 0 to 2.5% Silica fume = 0%, 5% and 10% Optimum combination of 0.30 w/c ratio, 2.0% SP and 5% silica fume	1-day compressive strength = 57.5 MPa 28-days compressive strength = 92.5 MPa 7-days Flexural strength = 6.7 MPa 28-days Flexural strength = 9.1 MPa	Grout with 5% replacement of SF and 2.0% SP produces cement grouts with desirable flowability and compressive strength required for SFP surfaces.	[48]

Table 2.
Summary of the various types of cement grouts used in literature.

7. Irradiated polyethylene terephthalate (PET) based cement grouts

The authors utilized an innovative and effective way of recycling waste PET in cement grouts for semi-flexible pavement surfaces. This was done by exposing waste PET to gamma rays, which, in fact, improve the crystallinity and chain-scission properties of PET. The waste PET was obtained from Plastic Recycling Factory, Ipoh, Malaysia. The initial particle size was in the range of 0.075 mm to 0.85 mm. After exposing to gamma rays, the PET was further sieved on 0.015 mm sieve to obtain a fine powder.

Utilizing regular PET in cement grouts causes a significant reduction in strength properties, however, some of the lost strength can be recovered back while using irradiated PET instead of regular PET. Similarly, silica fume and fly ash were also added for the purpose to achieve high strength cement grouts. The elemental and chemical composition of cement (OPC), silica fume and fly ash are given in **Table 3**.Initially, cement grouts were produced by varying water-cement (w/c) ratio (0.25 to 0.45) and superplasticizer (0–2%) and were evaluated for flowability using Malaysian flow cone and compressive strength at 1-day, 7-days and 28-days curing. Based on flowability in the range of 11 sec to 16 sec, maximizing compressive strength and taking into account the bleeding problem, w/c ratio of 0.35 and superplasticizer of 1% were selected. Further grouts were produced by replacing OPC with regular PET, Irradiated PET, fly ash and silica fume. The compositions are demonstrated in **Table 4**.

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	TiO_2	P_2O_5	Na_2O	Others
Cement	22.65	4.63	2.34	61.72	4.23	1.14	2.24	0.20	0.12	0.11	0.62
Silica Fume	92.5	0.92	0.8	0.93	1.6	0.5	0.82	—	—	0.2	1.73
Fly Ash	36.4	13.72	18.24	19	3.26	2.2	2.5	1.45	1.2	1.73	0.3

Table 3.
Elemental and chemical composition of cement, silica fume and fly ash.

Grout symbol	PET % (regular/irradiated)	Fly ash %	Silica fume %	Other constitutes
G1	0	0	0	0.35 w/c ratio 1% SP
G2	2.5	10	—	
G3	5	10	—	
G4	7.5	10	—	
G5	10	10	—	
G6	2.5	—	5	
G7	5	—	5	
G8	7.5	—	5	
G9	10	—	5	

Table 4.
Constitutes of PET based cement grouts.

7.1 Flow properties of PET-based grouts

The flowability/fluidity of cement grouts was determined by measuring the flow-out time of 1-liter grout using Malaysian flow-cone. The results of fluidity are demonstrated in **Figure 7**. it can be seen that increasing PET content tends to increase the flow-out time and hence causes a reduction in fluidity. However, no

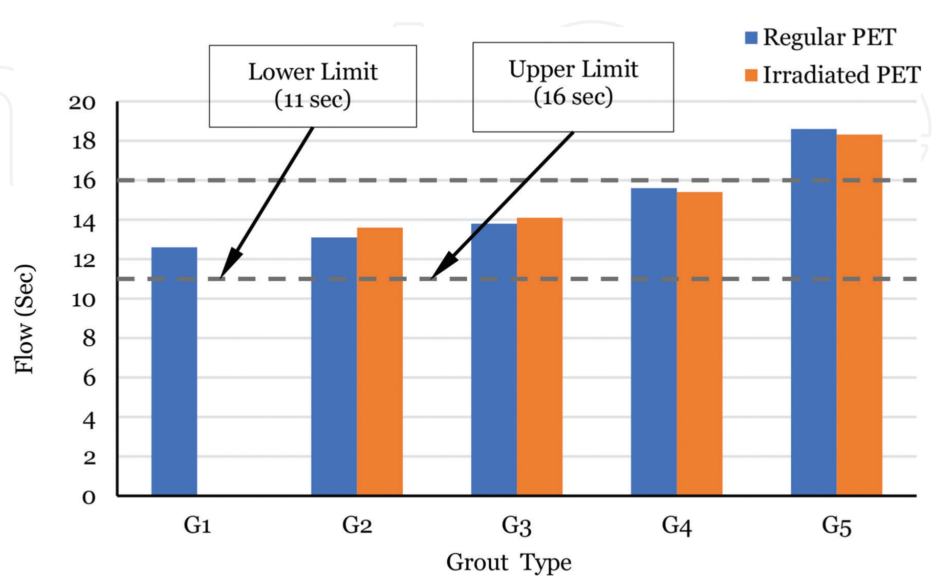

Figure 7.
Fluidity of cement grouts containing PET and FA.

significant change occurs due to the irradiation of the PET. Moreover, the fluidity of all grouts is within the range of 11 sec to 16 sec except grout containing 10% PET (regular and irradiated). The reduction in the fluidity of grout containing PET is due to the relatively large particle size of PET as compared to cement which restricts the free movement of a particle in the grouts.

Similar behavior is also noticed in grouts containing PET and silica fume as illustrated in **Figure 8**. The fluidity decreased with increasing PET content in the presence of silica fume as compared to controlled grouts. However, the fluidity of grouts containing silica fume is quite lower than that of grouts containing fly ash at the same PET contents. In this case, the fluidity of grouts containing 7.5% PET and 10% PET does not lie within the required range and hence cannot be recommended for SFP surfaces.

7.2 Strength of grouts containing irradiated PET

The compressive strength of grouts was determined by fabricating cube specimens of dimension 50 mm *50 mm *50 mm. After demolding, the specimens were cured in water and tested for compression test at 7-days and 28-days curing age. The results are illustrated in **Figures 9–12**.

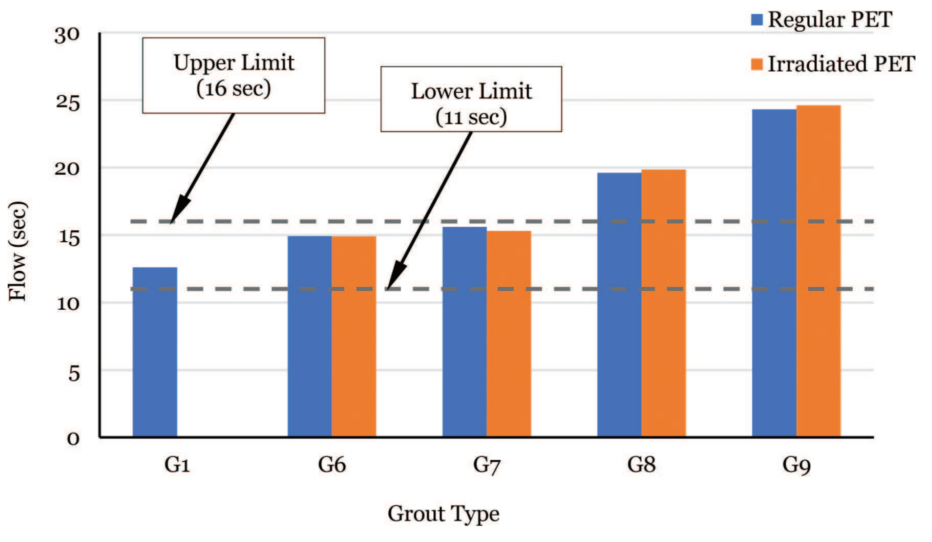

Figure 8.
Fluidity of cement grouts containing PET and SF.

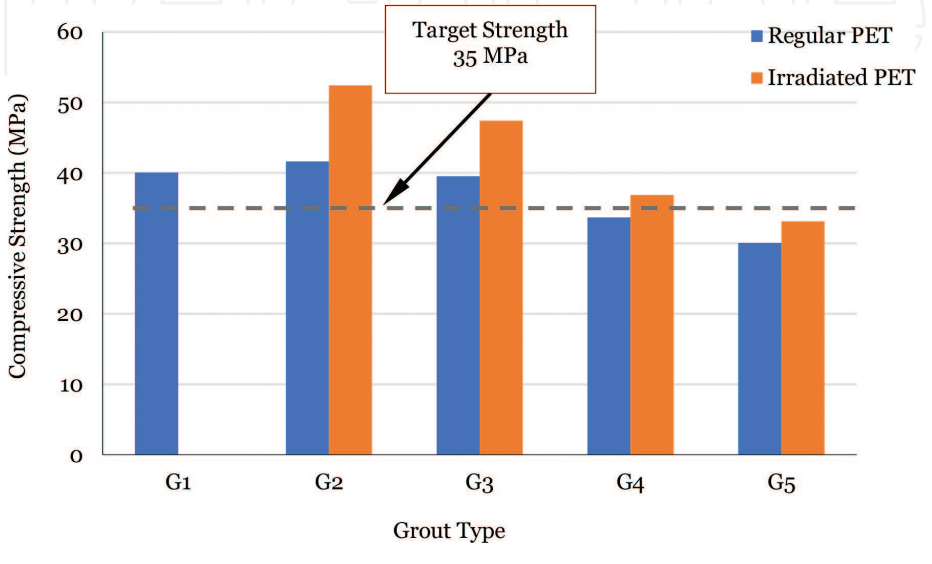

Figure 9.
Compressive strength (7-days) of grouts containing PET and FA.

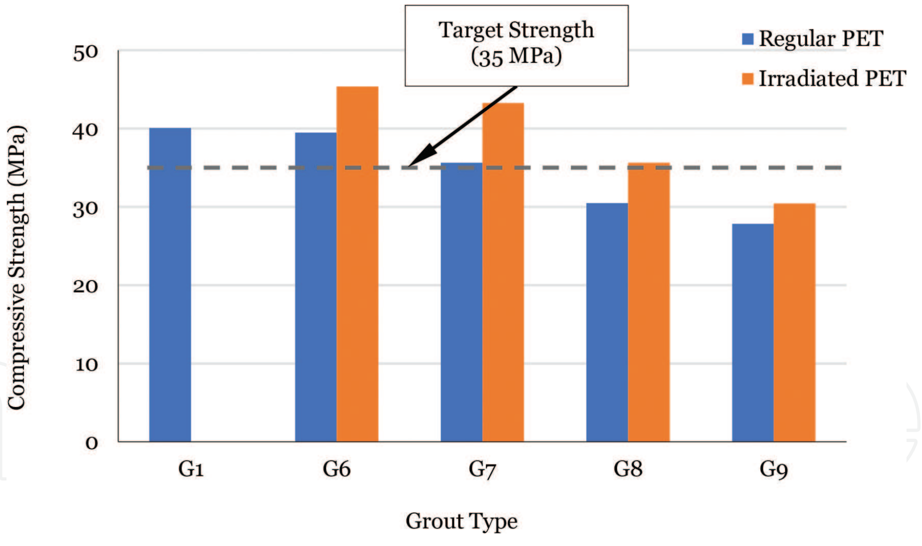

Figure 10.
Compressive strength (7-days) of grouts containing PET and SF.

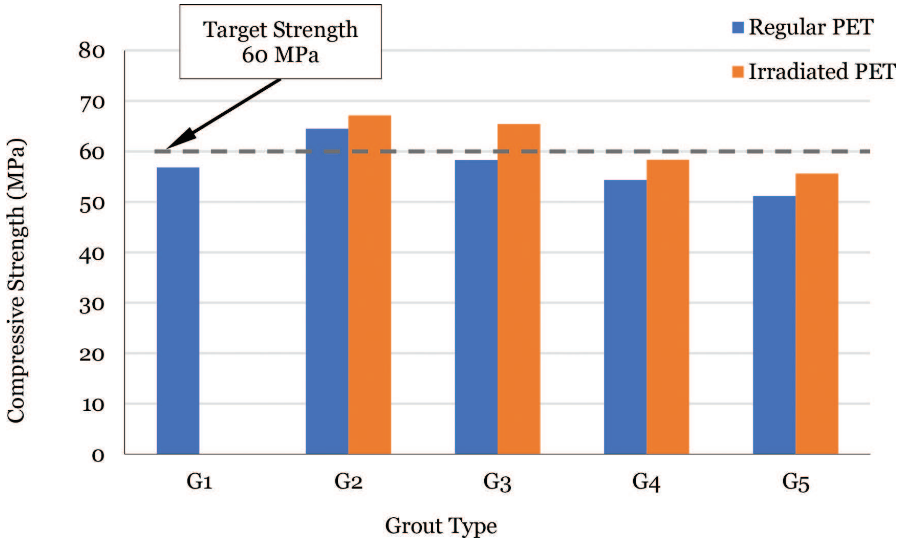

Figure 11.
Compressive strength (28-days) of grouts containing PET and FA.

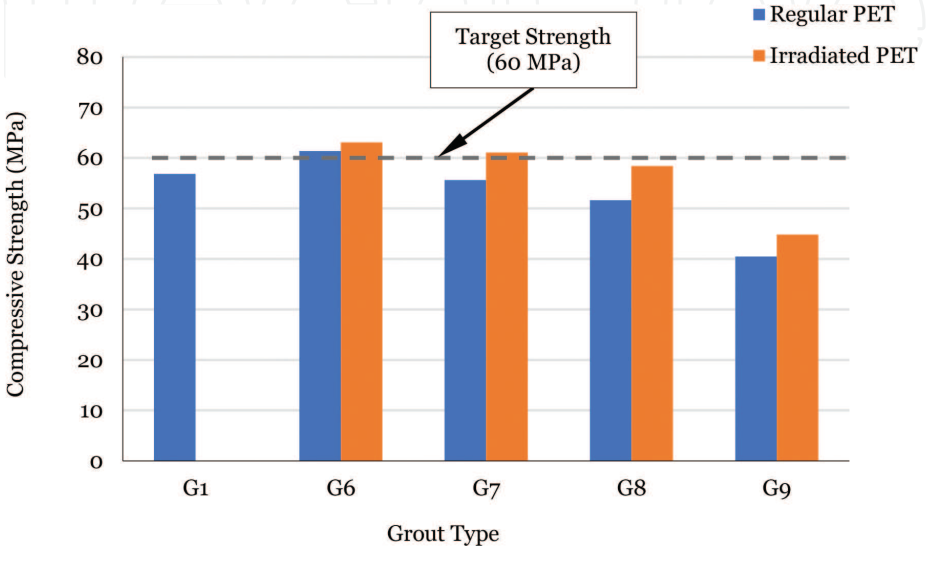

Figure 12.
Compressive strength (28-days) of grouts containing PET and SF.

It is a well-known fact that replacing cement with PET causes a significant reduction in strength properties. On the other hand, compressive strength is improved while using 10% FA as a cement replacement and in combination with a superplasticizer. It can be seen from **Figure 9**, grout containing 2.5% regular PET and 10% FA (G2) has slightly higher 7-days compressive strength compared to controlled grout (G1). Despite 10% FA, all other grouts containing regular PET (i.e 5%PET, 7.5%PET, and 10%PET) have 7-days compressive strength lower than that of control grout. It is due to the loss in compressive strength while replacing cement with PET. Interestingly, a significant amount of strength has been recovered while using irradiated PET instead of regular PET as show in G2 to G5. The strength recovery is higher at a lower percentage of PET (i.e 2.5% and 5%) and lower at higher percentages. The purpose of this study was to recycle the maximum percentage of waste PET while achieving the target 7-days compressive strength of 35 MPa. Hence, it can be seen that the cement grout containing 7.5% regular PET does not achieve the target strength, however, with the irradiation the same dosage of PET replacement reached the target strength. Similar behavior is noticed in the grouts containing silica fume and PET as shown in **Figure 10**. However, the 7-days compressive strength of all grouts containing regular PET (G6 to G9) is lower than controlled grout (G1).

Moreover, 28-days compressive strength gives a more clear picture to decide the final maximum percentage of PET that can replace cement in the grouts. **Figure 11** depicts that grout with 2.5% PET (both regular and irradiated) achieved the target strength of 60 MPa. However, grout containing 5% of regular PET does not reach the target line. Interestingly, 5% of irradiated PET recovered the strength loss and reached the target strength. Furthermore, 7.5% PET and 10% PET (both regular and irradiated) have lower compressive strength than the target value and hence cannot be recommended. The very similar behavior is also witnessed in the grouts containing silica fume in addition to regular and irradiated PET as shown in **Figure 12**. Grout containing 5% irradiated PET just achieved the target strength of 60 MPa while the strength of 5% regular PET is quite lower than the target line. Moreover, the overall strength of grouts containing FA is higher than that of grouts containing SF.

8. Conclusion

In the current study, cement in the grouts was replaced with PET (regular and irradiated), fly ash and silica fume and were evaluated for flowability and strength properties. Following conclusions are summarized from this study.

The air voids content in the range of 25–35% is generally required in mix designing the open-graded asphalt mixtures for semi-flexible pavement surfaces. These voids are required to ensure the interconnectivity of vids in the mixture to allow grout infiltration.

Highly flowable cement grouts are required to properly fill the voids in the open graded asphalt mix. Utilization of superplasticizer not only reduce the water-cement ratio but also improve strength properties up to some extent. Similarly, the pozzolanic reaction of fly ash and silica fume is also enhanced by using superplasticizer and help in improving 7-days and 28-days compressive strength as compared to controlled grout.

Utilizing regular PET causes a significant reduction in the compressive strength of grout. However, the irradiation process of PET (by exposing to gamma rays) recovers some strength which was lost due to regular PET. Similarly, the compressive strength was also improved by additional replacement of cement with fly ash and silica fume.

In achieving the target fluidity of 11–16 sec and 28-days compressive strength of 60 MPa, a maximum of 2.5% regular PET can be used as a cement replacement in addition to fly ash and silica fume. Interestingly, the same range of fluidity and target strength was achieved with 5% irradiated PET. Hence, the irradiation of PET can be used as an effective way to recycle a relatively large amount of plastics in the construction industry to achieve sustainability.

Finally, 0.35 w/c ratio, 1% superplasticizer, 5% irradiated PET in addition to 10% fly ash or 5% silica fume are recommended as a composition of cement grouts that can be used in designing semi-flexible pavement surfaces with an aim of sustainability and reducing greenhouse gas emission.

Author details

Muhammad Imran Khan[1]*, Muslich Hartadi Sutanto[1], Madzlan Bin Napiah[1] and Salah E. Zoorob[2]

1 Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Malaysia

2 Construction and Building Materials Program, Kuwait Institute for Scientific Research, Kuwait

*Address all correspondence to: muhammad_17007177@utp.edu.my

References

[1] Zarei, S., et al., Experimental analysis of semi-flexible pavement by using an appropriate cement asphalt emulsion paste. Construction and Building Materials, 2020. **230**: p. 116994.

[2] Cai, J., et al., Comprehensive service properties evaluation of composite grouting materials with high-performance cement paste for semi-flexible pavement. Construction and Building Materials, 2017. **153**: p. 544-556.

[3] Abedini, M., et al., Low-temperature adhesion performance of polymer-modified Bitumen emulsion in chip seals using different SBR latexes. Petroleum Science and Technology, 2017. **35**(1): p. 59-65.

[4] Moghaddam, T.B., M.R. Karim, and M. Abdelaziz, A review on fatigue and rutting performance of asphalt mixes. Scientific Research and Essays, 2011. **6**(4): p. 670-682.

[5] Xu, T. and X. Huang, Investigation into causes of in-place rutting in asphalt pavement. Construction and Building Materials, 2012. **28**(1): p. 525-530.

[6] Hou, S., T. Xu, and K. Huang, Investigation into engineering properties and strength mechanism of grouted macadam composite materials. International Journal of Pavement Engineering, 2016. **17**(10): p. 878-886.

[7] Ling, T.-Q., et al., The Application of Semi-Flexible Pavement on Heavy Traffic Roads. International Journal of Pavement Research and Technology, 2009. **2**(5).

[8] Oliveira, J.R.M., N.H. Thom, and S.E. Zoorob, Design of Pavements Incorporating Grouted Macadams. Journal of Transportation Engineering, 2008. **134**(1): p. 7-14.

[9] Disfani, M.M., et al., Performance evaluation of semi-flexible permeable pavements under cyclic loads. International Journal of Pavement Engineering, 2020. **21**(3): p. 336-346.

[10] Pratelli, C., et al., Preliminary In-Situ Evaluation of an Innovative, Semi-Flexible Pavement Wearing Course Mixture Using Fast Falling Weight Deflectometer. Materials (Basel, Switzerland), 2018. **11**(4): p. 611.

[11] Tran, T.N., et al. Semi-flexible material: The sustainable alternative for the use of conventional road materials in heavy-duty pavement. in Congrès International de Géotechnique–Ouvrages–Structures. 2017. Springer.

[12] LING, T.-q., et al., Research on performance of water-retention and temperature-fall semi-flexible pavement material. China Journal of Highway and Transport, 2010. **2**.

[13] Al-Qadi, I.L., H. Gouru, and R. Weyers, Asphalt Portland cement concrete composite: laboratory evaluation. Journal of transportation engineering, 1994. **120**(1): p. 94-108.

[14] Pei, J., et al., Design and performance validation of high-performance cement paste as a grouting material for semi-flexible pavement. Construction and Building Materials, 2016. **126**: p. 206-217.

[15] Afonso, M.L., et al., Development of a semi-flexible heavy duty pavement surfacing incorporating recycled and waste aggregates – Preliminary study. Construction and Building Materials, 2016. **102**: p. 155-161.

[16] Yang, B. and X. Weng, The influence on the durability of semi-flexible airport pavement materials to cyclic wheel load test. Construction and Building Materials, 2015. **98**: p. 171-175.

[17] Hirato, T., M. Murayama, and H. Sasaki, Development of high stability hot mix asphalt concrete with hybrid binder. Journal of Traffic and Transportation Engineering (English Edition), 2014. **1**(6): p. 424-431.

[18] Hassani, A., M. Taghipoor, and M.M. Karimi, A state of the art of semi-flexible pavements: Introduction, design, and performance. Construction and Building Materials, 2020. **253**: p. 119196.

[19] Cai, X., et al., Interlocking property evaluation of dual skeleton in semi-flexible pavement material by micromechanical model and X-ray computed tomography. Construction and Building Materials, 2020. **254**: p. 118934.

[20] Oliveira, J.R., Grouted macadam: material characterisation for pavement design. 2006, University of Nottingham: Nottingham.

[21] Corradini, A., et al., Improved understanding of grouted mixture fatigue behavior under indirect tensile test configuration. Construction and Building Materials, 2017. **155**: p. 910-918.

[22] An, S., et al., Laboratory and Field Evaluation of a Novel Cement Grout Asphalt Composite. Journal of Materials in Civil Engineering, 2018. **30**(8): p. 04018179.

[23] Gong, M., et al., Evaluation on the cracking resistance of semi-flexible pavement mixture by laboratory research and field validation. Construction and Building Materials, 2019. **207**: p. 387-395.

[24] Hassan, K., A. Setyawan, and S. Zoorob. Effect of cementitious grouts on the properties of semi-flexible bituminous pavements. in Proceedings of the 4th European Symposium on Performance of Bituminous and Hydraulic Materials In Pavements, Bitmat 4, 11-12 April 2002, Nottingham, UK. 2002. Routledge.

[25] Cihackova, P., et al., Performance characteristics of the open-graded asphalt concrete filled with a special cement grout. Baltic Journal of Road and Bridge Engineering, 2015. **10**(4): p. 316-324.

[26] Saboo, N., et al., Development of hierarchical ranking strategy for the asphalt skeleton in semi-flexible pavement. Construction and Building Materials, 2019. **201**: p. 149-158.

[27] Saboo, N., et al., Optimal proportioning of grout constituents using mathematical programming for semi flexible pavement. International Journal of Pavement Research and Technology, 2019. **12**(3): p. 297-306.

[28] Van de Ven, M. and A. Molenaar, Mechanical Characterization of Combi-layer. Asphalt paving technology, 2004. **73**: p. 1-22.

[29] Anderton, G.L., Engineering properties of resin modified pavement (RMP) for mechanistic design. 2000: U.S. Army Corps of Engineers, Engineer Research and Development Center.

[30] Setyawan, A., Development of semi-flexible heavy-duty pavements. 2006, University of Leeds.

[31] Ahlrich, R.C. and G.L. Anderton, Construction and Evaluation of Resin Modified Pavement. 1991, Army Engineer Waterways Experiment Station Vicksburg MS Geotechnical Lab: Army Engineer Waterways Experiment Station Vicksburg MS Geotechnical Lab.

[32] British Board of Agrement (BBA), Hardicrete Heavy Duty Surfacing. 1994, British Board of Agrement (BBA), Agrement Certificate No 88/1969. Watford.

[33] British Board of Agrement (BBA), Worthycim Heavy Duty Paving. 1996, British Board of Agrement (BBA), Agrement Certificate 87/1900. Watford.

[34] ApS, C. A Jointless Wearing Course with High Strength for High Loads. 2018 [cited 2018 December]; Available from: http://www.confalt.com/confaltr.html.

[35] Densit-a/s, "Densiphalt Handbook". 2000, Aalborg,.

[36] Ahlrich, R.C. and G.L. Anderton. Resin Modified Pavement in Airfield Applications. in Airport Pavement Innovations. Theory to Practice. Proceedings of Conference Held Sept 8-10, 1993, Vicksburg, Mississippi, USA. 1993.

[37] Ricci, R., Laboratory study of grouted macadams impregnated with mine waste geopolymeric binder. 2012, University Di Bologna.

[38] Anderton, G.L., Engineering properties of resin modified pavement (RMP) for mechanistic design. 2000: Engineer Research and Development Center Vicksburg MS Geotechnical Lab.

[39] Vavrik, W.R., et al., The bailey method of gradation evaluation: the influence of aggregate gradation and packing characteristics on voids in the mineral aggregate (with discussion). Journal of the Association of Asphalt Paving Technologists, 2001. **70**.

[40] AASHTO T 305, Standard method of test for determination of draindown characteristics in uncompacted asphalt mixtures. 2005, American Association of State Highway and Transportation Officials.

[41] ASTM D6390, Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures, in ASTM International, West Conshohocken, PA. 2017, ASTM International, West Conshohocken, PA: ASTM International, West Conshohocken, PA.

[42] Hou, S., T. Xu, and K. Huang, Aggregate Gradation Influence on Grouting Results and Mix Design of Asphalt Mixture Skeleton for Semi-Flexible Pavement. Journal of Testing and Evaluation, 2017. **45**(2): p. 591-600.

[43] REAM, Road Engineering Association of Malaysia, "Speciication of Semi-Rigid Wearing Course". 2007, Road Engineering Association of Malaysia (REAM).

[44] P.W.D, Public Works Department "Description of Workmanship and Materials (Semi-Rigid Pavement), Section E" City Hall Kuala Lumpur, Kuala Lumpur, Malaysia, 2003. 2003.

[45] Anagnostopoulos, C.A., Effect of different superplasticisers on the physical and mechanical properties of cement grouts. Construction and Building Materials, 2014. **50**: p. 162-168.

[46] Imran Khan, M., et al., Optimization of Cementitious Grouts for Semi-Flexible Pavement Surfaces Using Response Surface Methodology. IOP Conference Series: Earth and Environmental Science, 2020. **498**: p. 012004.

[47] Zhang, J., et al., Formulation and performance comparison of grouting materials for semi-flexible pavement. Construction and Building Materials, 2016. **115**: p. 582-592.

[48] Koting, S., et al., Effects of Using Silica Fume and Polycarboxylate-Type Superplasticizer on Physical Properties of Cementitious Grout Mixtures for Semiflexible Pavement Surfacing. The Scientific World Journal, 2014. **2014**: p. 7.

[49] Zhong, K., et al., Interfacial and mechanical performance of grouted open-graded asphalt concrete with latex modified cement mortar. Construction and Building Materials, 2020. **234**: p. 117394.

[50] Xu, Y., et al., High-Performance Semi-Flexible Pavement Coating Material with the Microscopic Interface

Optimization. Coatings, 2020. **10**(3): p. 268.

[51] Luo, S., et al., Open-graded asphalt concrete grouted by latex modified cement mortar. Road Materials and Pavement Design, 2018. **21**(1): p. 1-17.

[52] Wang, D., et al., Impact analysis of Carboxyl Latex on the performance of semi-flexible pavement using warm-mix technology. Construction and Building Materials, 2018. **179**: p. 566-575.

[53] Zhang, W., et al., Performance Characterization of Semi-Flexible Composite Mixture. Materials, 2020. **13**(2): p. 342.

[54] Cai, X., et al., Identification of microstructural characteristics in semi-flexible pavement material using micromechanics and nano-techniques. Construction and Building Materials, 2020. **246**: p. 118426.

[55] Zhang, H., et al., Study on the mechanical performance and application of the composite cement–asphalt mixture. International Journal of Pavement Engineering, 2019. **20**(1): p. 44-52.