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PERFORMANCE OF POLYMER GROUTS MADE FROM WASTES FOR PERMEABLE RIGID PAVEMENT CONNECTIONS

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Abstract — This research developed polymer grouts made from wastes such as fly ash, palm oil fuel ash, and silica fume. The selected polymer grouts served as an interlocking key between the StormPav covers and as a grout to seal the gaps between the interlocking keys and StormPav covers. Based on compressive strength and workability of the polymer grouts, mix ratio of resin to fly ash = 1:1.00 was chosen as the grout, while mix ratio of resin to fly ash = 1:1.50 was used to form an interlocking key. Mix ratios of resin to fly ash = 1:1.00 and resin to fly ash = 1:1.50 had a compressive strength of 98.90 MPa and 81.70 MPa, respectively, and flexural strength of 53.00 MPa and 61.90 MPa. Moreover, increasing the fly ash content in polymer grout decreased the water absorption and volume of permeable voids. In terms of shear strength, the mix ratio of resin to fly ash = 1:1.00 performed well as grout, with a determined shear strength of 3.98 MPa. Even after 25 days of exposure to the high concentration of sodium hydroxide, sulphuric acid, sodium chloride, and magnesium sulphate, the determined shear strength met the minimum shear strength requirement of 1.38 MPa as stated by the Iowa Department of Transportation. Therefore, it can be concluded that both selected mix ratios were suitable for use as grout and interlocking key due to their good physical and mechanical properties.

***Keywords*:** concrete, pavement, polymer grout, shear strength, waste

1.0 INTRODUCTION

Permeable pavement is not a new concept and it had been evolving since the 1960s [1]. Permeable pavements allow rainwater to infiltrate and then drain to the drainage system or an underground detention system for water storage. The permeable rigid pavement used in this study is called StormPav, and it is a patented Industrialized Building System (IBS) (Malaysia patent application no. PI 2016704420). Figure 1 illustrates the StormPav permeable rigid pavement which consisted of three components known as top cover, a cylinder, and a bottom cover that combined to form a singular modular unit reinforced with steel reinforcement. StormPav was cast using Grade 50 concrete with a crushing load of more than 100 kN/unit [1]. The schematic diagram in Figure 2 depicts a single modular unit of StormPav. All the precast components (top and bottom covers, and cylinder) will be erected on site. The purpose of this research was to determine appropriate grouts for sealing the gap between the interlocking keys and the StormPav covers, and also used to prepare the interlocking keys. This is because a suitable grout is required to connect the StormPav covers in order for the StormPav permeable rigid pavement to act monolithic.

Grout is used to fill voids and gaps [2]. Grouts are widely used in different fields in civil engineering such as crack injection, dynamic water grouting, foundation treatment, geothermal energy applications, precast construction, rock grouting, structural rehabilitation, and others [3–6]. There are two types of grouts known as cement-based grouts and chemical grouts [3, 4, 7]. The cement-based grouts can be further divided into clay-concrete slip, cement-water glass, and cement and flying ash grout [3]. Different types of admixtures or additives are used in cement grout to improve the performance of the grouts such as fly ash, silica fume, metakaolin, slag, coal dust, and others [5]. While, the chemical grouts can be divided into sodium silicate-based grouts, epoxy resin, unsaturated polyester, urea-formaldehyde resin, and polyurethane form [3, 7, 8]. As for chemical grouts, Fang et al. [8] reinforced the polyurethane foam with crushed stone.

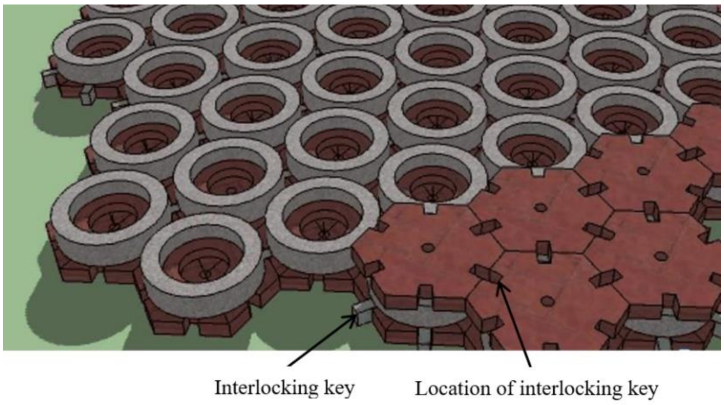

Figure 1 Precast StormPav permeable rigid pavement

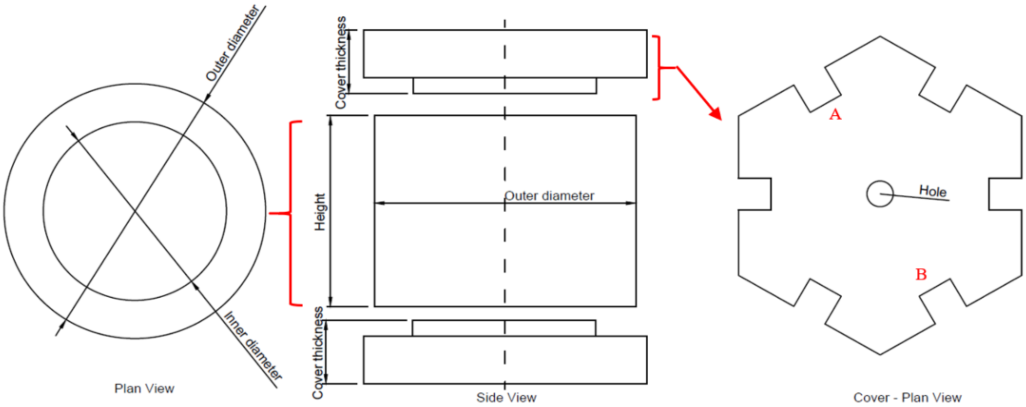

Figure 2 Schematic diagram of StormPav

The type of grouts chosen are determined by factors such as soil properties, project purpose, cost, and grout strength requirement [5, 7]. For steel structures, according to BSI [9], based on Eurocode 3, the characteristic strength is a minimum of 0.2 times the characteristic strength of the concrete foundation for grout thickness less than 0.2 times the smallest width of the steel base plate, and the characteristic strength is greater or equal to that of the concrete foundation for grout thickness greater than 50 mm. According to AISC [10], the compressive strength of the cement grout is at least twice that of the concrete foundation. According to ACI [11], the compressive strength of cement grout used between foundation and base for supporting the equipment and machinery should range from 35 MPa to 55 MPa, whereas a general guide by Parchem Construction Supplies [2] stated that the compressive strength of grout at day 1 should be 30 MPa and 60 MPa at day 28.

The chemical grout investigated in this study was orthophthalic unsaturated polyester resin grout incorporated with wastes such as silica fume (SF), fly ash (FA), and palm oil fuel ash (POFA). Polymer grout (PG) is a mixture of polymer, hardener and wastes or additives. As for polymer concrete, it is a mixture of polymer, hardener, and aggregate [12]. In contrast to cement-based grouts, the polymer is used as a binder and does not require water, but instead of requiring only heat, catalysts, or radiation to initiate the polymerization process [13]. Polymer concrete has high mechanical properties, is more durable, and performs well in corrosive environments and chemical attacks [12–15]. Furthermore, when compared to conventional cement concrete, the strength development of polymer-based concrete is rapid and has high bond strength to cement concrete [12, 14, 15]. Moreover, the addition of fillers such as FA, SF, and aluminium powder can improve the mechanical properties of polymer-based concrete while decreasing water absorption because the voids are filled with these fillers [12, 16, 17].

The purpose of this research was to determine appropriate grouts for sealing the gap between the interlocking keys and the StormPav covers, and also used to prepare the interlocking keys. So, POFA, FA, and SF were utilized to form PGs in order to reduce environmental pollution and to lower the cost of PG because the price of resin is expensive. The PGs were tested for compressive strength and the shear strength between the interlocking key and StormPav covers was investigated. Besides this, StormPav covers attached with the interlocking key were also immersed into different chemical solutions before tested for shear strength to investigate the effect of different chemical solutions on the shear strength.

2.0 MATERIALS AND METHODS

2.1. Materials

In the present work, PGs were made from mixing resin and wastes. Orthophthalic unsaturated polyester resin was used instead of cement as a binder in PG with methyl ethyl ketone peroxide as catalyst. The properties of the resin were shown in Table 1. For wastes, POFA, FA, and SF were used as filler to mix with resin to form different types of PGs. The properties of POFA, FA, and SF were shown in Table 2 [18–20]. The FA was classified as Class F in accordance with ASTM C 618 based on the determined chemical compositions of the total sum of silicon oxide, aluminium oxide, and iron oxide were more than 70%. FA had a specific gravity of 2.32 and POFA had a specific gravity of 2.16 [18] and SF had a specific gravity of 2.23.

Table 1 Properties of Resin

Properties	Remarks
Appearance	Hazy; pinkish
Thixotropic Index	1.5 – 2.8
Gel time at 25°C, minute	
- 1% MEKP	18 – 23
Specific Gravity	1.12
Volumetric Shrinkage, %	8

Table 2 Properties of Wastes

Chemical Composition	POFA [18]	FA (%) [19]	SF [20]
Al_2O_3	2.65	23.50	-
SiO_2	59.13	52.90	85.45
SO_3	0.76	0.29	-
CaO	10.90	6.25	0.16
Fe_2O_3	1.69	8.36	-
MgO	6.26	-	4.43
NaO	0.40	-	-
K_2O	6.54	-	0.15
LOI	6.86	-	1.91

There were four chemical solutions known as sodium hydroxide (NaOH), sodium chloride (NaCl), magnesium sulphate ($MgSO_4$), and sulphuric acid (H_2SO_4) used to treat the samples with a concentration of 1 Molar of NaOH, 1.1 Molar of NaCl, 0.49 Molar of $MgSO_4$ and 1 Molar of H_2SO_4. The use of NaOH was to represent the effect of cleaning products on PG such as detergents and shampoos. According to Bier [21], the normal pH value and concentration of NaOH in cleaning products are 11 and 0.001 M respectively. For NaCl, it was to simulate the effect of seawater on PG, and the concentration of NaCl in seawater is 0.589 M [22]. $MgSO_4$ was used to simulate sulphate attack from the soil on PG. According to ASTM C 1012, 0.352 M of $MgSO_4$ is required to carry out sulphate resistance test of concrete based on real sulphate concentration in soil. As for H_2SO_4, it was to simulate the effect of acid rain on PG. In actual life, the concentration of H_2SO_4 in acid rain is 2.5 µM [23]. For this research, the used concentration of chemical solutions were higher than a normal condition to accelerate the outcomes.

2.2. Methods

PGs were prepared by mixing orthophthalic unsaturated polyester resin and wastes. Due to the high cost of resin, a suitable amount of waste was added to reduce the overall cost and also to improve the physical and mechanical properties. 12 different mix ratios of resin to wastes were proposed and the mix ratios were 1 part resin to 0.50, 0.75, 1.00, and 1.50 part of wastes, by mass of the materials, respectively. In addition, the workability of fresh grouts were observed and mix ratios with low workability were not selected for the further compressive test.

PGs with good workability were selected. The resin and wastes were mixed homogeneously, poured into 50 mm cube, vibrated to remove air bubbles, and then cured at ambient temperature until the designated testing ages (2 hours, 24 hours, and 7 days) for the compressive test. After that, two mix ratios were selected based on the conducted compressive strength test for further tests. From these two selected mix ratios, the more workable mix was used as PG, and the less workable mix was used to produce interlocking keys for StormPav. The water ponding test was conducted by using 50 mm x 100 mm x 100 mm samples which were prepared using the selected two mix ratios. In addition, ASTM International [24] C 642 was used to investigate the physical properties of PGs.

For the effect of shear strength, the interlocking keys, 50 mm x 50 mm x 100 mm, were prepared and cured for 7 days at ambient temperature. The prepared interlocking keys were placed at locations A and B as shown in Figure 2. Before that, the surface area of the connections were cleaned. After that, the PG was mixed and poured on top of the interlocking keys to seal the gap between the interlocking keys and StormPav cover. The PG was poured until on the same level as the cover and the shear samples were cured at ambient temperature and tested at the designated testing age. Prior to chemical solutions immersion, the shear samples were cured at ambient temperature for 7 days. After curing, the top surface of the shear samples were immersed into the chemical solutions for about 2 mm in depth. Direct immersion was performed for 25 days (short-term analysis) and tested for shear strength after immersion. Shear strength was determined using SE 100 Universal Testing Frame, 400 kN, and the schematic diagram of the shear strength test was shown in Figure 3. Before conducting the shear strength test, a steel plate with a thickness of 10 mm and a diameter of 200 mm was placed on top of the cover. To calculate the shear strength, a simple mathematics calculation involving failure load and the connection area between the interlocking key and StormPav were used.

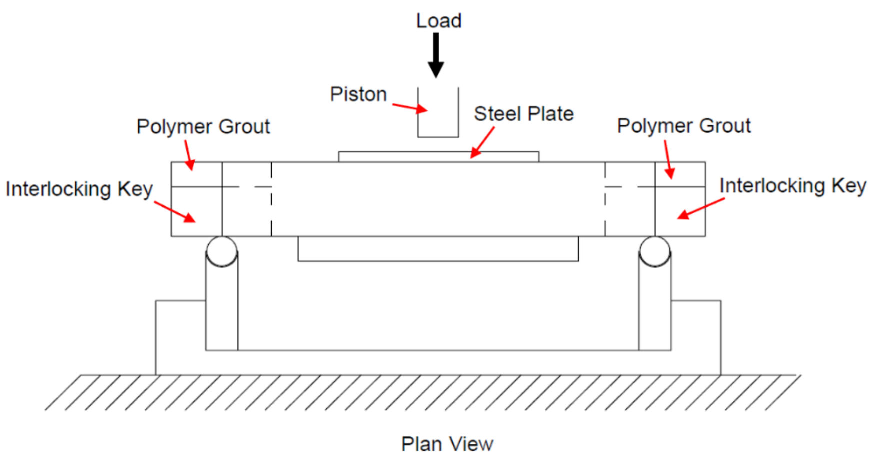

Figure 3 Schematic diagram of shear test arrangement

3.0 RESULTS AND DISCUSSION

3.1. Performance of Polymer Grouts

A total of 12 different mix ratios of resin to wastes was proposed. To determine the workability of these mix ratios, the easiness of stirring and pouring the mixtures was used as an indicator, and the results are shown in Table 3. The results indicated that the use of SF in PG is not preferable compared to FA and POFA. This is because increasing the SF content in PG decreased the workability. Thus, only 8 different mix ratios and pure resin were selected for the compressive test.

These selected 8 different mix ratios and pure resin were prepared and cured at ambient temperature and tested for compressive strength at the designated testing ages. The samples were cured up to 7 days because polymer concrete can achieve its 100% strength at day 7 [25]. The strength developments of these 8 PGs were shown in Figure 4 including the control sample, pure resin sample. The strength development of pure resin and PGs were fast due to the rapid curing characteristic of resin. At 2 hours of testing age, all the PGs and pure resin samples achieved more than 50% of their optimum compressive strength except mix ratio of R:POFA = 1:1.00. After 24 hours, the pure resin sample and PGs achieved more than 75% of their respective optimum compressive strength. On day 7 (168 hours), all the PGs had compressive strength ranging from 71% to 166% higher than pure resin. The results indicated that the mechanical properties of PGs were improved with the adding of filler in pure resin because filler filled the voids in the samples and was proven by Gorninski et al. [16].

Mix ratio of R:SF = 1:0.50 had a compressive strength of 108 MPa and was the highest. However, the resin to silica fume ratio is not economic due to the high cost of resin with the use of SF was only 0.50 part. Moreover, fresh PG contained more than 0.50 part SF had poor workability. On the other hand, fresh PG containing FA had the highest workability compared to SF and POFA at a similar ratio, and showed a high compressive strength than using POFA as filler. The compressive strength of PG contained POFA was lower than PG contained SF and FA because the specific gravity of POFA was lower than SF and FA. By comparing the same mix ratio for R:SF, R:FA and R:POFA, the density of the samples were different due to the difference in specific gravity and this affected the compressive strength due to the excessive POFA as compared to other types of PG. Thus, from the economic aspect, mix ratio of R:FA = 1:1.00 and R:FA = 1:1.50 were chosen as the optimum mix ratio of PGs.

Table 3 Workability of Different Types of PGs

Mix Ratio	Workability
Pure Resin	Good
R:SF = 1: 0.50	Good
R:SF = 1: 0.75	Poor
R:SF = 1: 1.00	Poor
R:SF = 1: 1.50	Poor
R:FA = 1:0.50	Good
R:FA = 1:0.75	Good
R:FA = 1:1.00	Good
R:FA = 1:1.50	Good
R:POFA = 1:0.50	Good
R:POFA = 1:0.75	Good
R:POFA = 1:1.00	Good
R:POFA = 1:1.50	Poor

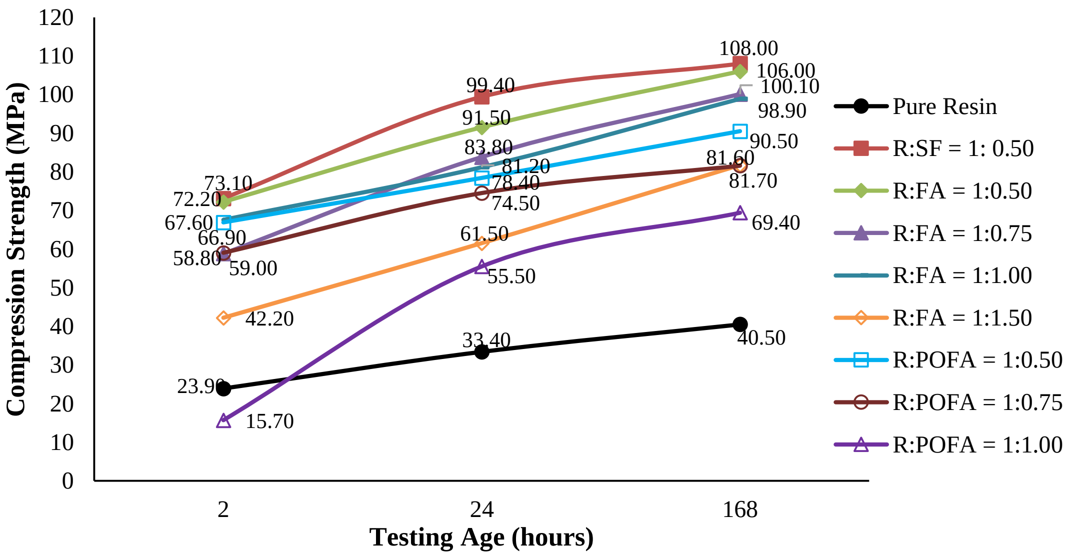

Figure 4 Strength development of different types of PGs

According to Ben [26], the performance of the connections between the concrete elements constructed using grouts must equal to or better than the concrete elements which are going to be connected and also provides sufficient strength to ensure sufficient stress transfer and long-term performance. Manisha et al. [5] also mentioned that the strength requirement of grout depends on its application. The selected grouts, mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50, had compressive strength (i) more than as mentioned in Eurocode 3 (BSI [9]), (ii) 1.97 and 1.63 times higher than the compressive strength of the concrete used for StormPav (Grade 50) but did not achieve minimum twice the strength as requested by AISC [10], (iii) greater than the compressive strength as mentioned by ACI [11], and (iv) more than 30 MPa at 2 hours testing age compared to 30 MPa at 24 hours as requested by Parchem Construction Supplies [2].

Therefore, as can be observed from the selected mixes, mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50 had compressive strength greater than the concrete used for StormPav. Mix ratio of R:FA = 1:1.00 had a compressive strength of 98.90 MPa, while mix ratio of R:FA = 1:1.50 had a compressive strength of 81.70 MPa. PG with mix ratio of R:FA = 1:1.50 was used to form interlocking keys, and PG with mix ratio of R:FA = 1:1.00 was chosen as a grout to seal the gap between the interlocking key and the StormPav covers. Mix ratio of R:FA = 1:1.00 was chosen as PG because it had higher workability than mix ratio of R:FA = 1:1.50 due to low fly ash content. Moreover, mix ratio R:FA = 1:1.50 was chosen to form interlocking key instead of mix ratio R:FA = 1:1.00 because the amount of required resin was less and this can reduce the cost.

3.2. Physical Properties of PGs

Physical properties such as voids, density, absorption, and water absorption (water ponding) were conducted for mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50. ASTM International [24] C 642 was referred to conduct the physical properties test which was void content, density, and absorption of PGs. 50 mm cubes were prepared and cured for 7 days at ambient temperature before the test was conducted. Table 4 shows the physical properties of two different PGs with mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50. From Table 4, the results indicated that the increase of FA in PG led to the reduction in absorption after immersion, absorption after immersion and boiling, and volume of permeable voids. This shows that FA can fill and reduce the void contents in PG and is proved by the research conducted by Gorninski et al. [16].

Table 4 Physical Properties of PGs

Physical Properties	**R:FA = 1:1.00**	**R:FA = 1:1.50**
Absorption After Immersion (%)	0.127	0.125
Absorption After Immersion and Boiling (%)	0.401	0.277
Bulk Density, Dry (kg/m^3)	1529.2	1628.7
Bulk Density After Immersion (kg/m^3)	1531.1	1630.7
Bulk Density After Immersion and Boiling (kg/m^3)	1535.3	1633.2
Apparent Density (kg/m^3)	1538.6	1636.1
Volume of Permeable Voids (%)	0.613	0.450

Besides that, PGs with mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50 were cast and cured for 7 days at ambient temperature before conducting water ponding test. The objective of this test is to determine the rate of infiltration of water into PGs and is crucial in determining the durability of PG under different ponding duration. Figure 5 shows the water absorption analysis of PGs with mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50. From Figure 5, the results indicated that increasing FA content in PG decreased water absorption and the reduction was 69.30% at the end of the test. This showed that increase of FA content led to the reduction in voids in PG and was also proved by Gorninski et al. [16].

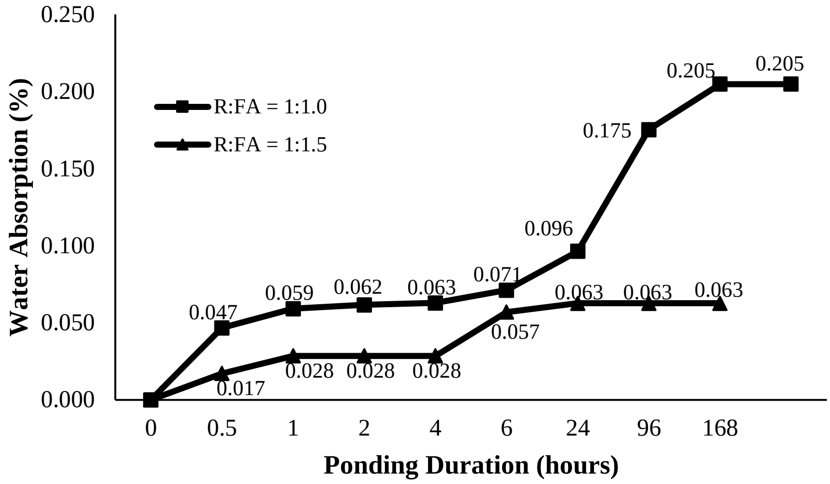

Figure 5 Water absorption of PGs

3.3. Flexural Strength of PGs

As mentioned, mix ratio of R:FA = 1:1.00 had a compressive strength of 98.90 MPa while mix ratio of R:FA = 1:1.50 had a compressive strength of 81.70 MPa. For their respective flexural strength, the strength developments of the selected PGs were investigated. The size of the samples were 80 mm x 10 mm x 10 mm, curing at ambient temperature and tested at their designated testing ages. Small size of the sample was used to save cost and make the handling easy. The flexural strength development of the selected PGs was shown in Figure 6. Mix ratio of R:FA = 1:1.00 had an optimum flexural strength of 53.00 MPa and mix ratio of R:FA = 1:1.50 had an optimum flexural strength of 61.90 MPa. The result indicated that both PGs achieved a minimum of 35% and 50% of their flexural strengths at testing ages of 2 hours and 4 hours, respectively. This showed that the strength development of PGs are fast.

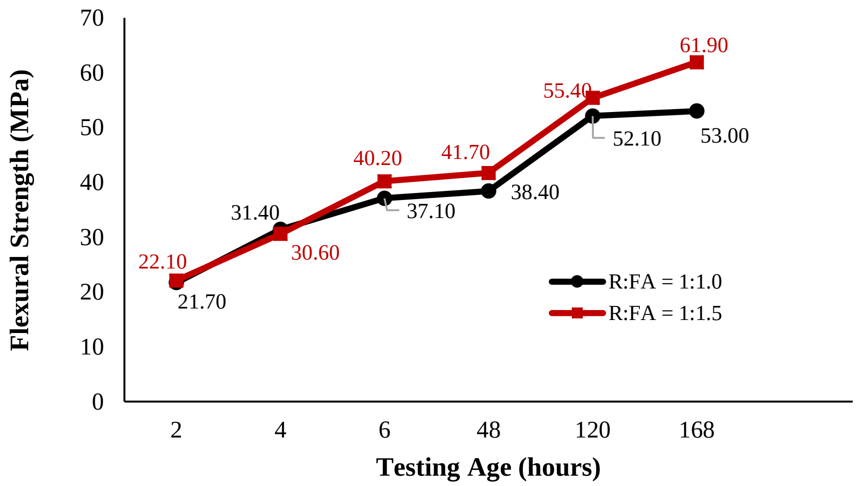

Figure 6 Flexural strength development of PGs

3.4 Shear Strength

The shear strength development was shown in Figure 7. The hardening process of PG is very fast and at 3 hours testing age, the shear strength achieved 51.50% of its optimum shear strength, 3.98 MPa. According to Harris [27], the minimum shear strength requirement as stated by the Iowa Department of Transportation is 1.38 MPa. From Figure 7, the result indicated that at 3 hours testing age, the shear strength between the interlocking key and StormPav covers by using mix ratio of R:FA = 1:1.00 as PG achieved the minimum shear strength requirement.

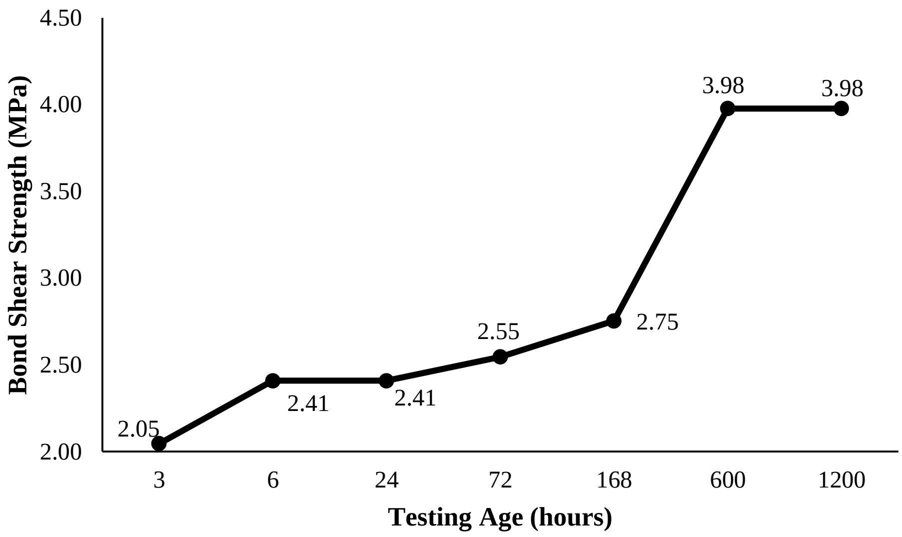

Figure 7 Shear strength of PG

During the shear strength test, two types of failure occurred on the samples, (i) at the StormPav cover and (ii) at the grouting part. This was due to the different roughness of bonding surfaces in which a rough surface will result in a stronger bond than a smooth surface. The PG with mix ratio of R:FA = 1:1.00 had high workability and was able to fill the small holes on rough bonding surfaces, thus, grabbed the StormPav cover stronger compared to the smooth surface. Therefore, when the bonding is too strong, the StormPav cover which was made from conventional concrete with low flexural strength might break and fail.

Besides that, the effect of different chemical solutions toward shear strength between the interlocking key and StormPav covers were investigated as shown in Figure 8. From Figure 8, the control means the shear sample did not go through chemical immersion. After 25 days of different chemical solutions immersion, a reduction in shear strength was determined for all the shear samples. The most severe was shear samples immersed with sodium hydroxide and magnesium sulphate, and their shear strengths were 2.80 MPa. For shear samples immersed with sodium hydroxide and magnesium sulphate, the shear strength reduction was 29.60%. Although the chemical solutions had caused a reduction in shear strength but still achieved minimum shear strength requirement, 1.38 MPa [27], and noted that the concentrations of chemical solutions were 1.1 Molar NaCl, 1.0 Molar NaOH and H_2SO_4, and 0.49 Molar $MgSO_4$, which were higher than the actual environment.

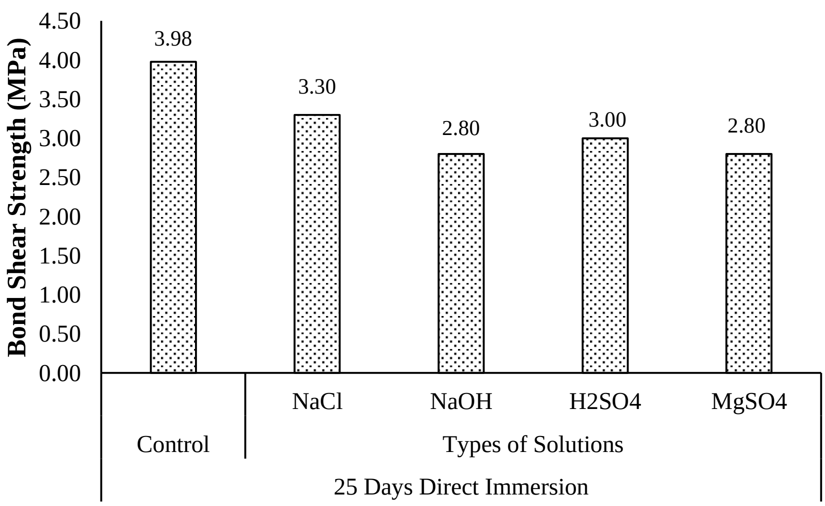

Figure 8 Effect of different chemical solutions on shear strength

From observation, before conducting the shear strength test, the shear samples which were immersed in NaCl and $MgSO_4$ did not show any significant change. For shear samples immersed in H_2SO_4, significant decay on the

StormPav cover's surface was observed but there was no change on PG. So, instead of PG, the decay at the StormPav cover was the reason for causing a decrease in shear strength. Meanwhile, there was no significant change at the surface of the StormPav cover that was being immersed in NaOH. However, the color of PG had become paler and also led to the formation of small cracks. Thus, it was believed that NaOH had caused the PG to become weaker and decreased in shear strength.

4.0 CONCLUSION

The objective of this research was to investigate the performance of PGs which were made from different wastes (POFA, FA, SF) in terms of compressive strength of the PGs and shear strength between the interlocking key and StormPav covers by using the selected PGs. The suitability of different wastes, POFA, FA, and SF, in PGs were determined, and mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50 were selected for further physical and mechanical properties tests. From the results and analysis, it was concluded that:

I. Mix ratios of R:FA = 1:1.00 and R:FA = 1:1.50 were selected as PGs and both PGs had a compressive strength of 98.90 MPa and 81.70 MPa, respectively. Mix ratio of R:FA = 1:1.00 was chosen as grout to seal the gap between the interlocking key and the StormPav covers, and mix ratio of R:FA = 1:1.50 was used to form the interlocking key.
II. Increase of FA content in PG can reduce the voids in PG. This was proven with the reduction of 69.30% of water absorption and reduction of 26.60% of the volume of permeable voids from mix ratio of R:FA = 1:1.00 to mix ratio of R:FA = 1:1.50.
III. Mix ratio of R:FA = 1:1.00 and mix ratio of R:FA = 1:1.50 had flexural strength of 53.00 MPa and 61.90 MPa, respectively. Both PGs achieved a minimum of 35% and 50% of their flexural strengths at testing ages of 2 hours and 4 hours, respectively.
IV. Mix ratio of R:FA = 1:1.00 was used as PG to seal the gap between the interlocking key and StormPav covers. The determined shear strength was 3.98 MPa and required less than 3 hours to achieve the minimum shear strength requirement of 1.38 MPa as stated by the Iowa Department of Transportation.
V. Shear samples were treated for 25 days with 1.1 Molar NaCl, 1.0 Molar NaOH and H_2SO_4, and 0.49 Molar $MgSO_4$ which were higher than the actual environment, before being tested for shear strength. The determined shear strength achieved the minimum shear strength requirement of 1.38 MPa as stated by the Iowa Department of Transportation.

Therefore, from this research, it can be concluded that mix ratio of R:FA = 1:1.00 was suitable to be used as grout to seal the gap between the interlocking key and StormPav covers, while mix ratio of R:FA = 1:1.50 was suitable to be used as an interlocking key. This is due to both PGs performed well in terms of physical and mechanical properties.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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