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Bending and Bonding Properties of Sandwiched Polymer Concrete Composites

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ABSTRACT

It is foreseen that the properties of Polymer Concrete (PC) can be further enhanced if the PC is bonded to or sandwiched between Glass Fibre Reinforced Plastic (GFRP) laminates, later termed as PC-GFRP system. In the present investigation, the performance of PC-GFRP was assessed in terms of its bending strength and bonding strength between PC and GFRP. Panels of PC size 500 mm × 500 mm × 20 mm were prepared. The panels then were cut into specimens of appropriate geometry and dimensions required for the tests. Four (4) different resin contents and different percentages of aggregate of different particle size distributions were employed in preparing the PC-GFRP specimens. A batch of PC specimens was layered with a Glass Fibre Reinforced Plastic (GFRP) laminate on one side (SSL) and the other batch PC specimens were sandwiched with two GFRP laminates (DSL). The PC-GFRP specimens were tested their bending strength under three-point load test and bonding strength between PC as a core material and glued GFRP laminate(s). The results showed that an increase in the resin content increases the bending strength of the PC regardless of the aggregate grading. The results also revealed that the PC specimens with well-graded aggregate recorded the highest bending strength, with coarser grading resulted in further increase. The bending strength of the PC-GFRP

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system improved significantly when the PC was externally reinforced with a GFRP laminate (SSL) but did not improve further when another layer of GFRP laminate was applied (DSL). The bonding strength between PC and GFRP was found to be increased as the resin content increases and the GFRP laminate bonded better to the PC as a core material if made of the overall aggregate size.

Keywords*: Polymer concrete (PC), Glass Fibre Reinforced Plastic (GFRP), PC-GFRP system, sandwiched and layered PC*

Introduction

Composite materials such as Fibre Reinforced Polymer (FRP) offer multitudes of benefits such as high specific strength, high corrosion resistance, high fatigue resistance and superior in mechanical properties [1, 2]. However, its high cost to date has hindered its use and concrete based materials are still the most economic option for civil engineering applications. Concrete, on the other hand requires modification to enhance its properties to improve mainly its tensile and flexural strengths, and as such Polymer Concrete (PC) has been introduced [3, 4]. Nevertheless, PC is still far away to compete that of FRP in terms of its mechanical properties. Therefore, an innovative and cost-effective way by assembling together PC and FRP materials to take benefit from the best mechanical properties of the both materials have been explored in the present study.

PC is made by modifying ordinary cement mortar with polymer or monomers and therefore no water is used. PC was given several names such as plastic concrete, organomineral concrete, Duroplast, Dezament and Plexilite [5], resin concrete [6, 7]. Studies on the maximization of the properties of PC by varying the materials and the formulation have also been conducted by Vipulanandan and Merbakia, [8]; Vipulanandan and Eliza, [9]; Alzaydi *et al.* [4]; Junjian and Vipulanandan [10]. Polyesters, vinyl ester or epoxy resins have been used for the purpose, with polyester resin, the most common due to low price and corrosion resistance [9]. Silica sand, gravel, or fly ash has been used as aggregates or filler in PC. Catalyst or hardeners are added to the resin prior to mixing and casting. Sand with particle sizes between 0.84 mm and 0.59 mm was used in fracture studies [8].

To be innovative, PCs characterized by its high flexural strength as compared to that of conventional cement concrete can be further enhanced by externally reinforcing them with composite materials such as FRP. Studies have shown that the flexural strength of the reinforced beam of normal concrete would be enhanced when bonded externally with Fibre Reinforced Polymer (FRP) [11, 12]. Hence, this present research is aimed at further enhancing the mechanical properties of PCs by applying laminate of GFRP to PCs to produce a cheaper alternative advanced material. Sandwiching of less strong PC materials with composite materials of higher strength can improve the strength of the resulting composites over that of the PC core alone while reducing the cost of using in total the composite materials alone.

In establishing this unique combination of the two materials, the improvement in the bending strength of the total system and the bonding strength between the two materials due would become a major concern. Therefore, in the present investigation, bending strength of the series of PC made of different resin content and aggregate grading and bonding strength of PC-GFRP specimens were looked into.

Experimental Set Up and Sample Preparation

Materials for PC

Four (4) main ingredients to produce PC are polymer resin, catalyst, sand and filler. A commercial unsaturated polyester resin, Polymal 820WPT/820PT was used as a resin and methyl ethyl keton peroxide [MEKP] as a catalyst. Mining sand and granite coarse aggregate were used as aggregate and Haichen Talc Powder as filler to fill the gaps between coarser particles. Water was not used for the preparation of PC panels.

Preparation of Core PC Specimen for Bending Strength Test

For bending strength test, a series of four (4) polymer concrete (PC) specimens of four different ratios of sand, resin and talcum powder (filler) namely 85:10:5, 80:15:5, 75:20:5 and 70:25:5 (by weight) of the total weight designated Mix A, B, C and D, respectively were cast. The four (4) ranges of resin: aggregate ratio selected represents the high side of resin content which was more than enough to coat the filler to the ratio of just enough to coat the filler.

For each serial, three different particle size distributions of aggregates were used and designated Type I, II and III. Type I grading contained 80 % medium-size-distribution of aggregates with sizes ranging from 3.35 mm to 2.0 mm and 20 % fine-size-distribution of aggregates with sizes ranging from 1.18 mm to 600 mm of mining sand. For Type II, it was 50 % crushed gravel aggregate with aggregate sizes ranging from 5.0 mm to 8.0 mm and 50 % well-graded mining sand. Type III was 100 % as-received mining sand. Plain polymer (with no aggregate and filler) was also cast as a control specimen.

Resin and talcum powder were mixed homogeneously. After the mix was homogeneous, aggregate was added and stirred manually until all materials mixed properly. Subsequently, 1 % of hardener (catalyst) MEKP from the weight of resin was added. The 1 % hardener was found to harden the PC specimens within 5 to 6 hours.

Then, the PC mixture was poured into the mould made of steel with dimension of 500 mm × 500 mm × 20 mm for bending strength test and 500 mm × 500 mm × 25 mm for bonding strength test. The mould was coated with wax prior to pouring to ensure that the specimens were not glued to the mould. The top surface of moulded specimens was covered using the mould steel cover. After that, the moulded specimen was clamped and pressed with a minimum amount of pressure to get rid the air bubbles. The moulded specimen was demoulded after 24 hours casting and the demoulded PC specimens were left exposed to the air in the laboratory at room temperature for about a week. The panels then were cut using electric cutter into specimens of appropriate geometry and dimensions required for the tests. For bending strength test, the specimen size was 220 mm × 20 mm × 20 mm. For bonding strength test, the size specimen required is 140 mm × 25 mm × 25 mm.

Bonding and Sandwiching of PCs with GFRPs

GFRP laminate made of three (3) plies of glass fibres, namely chopped strand mat (CSM) and woven roving (WR) were supplied by a local company with an average thickness of 3 mm. For bending strength, the laminates were cut and glued to the core PCs on one side and termed as singly-sided lined PC (SSL) and both sides, doubly-sided lined PC (DSL).

Testing for Bending and Bonding Strengths

The bending strength was conducted in accordance with ASTM D 790 (96a). The test was conducted on ten (10) identical specimens for replications. In the bending strength test, the SSL specimens were positioned with the GFRP layer carrying the largest tensile bending stress as shown in Figure 1, and the DSL specimen as in Figure 2.

The bending strength can be calculated using the bending strength formulation as follows:

$$\sigma_{bend} = 3Pl \,/\, 2bd^2 \qquad (1)$$

where

σ_{bend} is the bending tensile strength (N/mm^2)
P is the maximum load applied to the specimen until failure (N)
l is the support span (mm)
b is the width of the specimen tested (mm)
d is the depth of specimen tested (mm)

For bonding strength test method as described by Gower [23] was adopted. The schematic set-up for bonding strength test is as shown in Figure 3. The bonding strength can be calculated using the bonding strength formulation as follows:

$$\tau_{bond} = P/2al \qquad (2)$$

where

τ_{bond} is the bonding strength (N/mm^2)
P is the maximum load applied to the specimen until failure (N)
l is the bond length (mm)
a is the width of the specimen tested (mm)

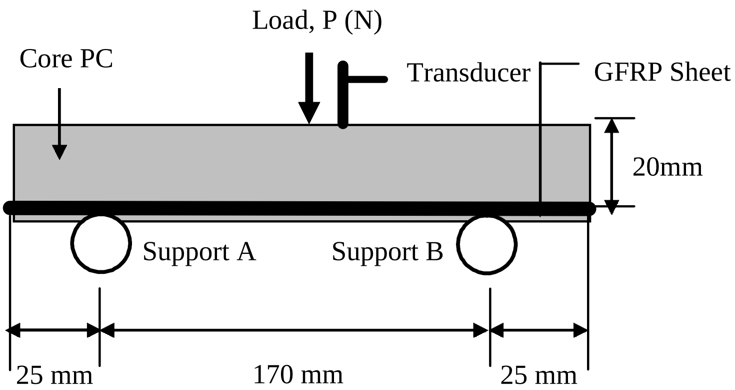

Figure 1: SSL Specimen under a Symmetrical Three-point Bending

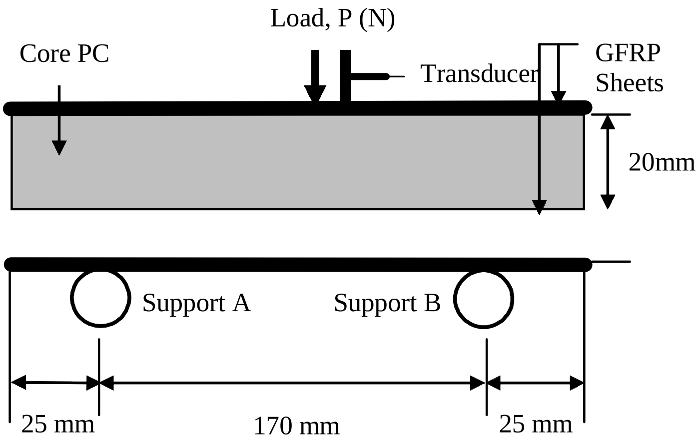

Figure 2: DSL Specimen under a Symmetrical Three-point Bending

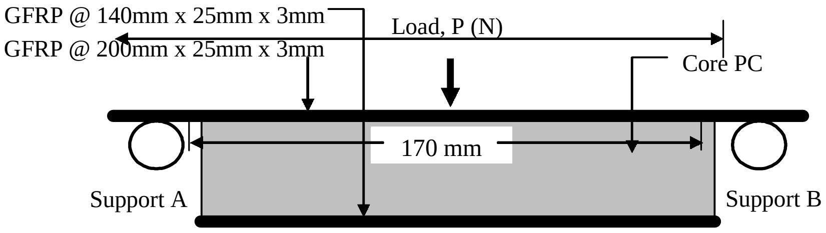

Figure 3: Schematic Diagram of Core PC Specimen Bonded with GFRP Laminates for Bonding Strength Test

Results and Discussion

The bending strength of PC, SSL and DSL specimens for the four (4) series of PC specimens and the bonding strength of SSL and DSL specimens are presented in the subsequent sections.

Bending Strength

Table 1 and Figure 4 present the results of the bending strength of PCs made of four (4) mix formulations using three (3) different aggregate grading. The average of ten (10) results of the bending strength for core PC, SSL and DSL are also presented in a tabular form and shown in Tables 2 and 3.

Table 1 and Figure 4 summarise the bending strength of the PC specimens made of four (4) different formulations for all the three (3) types of aggregate grading. Each formulation comprised 10 %, 15 %, 20 % and 25 % of resin content from the total weight of a PC. The results indicate not only increasing in bending strength with the amount of resin, but also with the introduction of higher content of coarser aggregates.

Table 1: Average Bending Strength of Polymer Concrete (PC) Specimens Made of Different Resin Content and Aggregate Grading

Average Bending Strength (N/mm^2)				
Aggregate Grading (%)	Mix Proportion			
	A (85:10:5)	B (80:15:5)	C (75:20:5)	D (70:25:5)
Type I (80 % medium size: 20 % fine size)	10.5	18.3	26.9	38.0
Type II (50 % overall mining sand: 50 % crushed gravel aggregate)	12.4	21.2	27.8	57.0
Type III (100 % overall mining sand)	15.3	24.7	30.0	60.4

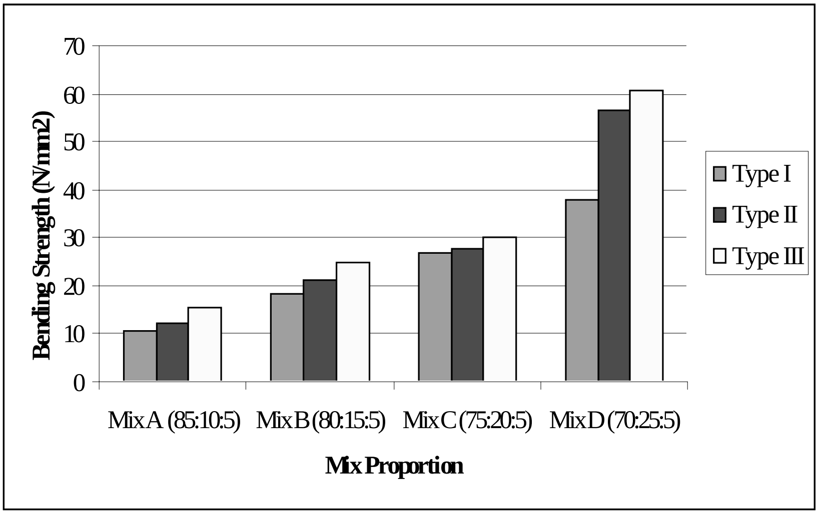

Figure 4: Bending Strength of PCs of Four (4) Different Mix Proportions with Respect to Different Aggregate Grading

Including coarser particle size of aggregates, for example, gravel size of 5 mm was shown to lead to an increase in the bending strength of the PCs over those of medium and finer size of aggregates.

The average bending strength tested on ten (10) replicate of plain polymer (with no aggregate and filler) specimens was found to be 37.6 N/mm^2 and it is higher than those of PC specimens made of resin content up to 20 % of the total weight. PC specimens made of 25 % polymer (resin) and 75 % aggregate/filler (Mix D) attained the highest bending strength, recording a value close to twice that the plain polymer itself. Any further increase in the bending strength would not be expected by increasing the resin content to more than 25 % as the bending strength of the resulting PCs would approach that of a plain polymer of 37.6 N/mm^2. The strength of an individual aggregate might be higher than the polymer itself but the aggregate would need sufficient polymer to bind them together for an effective stress transfer between them as a composite material. PCs with only 10 % resin content (Mix A) were found to be only sufficient to coat but not bind the aggregates. In the case of Mix D with a 25 % resin content, an excess resin was observed and this would act as an external reinforcement to the PC specimens, thus, leading to a higher load carrying capacity if positioned at the extreme tensile region during the application of transverse loading.

The optimum content of resin in PC could be varied depending on the grades of resin, types of resin, curing methods, agitation mechanisms and particle size distributions of aggregates. Previous research by Dennard [11] found that PC made of 12 % polyester resin recorded the highest bending strength, a finding later confirmed by Blaga and Beaudoin [12] and Victor *et al.* [13]. They also found that as the aggregate particle size became finer, the resin content required increased by 30% due to higher specific surface area in order to maintain the strength. It is for this reason that a much coarser aggregate was attempted in the present investigation. Vipulanandan and Eliza [9] claimed that the strength of PC was almost unchanged with increasing polymer content up to 20 % and another research work by Mikhailov *et al.* [14] recommended that the optimum content of resin ranged from 5 to 30 % of the total weight of PC. Ribeiro *et al.* [15] concluded that the use of 20 % epoxy resin content increased the bending strength of PCs compared to that using polyester resin of the same amount. However, since PCs made of polyester resin are almost five (5) times cheaper than those of epoxy while the bending strength of the former is only 17 % smaller than the latter, the use of polyester resin could still be the best option.

An analysis of variance (ANOVA) was performed to determine the relationship between the increase in the resin content and the bending strength. The Pearson correlation reveals a strong linear relationship between the percentage of the resin content and the bending strength of 0.81.

Table 2 and Figure 5 show the average bending strength of PC and SSL specimens. Applying the PCs on one side with a GFRP laminate acting as an external reinforcement, it improves significantly of the resulting composites. An increase of up to 600 % is reported, with the smallest increase being about 68 %.

Sandwiching of core materials with higher strength and stiffness skin materials can increase the strength of the whole system as the stress carried by the core material can be transferred to the sandwiching material

Table 2: Average Bending Strength of PCs Lined on One Side with GFRP Laminate (SSL)

Aggregate Grading Design	Average bending strength (N/mm^2)							
	PC				SSL			
	Mix Proportion				Mix Proportion			
	A (85:10:5)	B (80:15:5)	C (75:20:5)	D (70:25:5)	A (85:10:5)	B (80:15:5)	C (75:20:5)	D (70:25:5)
Type I	10.5	18.3	26.9	38.0	73.1	78.1	88.8	92.6
Type II	12.4	21.2	27.8	56.7	67.0	70.1	82.7	99.8
Type III	15.3	24.7	30.0	60.5	74.0	78.5	92.3	101.7

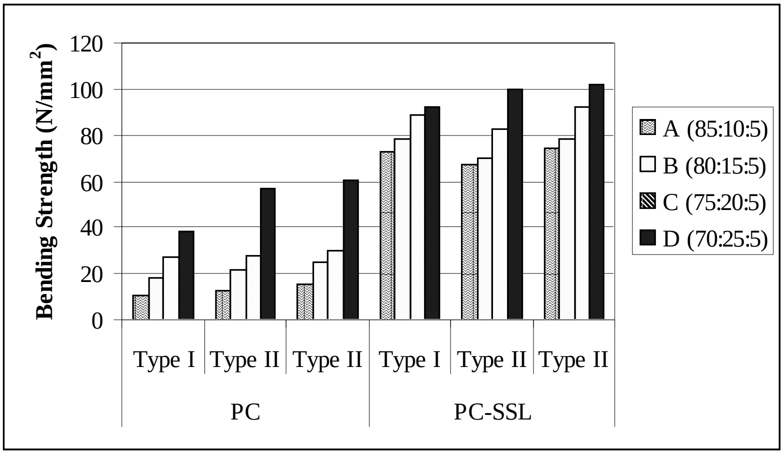

Figure 5: Bending Strength of PCs and SSL Specimens of Different Mix Formulations with Respect to Different Aggregate Grading

via interfacial shear [1, 16, 17]. GFRP plates have been used to strengthen concrete beams and they have been shown to improve the strength of the concrete beams as the GFRP plates carried a portion of the tensile force which decreased the stress in the embedded steel reinforcement [1, 18]. A statistical analysis by the Pearson correlation indicated a strong relationship between the bending strength of PCs and those subsequent to sandwiching. Table 3 shows the average bending strength of PCs of four (4) different mix formulations and those PCs sandwiched between GFRP sheets (DSL).

Table 3: Average Bending Strength of PCs Lined on Both Sides with GFRP Laminates (DSL)

Aggregate Grading Design	Average bending strength (N/mm^2)							
	PC				DSL			
	Mix Proportion				Mix Proportion			
	A (85:10:5)	B (80:15:5)	C (75:20:5)	D (70:25:5)	A (85:10:5)	B (80:15:5)	C (75:20:5)	D (70:25:5)
Type I	10.45	18.34	26.88	37.98	46.45	57.79	61.89	63.06
Type II	12.37	21.16	27.75	56.74	60.61	65.03	70.10	82.69
Type III	15.33	24.67	30.02	60.49	70.05	76.53	85.49	92.48

It is shown that sandwiching the PC core specimens with GFRP laminate, did increase the bending strength of DSL from those of PCs. However, there is no additional advantage of DSL over those of SSL. Another GFRP laminate that positioned far away from the tension zone would not contribute much to the strength of the total system under bending. Additional GFRP laminate if positioned opposite to the extreme tensile region during the application of transverse loading will not be benefited to increase the bending strength of the PC-GFRP system. Figure 9 highlights the slightly lower bending strength of DSL specimens than those of SSL specimens, a phenomenon that would be attributed to the workmanship of laboratory-prepared lined and sandwiched PCs.

The improvement in the bending strength of the lined PCs is tremendous and those PCs with a lower content of resin benefited the most from the lining arrangement. This could be due to the presence of excess resin in those PCs of higher resin content that could have acted as an external reinforcement to the PC specimens so that bonding a GFRP laminate to their soffits resulted in a smaller increase than those

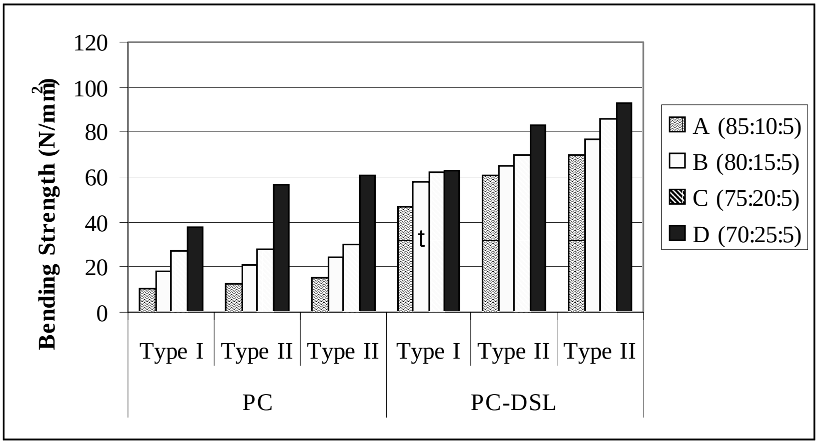

Figure 6: Bending Strength of DSL Specimens for PCs Made of Different Particle Size Distributions of Aggregate

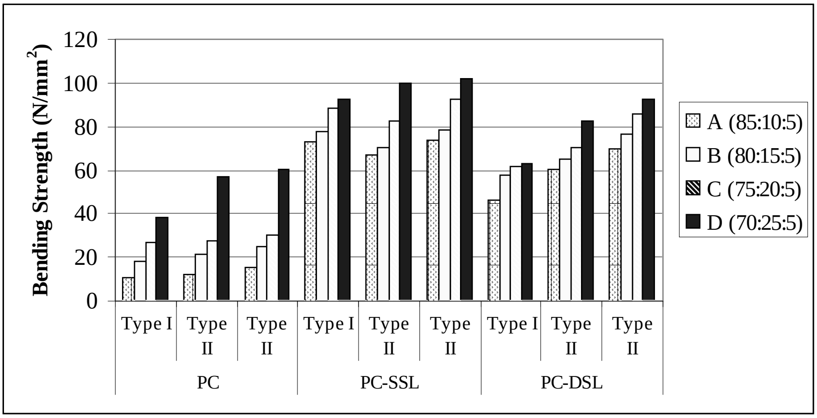

Figure 7: Bending Strength of PC, SSL and DSL Specimens Made of Different Particle Size Distribution of Aggregate

PCs of lower resin content. The percentage increase in the bending strengths of SSL and DSL specimens is summarised in Table 4.

Bonding Strength

Table 5 and Figure 8 show the average of ten (10) results of the bonding strength attained for PC-GFRP to cause debonding of the glued GFRP

Table 4: Percentage of Increase in Bending Strength of Core PC to SSL and DSL Specimens

	Percentage Increase (%)				
	Mix proportion				
	Aggregate Grading	A (85:10:5)	B (80:15:5)	C (75:20:5)	D (70:25:5)
Core PC to PC-SSL	Type I	599.14	325.79	230.17	143.76
	Type II	441.88	231.29	197.95	75.80
	Type III	382.58	218.04	207.33	68.04
Core PC to PC-DSL	Type I	344.50	215.10	130.25	66.03
	Type I	389.98	207.33	152.61	45.73
	Type III	357.95	210.21	184.78	52.88

laminates from core PC specimens. It indicates that the bonding strength increases with increasing of resin content and it is appeared the PC specimens made of 100 % overall size of sand can be bonded better with GFRP laminate(s) than those made of mixture of different portion of sand size. The bonding strength was improved by about 30.0 % as compared to those made of Type I.

The smooth surface of the PC specimens made of higher content of resin was found not to compromise the bonding strength between GFRP laminate and the PC as a core material in fact give the highest bonding strength among those of tested. This assumption arose from the findings

Table 5: Average Bonding Strength between PC-GFRP Specimens

Average Bending Strength (N/mm^2)				
Aggregate Grading (%)	Mix Proportion			
	A (85:10:5)	B (80:15:5)	C (75:20:5)	D (70:25:5)
Type I (80 % medium size: 20 % fine size)	0.011	0.014	0.016	0.020
Type II (50 % overall mining sand: 50 % crushed gravel aggregate)	0.017	0.020	0.020	0.024
Type III (100 % overall mining sand)	0.020	0.023	0.024	0.030

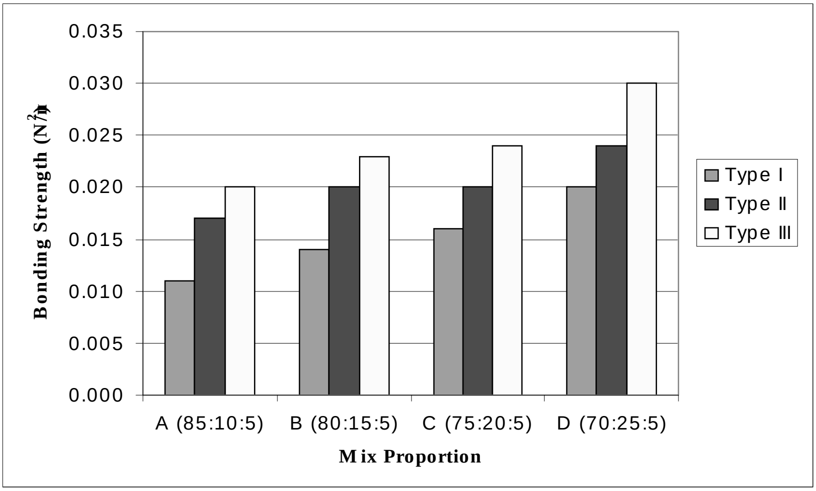

Figure 8: Average Bonding Strength of PC-GFRP Specimens Made of Different Mix Proportion and Different Aggregate Grading

obtained in previous research that revealed the surface condition of the core material was found to influence significantly the bonding strength between FRP laminate and the concrete as a core material [1, 19]. For instance, the bonding capacity between FRP and the concrete prism was found to be doubled when the concrete surface was roughened by spraying with water jet prior to the bonding process as compared to those of that sandblasting.

Meanwhile, Miller [17] and Nanni [1] investigated the bonding between laminated FRP to concrete. It was found that the performance of the specimen with roughened surface was much better than that of the specimen with sandblasted surface.

The regression analysis, for bonding strength value of core PC with adhered GFRP laminates however, yielded that only 38.7 % chance that the change of bonded strength due to change in resin content while 57.3 % chance that the variation in bond strength can be explained by the different aggregate grading used.

Conclusions

From the experimental work, conclusions that may be drawn are as follows:

1. PCs with 25 % resin content could be the most cost-effective in giving the bending strength.
2. Using coarser particle size distribution of aggregates would result in PCs of higher bending strength, particularly when well-graded aggregate is used.
3. Applying a GFRP sheet to the extreme tension fibre of a PC would enhance the ability of the resulting SSL to carry higher loads, with the increase being more pronounced for PCs of lower resin content.
4. Sandwiching PCs with GFRP sheets does not result in further enhancement of the load-carrying capacity of the composites.
5. The different grading of aggregate used in preparing PC could influence the bonding strength between PC and the GFRP laminate/(s).

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