Normal Concrete to Polymer Concrete Bond Strength: Mohr-Coulomb Theory

Mohd Warid Hussin[1], Nur Hafizah A. Khalid[1], Mohammad Ismail[2], Mohamed A. Ismail[3], Azman Mohamed[4], Nur Farhayu Ariffin[1], Nor Hasanah Abdul Shukor Lim[1], Mostafa Samadi[1].

[1]Institute for Smart Infrastructure and Innovative Construction (ISIIC),
Universiti Teknologi Malaysia, 81310 Johor, Malaysia
[2]Department of Structure and Materials, Faculty of Civil Engineering,
Universiti Teknologi Malaysia, 81310 Johor, Malaysia
[3]School of Architecture and Architectural Engineering, College of Engineering Sciences,
Hanyang University ERICA Campus. South Korea
[4]Department of Geotechnics and Transportation, Faculty of Civil Engineering,
Universiti Teknologi Malaysia, 81310 Johor, Malaysia
*Corresponding Author: Email: fiza_ johor2003@yahoo.com.sg

ABSTRACT

This paper discusses an experimental study conducted to evaluate the bonding strength between normal concrete (NC) and polymer concrete (PC) substrate. Ground palm oil fuel ash (GPOFA) was incorporated as micro-filler in this polymer concrete (PC-GPOFA) to investigate its effect on bonding strength. As comparisons, PC containing others filler were prepared, i.e., PC incorporating calcium carbonate (PC $CaCO_3$), silica sand (PC Sand), and unground POFA (PC UPOFA) filler. Two tests were conducted to investigate the bonding between two substrates - slant shear and splitting tensile tests. After critical condition surface (smooth surface) was prepared, the effect of bonding was determined using mohr-coulomb theory. Overall results indicated that PC incorporating GPOFA improved the bonding to normal concrete. This result indicates that the bonding strength of NC to PC at critical condition is affected by self-adhesion of polymer concrete to the normal concrete. The self-adhesive characteristic of polymer concrete to normal concrete can be easily identified in mohr-coulomb analysis. All-in-all, the PC incorporating ground POFA could improve the bonding to the normal concrete.

Keywords: polymer concrete, concrete to concrete bond, mohr-coulomb, bonding strength, pure shear strength

1. INTRODUCTION

Common structural strengthening applications such as strengthening of existing concrete member and precast concrete member with cast in-place parts are most related to structural concrete-to-concrete structure, and this is the same for polymer concrete (PC). As such, structural concrete-to-concrete interfaces ought to be scrutinized to understand its bonding strength, which is affected by several factors: (i) preparation of the substrate surface, (ii) bonding agent at the interface, (iii) mechanical properties of both concrete substrates, (iv) moisture content of the substrate, (v) curing condition of both concrete substrates, (vi) stress state at the interface, and (vii) amount of steel reinforcement crossing the interface, among others.

In order to evaluate the behaviour and/or the strength of concrete-to-concrete interface, several tests have been made available and can be categorized according to the stress resultant at the interface, which are axial, bending and shear tests. Regardless of these, the slant shear test remains the most common test done to measure the adhesion between concrete substrates. In slant shear test, the interface is subjected to both shear and stress distributions at the interface. Slant shear test becomes prevalent to simplify the experimental setup and because of its high sensitivity to variations parameter [1]. It is applicable not only to normal/shear stress [2], but also to zero normal stress [3].

The main objective of this research is to investigate normal concrete (NC) to polymer concrete (PC) bond at critical condition (smooth interface) by using mohr-coulomb theory. The bond strength between these two substrates had been determined before being analysed using the mohr-coulomb theory. Four types of PC substrate were employed, i.e., PC incorporating ground POFA, calcium carbonate, unground POFA and silica sand; these substrates were all bonded to NC. All types of NC to PC substrate were tested under compression and splitting tensile tests to investigate the bonding strength between the two substrates. The findings of this work are expected to bring more knowledge and information about the potential of using PC incorporating palm oil fuel ash as substrate to bond to NC substrate.

2. EXPERIMENTAL

2.1. Materials and Mix Proportions

In this study, the resin used to produce PC was isophthalic polyester. The optimum mix proportions of various PC were properly designed and manufactured as shown in Table 1. However, the mix proportions were limited to low binder content of about 12% of resin in accordance with previous researchers [4-7]. In this study, the low amount of polymer binder was able to produce PC with adequate strength at low cost. The coarse aggregates was limited to 30% for all mix proportions and the rest was fine aggregates. Additionally, four types of fillers were used in the PC material, i.e., calcium carbonate ($CaCO_3$), ground palm oil fuel ash (ground POFA), silica sand, and unground palm oil fuel ash (Unground POFA); the particle size distribution of the filler is as presented in Figure 1. The general sample notations of mix proportion are as follows:

PC $CaCO_3$: PC incorporating calcium carbonate
PC GPOFA : PC incorporating ground POFA
PC Sand : PC incorporating silica sand
PC UPOFA : PC incorporating unground POFA

Table1: Mix Proportions of Polymer Concrete

Concrete Materials	Mix Proportions (kg/m^3)			
	PC $CaCO_3$	PC GPOFA	PC Sand	PC UPOFA
Polyester Resin	132	132	132	132
Filler	270	136	258	970
Fine Aggregate	1238	1141	1238	1238
Coarse Aggregate	750	750	750	750

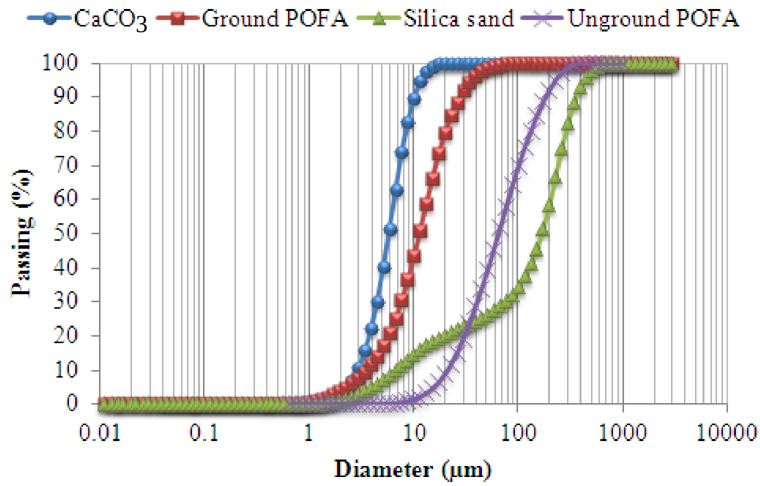


Figure 1: Particle Size Distribution of Fillers

The mix proportion of normal concrete is presented in Table 2. The main materials for making normal concrete in this study were cement, coarse aggregates, fine aggregates, and tap water. The characteristics strength was designed for 30 N/mm^2 with a slump of 30-60 mm.

Table 2: Mix Proportion of Normal Concrete

Concrete materials	Mix proportions (kg/m^3)
Cement	427
Coarse aggregate	950
Fine aggregate	810
Water	213

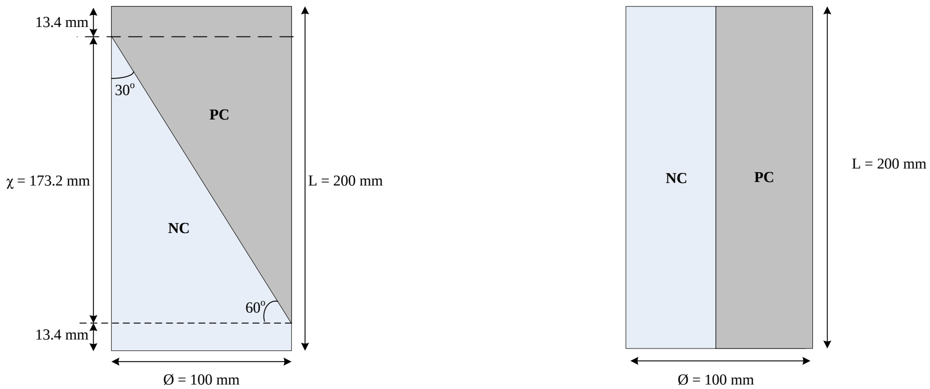
2.2 Bonding Test

There were two tests involved to investigate bonding behaviour between NC and PC substrate - slant shear test under compression load and splitting tensile test. In this study, the testing was limited to the critical bonding condition only. Critical bonding condition indicates a condition where the specimen has smooth surface and does not have any adhesive applied on the surface to produce bonding between two substrates. All tests strictly followed BS6319 [8].

For the half slant-shear specimen, the hardened normal concrete was diagonally slanted at 30^o angle from vertical. According to BS6319 [8], this angle is recommended to represent the failure stress corresponding to a smooth surface, and is close to the minimum stress. Dimension of the slanted specimen is presented in Figure 2. A total of 20 specimens (five specimens per PC type) were tested. The slant shear test was conducted using an Olsen universal testing machine with load cell of 200 kN. Similar amount of half cylindrical specimen was also prepared for the splitting tensile test, conducted using Instron universal testing machine with loading rate of 3 kN/s. The dimension for bonding specimens is as given in Figure 2. Figure 3 shows the slant shear and splitting tensile tests. The general sample notations for bond substrate are as follows:

NC-PC $CaCO_3$: NC to PC incorporating calcium carbonate
NC-PC GPOFA : NC to PC incorporating ground POFA
NC-PC Sand : NC to PC incorporating silica sand

NC-PC UPOFA : NC to PC incorporating unground POFA



(a) (b)

Figure 2: Dimension of bonding specimens

(a) (b)

Figure 3: Bonding Test: (a) Slant shear under compression load and (b) splitting tensile

2.3 Mohr-Coulomb Theory

Bond failure envelope can be obtained using slant shear test (f_{ci}) results in shear combined with splitting tensile (f_{ti}) results; both can also be estimated using mohr-coulomb concept. Then, the pure shear stress (τ_o) can be obtained. This theory has been introduced previously by Santos [9] for concrete-concrete bond. Figure 4 shows the failure envelope for adhesive and cohesive failure, which are the two conceivable failure mechanisms under slant shear test. Adhesive failure refers to the interface debonding and cohesive failure is about the crushing of the weakest concrete [10]. Since smooth surface was prepared for bonding interface, cohesive failure was therefore ignored in this study.

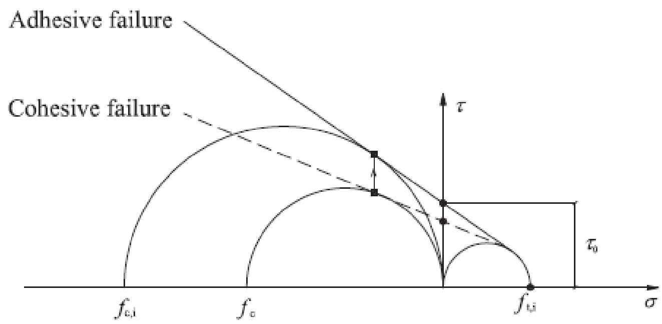


Figure 4: Failure Envelope using Mohr-Coulomb Concept [9,10]

3. RESULTS AND DISSCUSSION

3.1. Bonding Strength

Figures 5 and 6 show the average load-deflection and tensile strength for different NC to PC substrate under slant-shear and splitting tensile tests, respectively. Under the slant shear test, the load-deflection behaviour clearly showed that all materials were brittle. In terms of mode of failure, generally all specimens were broken at the interface between PC and NC substrate, which meant that adhesive failure had clearly occurred [9]. This showed that the materials had sufficient ability to sustain maximum test load, and such allowable critical failure mode strongly reflects the materials' self-adhesion.

During the slant-shear and splitting tests, the NC to PC $CaCO_3$ substrate specimen demonstrated the highest bonding strength. The substrate could sustain high load with larger deflections since calcium carbonate has superior micro-filler characteristics. On the other hand, the PC to Iso-GPOFA substrate specimen had comparable bonding strength with the PC to Iso-Sand substrate specimen. Additionally, it was obvious that the PC to Iso-UPOFA substrate specimen had the lowest bonding strength because unground POFA had the highest cellulose structure which might have led to poor combination of materials in PC. Thus, it becomes clear that PC with ground POFA has higher potential in becoming PC's substrate to NC.

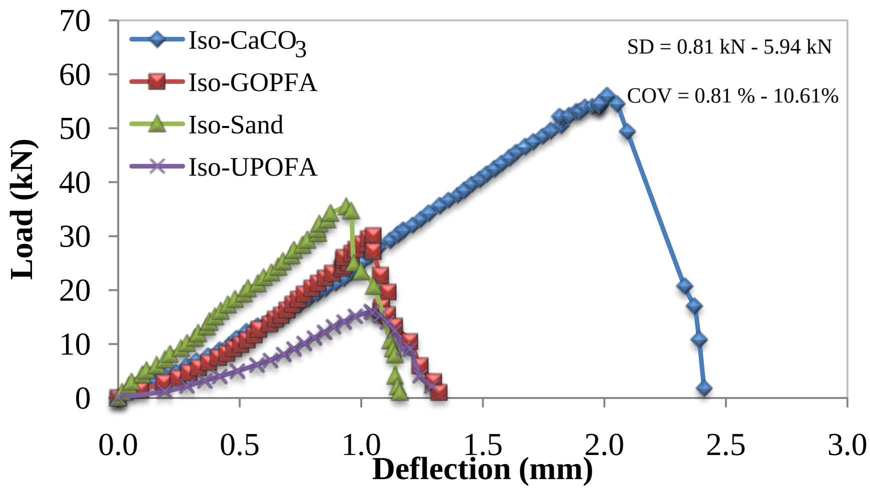


Figure 5: Average of Load-Deflection Behavior under Slant Shear Test for Different Type of PC

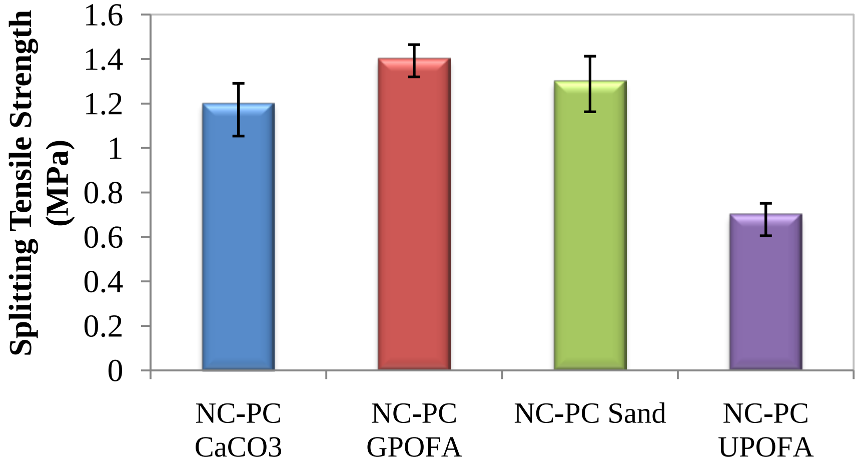


Figure 6: Splitting Tensile Strength for Different Type of Substrates

3.2 Mohr-Coulomb Analysis

Slant shear and splitting tensile results were combined before the analysis using mohr-coulomb theory. Tables 4 and 5 present the summary of desired parameter to be considered in mohr-coulomb analysis. Since adhesive failure had occurred, only the interfacial slant shear strength in compression (f_{ci}) and tension (f_{ti}) were scrutinized. The nomenclature used is:

F_c	:	Compression maximum load in kN
F_{ci}	:	Shear compression load in kN (angle of 60 divided to cos 30)
A_c	:	Compression area in mm^2
A_{ci}	:	Shear Area in mm^2 (compression action)
f_c	:	Concrete compressive strength in MPa (slant shear action)
f_{ci}	:	Interface compressive strength in MPa
F_t / F_{ti}	:	Tension maximum load in kN
A_t	:	Tension area in mm^2
A_{ti}	:	Shear Area in mm^2 (tension action)
f_c	:	Concrete tensile strength in MPa (tensile splitting action)
f_{ci}	:	Interface tensile strength in MPa
τ	:	Pure shear strength in MPa

Table 3: Summary of Desired Parameter to be Considered in Mohr-Coulomb Analysis under Slant Shear Results

Type of Substrate	F_c (kN)	F_{ci} (kN)	A_c (mm^2)	A_{ci} (mm^2)	f_c (MPa)	f_{ci} (MPa)
NC-PC$_{CaCO3}$	56	64.67	7862.5	14152.5	7.12	4.57
NC-PC$_{GPOFA}$	30	34.64	7862.5	14152.5	3.82	2.45
NC-PC$_{Sand}$	35	40.42	7862.5	14152.5	4.45	2.86
NC-PC$_{UPOFA}$	16	18.48	7862.5	14152.5	2.03	1.31

Table 4: Summary of Desired Parameter to be Considered in Mohr-Coulomb Analysis under Splitting Tensile Results

Type of Substrate	F_t / F_{ti} (kN)	A_t (mm^2)	A_{ti} (mm^2)	F_t (MPa)	F_{ti} (MPa)
NC-PC$_{CaCO3}$	11	7862.5	20000	1.4	0.55
NC-PC$_{GPOFA}$	9.4	7862.5	20000	1.2	0.47
NC-PC$_{Sand}$	10.2	7862.5	20000	1.3	0.51
NC-PC$_{UPOFA}$	5.5	7862.5	20000	0.7	0.28

Figure 6 shows the adhesive bond failure envelope which was estimated using mohr-coulomb theory. The bonding strength between NC and PC at critical condition (smooth surface) was influenced by pure shear strength. Pure shear strength, in this study, is the strength where the PC had self-adhered to the NC. It also means that the PC $CaCO_3$ had superior self-adhesion to other specimens with pure shear strength, τ 0.81 MPa. However, PC GPOFA and PC Sand had comparable self-adhesion to NC with pure shear strength, marked at τ 0.54 MPa and 0.61 MPa, respectively. Utilization of POFA improved the NC to PC bond, but only the ground POFA was qualified to be used as micro-filler in PC substrate. This was observed when the NC to PC UPOFA bond showed very minimal pure shear strength, marked at τ with 0.30 MPa. This situation gave insight that NC to PC UPOFA substrate had very poor bond and this PC had the worst self-adhesion to NC. Additionally, the highest pure shear strength, τ, gave the highest bonding strength between NC and PC.

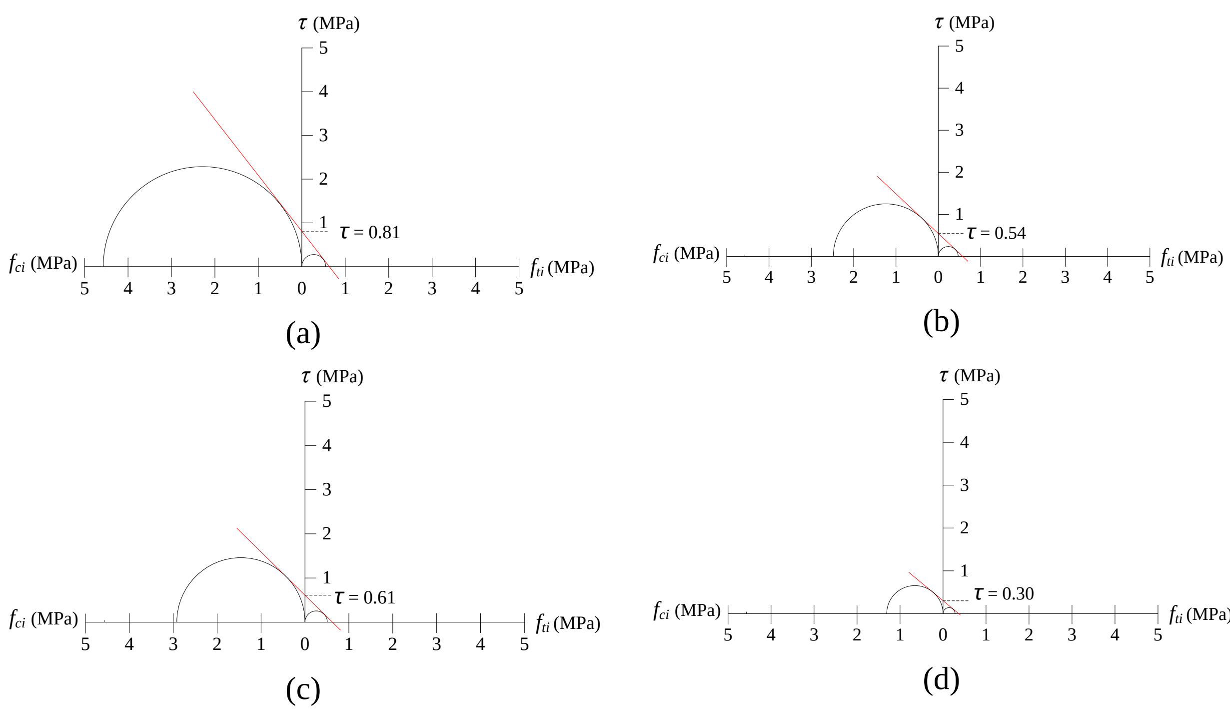


Figure 6: Adhesive Bond Failure Envelope using Mohr-Coulomb Theory (a) NC-PC $CaCO_3$ (b) NC-PC GPOFA (c) NC-PC Sand (d) NC-PC UPOFA

4. CONCLUSIONS

The following conclusions have been drawn from the present study:

1. NC to PC $CaCO_3$ substrate had superior bond to others. However, the NC to PC GPOFA and NC to PC sand specimens had comparable bonding strength. The NC to PC UPOFA specimen showed the worst bonding.
2. PC incorporating palm oil fuel ash improved the bonding to PC. However, only PC incorporating ground POFA improved the bonding, not that with unground POFA.
3. The pure shear strength, τ, influenced the bonding strength. The highest pure shear strength gave the highest bonding strength.
4. Pure shear strength was found in this study, indicating that PC had self-adhesion to NC at the critical bonding condition.

REFERENCES

[1] Santos, D.S., Santos, P.M.D., and Dias-da-Costa, D. 2012. Effect of Surface Preparation and Bonding Agent on the Concrete-to-Concrete Interface Strength. Construction and Building Materials. 37: 102–110.

[2] Austin, S., Robins, P., and Pan, Y. 1999. Shear Bond Testing of Concrete Repairs. Cement and Concrete Research. 29:1067–1076.

[3] Naderi, M. 2009. Analysis of the Slant Shear Test. Adhesion Science and Technology. 23: 229–245.

[4] Fowler, D. 1999. Polymers in Concrete: A Vision for the 21st Century. Cement and Concrete Composites. 21: 449–452.

[5] Varughese, K.T. and Chaturvedi B.K. Fly Ash as Fine Aggregate in Polyester based Polymer Concrete. Cement and Concrete Composites 18: 105–108.

[6] Haidar, M., Ghorbel, E. and Toutanji, H. 2011. Optimization of the Formulation of Micro-Polymer Concretes. Construction and Building Materials. 25: 1632–1644.

[7] Reis, J.M.L. 2011. Effect of Aging on the Fracture Mechanics of Unsaturated Polyester based on Recycled PET Polymer Concrete. Materials Science and Engineering: A. 528: 3007–3009.

[8] BS 6319. 1984. Slant Shear Test Method for Evaluating Bonding Strength of Epoxy System. London: BSI British Standard.

[9] Santos, P. 2009. Assessment of the shear strength between concrete layers. PhD thesis. University of Coimbra.

[10] Saldanha, R., Júlio, E., Dias-da-Costa, D., and Santos, P. 2013. A Modified Slant Shear Test Designed to Enforce Adhesive Failure. Construction and Building Materials. 41: 673–680.