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Bonding Strength between Geopolymer Fly Ash to Ordinary Portland Cement Concretes using Mohr-Coulomb Theory

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Abstract: This paper presents an experimental study to analyse the bonding strength between geopolymer concrete (GC) and normal concrete (NC) bond substrate. Three different strengths of GC which were 80 MPa, 85 MPa and 90 MPa were bonded to 30 MPa NC and denoted as NC30-GC80, NC30-GC85 and NC30-GC90. Slant shear and split tensile tests were conducted to investigate the bonding strength between two different substrates. The effect of bonding was then determined by using Mohr-Coulomb theory where critical bonding condition (smooth surface) was created. From the analysis, it was found that NC30-GC80 had the most powerful self-adhesion between GC towards NC. This result indicated the highest bonding strength of GC to NC at critical condition. Such strong bond was obtained by the effect of self-adhesive from GC to NC. The self-adhesive characteristic which represented by pure shear strength was obtained from Mohr-Coulomb theory.

Keywords: Geopolymer concrete, concrete-to-concrete bond, Mohr-Coulomb, self-adhesive, bonding strength, pure shear strength

1. Introduction

Concrete-to-concrete interfaces are frequently applicable in new construction, rehabilitation and strengthening of existing structures. Generally, fresh or hardened concrete parts are placed against a hardened existing concrete. Placing hardened concrete parts to another hardened concrete substrate are usually applied in precast industry. Meanwhile, addition of new fresh concrete layer onto a hardened concrete substrate is frequently implemented in rehabilitation and precast construction. The comparable process was applied to interface between geopolymer concrete to other concrete types structures. Therefore, structural concrete-to-concrete interfaces is one of the major areas to be concerned. There are

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several factors affecting the concrete-to-concrete bond strength including i) preparation of substrate surface, ii) usage of bonding agent at the interface, iii) mechanical properties of both concrete substrate, iv) moisture content of substrate, v) curing condition of both concrete substrate, vi) interfacial stress state, vii) presence of cracking in the substrate and viii) amount of steel reinforcement crossing the interface among others (Husin *et al.*, 2015).

There are several tests that can be considered to analysed the strength behaviour of concrete-to-concrete interface which are axial, bending and shear tests. Those tests can be classified according to the stress resultant at the interface. Nonetheless, slant shear test is the most recurrent test done to investigate the adhesion between concrete substrates. Additionally, interfacial shear stress distribution of both substrates affects the slant shear test result. Due to high sensitivity to many specifications, slant shear test is extensively carried out to summarize the experimental set up (Santos *et al.*, 2012, Lee *et al.*, 2013, Tahir *et al.*, 2009). Besides that, slant shear test can also be conducted to normal/shear stress as well as zero normal stress (Austin *et al.*, 1999, Teychenne *et al.*, 1997).

This study focused on geopolymer concrete (GC) to normal concrete (NC) bond substrate particularly at critical condition which involved smooth interface. Mohr-Coulomb theory was applied in this research in order to determine the bonding strength. Three types of GC with different strengths which were 80 MPa, 85 MPa and 90 MPa were casted before bonded to NC. All samples were then tested under slant shear and split tensile tests to determine the bonding strength between GC to NC.

2. Structure

2.1 Materials and Mix Proportions

In this study, GC with strengths of 80 MPa, 85 MPa and 90 MPa were prepared according to Design of Normal Concrete Mixes [7]. The mix proportion of fly ash, coarse aggregates, fine aggregates and alkaline activator for each targeted strength can be referred in Table 1. For GC, fly ash was used to completely substitute Ordinary Portland Cenment (OPC). Alkaline activator including sodium hydroxide (NaOH) solution and sodium silicate solution were used to enhance the geopolymerization process occurred in geopolymer mix. This reaction is compulsory to ensure that fly ash reacts completely with the alkaline solution to produce the optimum GC strength (Nazari *et al.*, 2011, Zhao & Sanjayan, 2011, Ghosh K. & Ghosh P., 2012, Joshi & Kadu, 2012, Petermann *et al.*, 2010).

Table 1 - Mix proportion of geopolymer concrete respective to targeted strength

Targeted Strength (MPa)	Mix Proportions (kg/m3)				
	Fly Ash	Coarse Aggregates	Fine Aggregates	Alkaline Activator	
				NaOH	Sodium Silicate
80	421	1364	455	46	114
85	500	1305	435	46	114
90	533	1280	427	46	114

Mixed proportion for NC is shown in Table 2. The primary materials used to yield NC were cement, coarse aggregate, fine aggregate and water. The characteristic strength of NC was designed as 30 N/mm^2.

Table 2 - Mix proportion of normal concrete with respective targeted strength

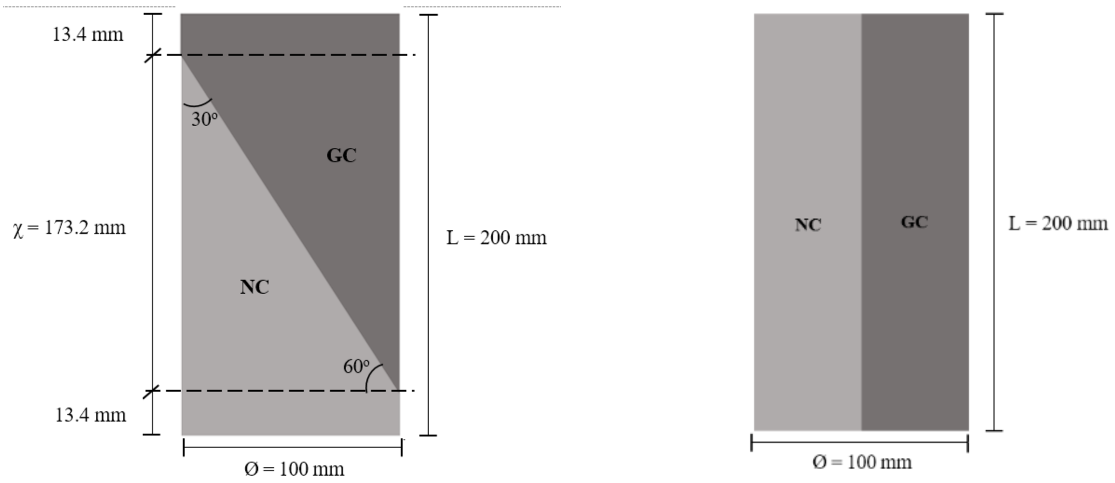
Targeted Strength (MPa)	Mix Proportions (kg/m^3)			
	Cement	Coarse Aggregates	Fine Aggregates	Water
30	421	1364	455	160
40	500	1305	435	160
60	533	1280	427	160

All tables should be numbered with Arabic numerals. Every table should have a caption. Headings should be placed above tables, left justified. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which the authors may find useful.

2.2 Specimen Preparation and Bonding Test

In order to investigate the bonding between GC and NC substrate, two fundamental tests namely slant shear and split tensile tests were conducted. In this study, only critical bonding condition where the smooth surface took action between the two different substrates was considered. In addition, no adhesive was applied on the surface to yield bonding between those two concrete types. Both slant shear test and split tensile test were conducted according to BS631.

For half slant shear samples, the hardened normal concrete was diagonally slanted at 30^o angle from vertical. The recommended bond angle of 30o represents the failure stress corresponding to a smooth surface which was close to the minimum stress. A total of nine samples (three samples for each GC strength) were moulded for slant shear test. As for split tensile test, half cylindrical samples were prepared prior to the testing. All nine samples (three samples for each GC strength) were then tested using 250kN capacity loading machine until failure. The dimensions used to prepare half slanted and half cylindrical samples are illustrated in Figure 1. Meanwhile, Figure 2 shows samples were tested under slant shear and split tensile tests. All samples were classified by their respective GC strength which were NC30-GC80, NC30-GC85 and NC30-GC90.



(a) (b)

Fig. 1 - Dimension of bond substrate

(a) (b)

Fig. 2 - Bonding test (a) slant shear test and; (b) split tensile

2.3 Mohr-Coulomb Theory

Mohr-Coulomb theory was used to determine the failure envelope which can be obtained from split tensile test and slant shear test. By analysing results from both tests, two failure envelope mechanisms, namely adhesive and cohesive can be achieved. The term adhesive failure is about the interface debonding while cohesive failure is the crushing of the weakest concrete (Saldanha *et al.*, 2013, Santos & Júlio, 2012, Santos *et al.*, 2007). Interfacial slant shear strength in compression (f_{ci}) and tension (f_{ti}) were used to obtain pure shear strength (τ) as illustrate in Figure 3. Since the bonding interface was prepared with smooth surface, cohesive failure therefore, was ignored in this study.

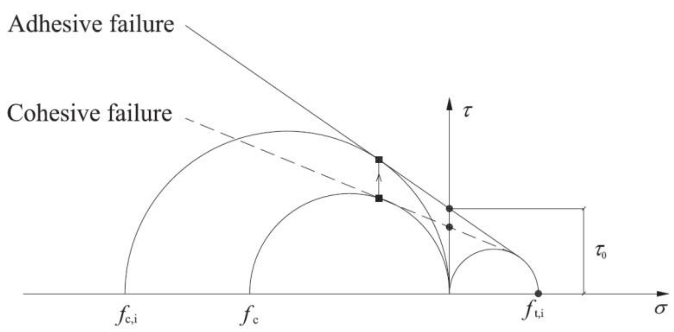


Fig. 3 - Failure envelope using Mohr-Coulomb theory

3. Result and Discussion

3.1 Mohr-Coulomb Theory

Results from split tensile and slant shear tests were combined and used to obtain the pure shear stress. The bonding strength was derived from geopolymer concrete self-adhesion. Since only adhesive failure took part in this study, interface slant shear strength in compression (fci) and interface tensile strength (fti) were used. Table 3 summarized the paraphrase used in Mohr-Coulomb theory (Khalid *et al.*, 2016).

Table 3 - Lists of abbreviations used in Mohr-Coulomb theory

Abbreviations	Meaning
F_c	Compression maximum load in kN
F_{ci}	Shear compression load in kN (refer Figure 3.24a)
A_c	Compression area in mm^2
A_{ci}	Shear Area in mm^2 (refer Figure 3.24a)
f_c	Concrete compressive strength in MPa (slant shear action)
f_{ci}	Interface compressive strength in MPa
F_t	Tension maximum load in kN
F_{ti}	Shear tensile load in kN (refer Figure 3.24b)
A_t	Tension area in mm^2
A_{ti}	Shear Area in mm^2 (refer Figure 3.24b)
f_t	Concrete tensile strength in MPa
f_{ti}	Interface tensile strength in MPa
τ	Pure shear strength in MPa

Cohesive failure envelope of Mohr-Coulomb in this study was ignored since cohesive failure was unnecessary to obtain pure shear strength. The compulsory parameters to sketch Mohr Coulomb's adhesive shear envelopes obtained from slant shear and split tensile tests were tabulated as in Tables 4 and 5 respectively

Table 4 - Summary of required parameters to be analysed and used in Mohr Coulomb analysis from slant shear results

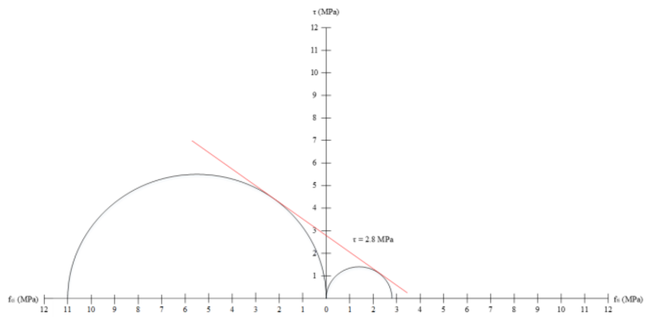
Type of bond substrate	NC30-GC80	NC30-GC85	NC30-GC90
F_t / F_{ti} (kN)	55.4	40.7	39.9
A_t (mm^2)	7862.5	7862.5	7862.5
A_{ti} (mm^2)	20000	20000	20000
f_t (MPa)	7.0	5.2	5.1
f_{ti} (MPa)	2.8	2.0	2.0

Table 5 - Summary of required parameters to be analysed and used in Mohr Coulomb analysis from split tensile results

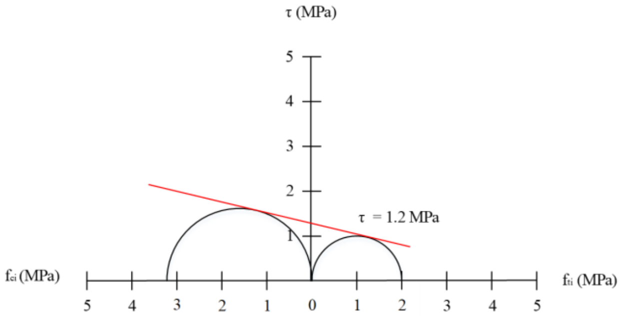
Type of bond substrate	NC30-GC80	NC30-GC85	NC30-GC90
F_c (kN)	135.1	38.8	121.5
F_{ci} (kN)	156.0	44.8	140.2
A_c (mm^2)	7862.5	7862.5	7862.5
A_{ci} (mm^2)	14152.5	14152.5	14152.5
f_c (MPa)	17.2	4.9	15.5
f_{ci} (MPa)	11.0	3.2	9.9

The adhesive bond failure envelope for all bond substrates which estimated using Mohr-Coulomb theory can be referred to Figure 4. The bonding strength between GC and NC at critical condition with smooth surface was affected by pure shear strength. In this study, pure shear strength indicated self-adhesive behaviour of GC to NC. The bond envelopes proved that different GC strength resulted in different pure shear strength value. Above all, pure shear strength was the strength at which the GC had self-adhered to the NC interface.

Referring to Figure 4, it can be seen that NC30-GC80 had the strongest self-adhesive compared to other GC strengths with pure shear strength, τ of 2.8 MPa. Meanwhile, NC30-GC85 and NC30-GC90 yielded pure shear strength, τ of 1.2 MPa and 2.2 MPa respectively. Such minimal pure shear strength value obtained from NC30-GC85 indicated that the GC has the lowest ability to self-adhered to NC and least bonding strength. From the Mohr-Coulomb theory, it can be concluded that higher pure shear strength specified higher GC to NC bonding strength. Therefore, it can be clarified that NC30-GC80 bond substrate had the strongest self-adhesive behaviour which subsequently could enhance the bonding strength between GC to NC.



(a)



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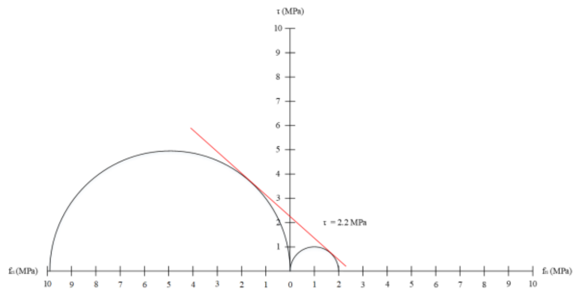

(c)

Fig. 4 - Adhesive bond failure envelope using Mohr-Coulomb theory (a) NC30-GC80; (b) NC30-GC85 and; (c) NC30-GC90

4. Conclusion

As a conclusion, NC30-GC80 had the superior self-adhesive behaviour geopolymer concrete and normal concrete by yielding the highest pure shear strength compared to others. Beside that, NC30-GC85 showed the weakest bond strength which indicated lowest self-adhesive characteristic between geopolymer concrete towards normal concrete. Therefore, the average results of bond strength of all bond substrates were NC30-GC90. The bonding strength of different substrates was affected by the pure shear strength. From the Mohr-Coulomb theory, it can be concluded that higher pure shear strength specified higher geopolymer concrete to normal concrete bonding strength. Consequently, it can be clarified that pure shear strength presented in this study specified that geopolymer concrete had self-adhesive to normal concrete at the critical bonding condition where smooth surface was adopted.

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