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Residual Friction of Bonding Behavior on Green Concretes Made with No-cement Binders

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Abstract*— In order to enhance the sustainability in construction, the study on using green cementing binder to replace the cement in ordinary concrete has been increased as a tendency in recent years. Researchers have recently begun using pull-out test to explore the compatibility of reinforced concrete on the basis of bonding behavior of the steel rebar embedded in concrete which was made with no-cement binders. In this study, a new hydraulic binder called SFC binder being composed of the mixture of three ingredients, the ground granulated blast furnace slag (S), low calcium Class F fly ash (F), and circulating fluidized bed combustion fly ash (C, CFBC fly ash). Bonding behavior of three kinds of OPC and SFC specimens with 28-day compressive strengths of 35 MPa, 45 MPa, and 55 MPa, respectively, were studied, where the specimen of OPC was served as the control group. The relation between the maximum bonding stress and the residual friction which happened at the descending stages after peak of the pull-out test was investigated. The experimental results indicated that the bonding stress was proportional to residual friction in each specimen. The residual frictions of SFC concrete were greater than those of OPC concrete under the higher grades of equivalent 28-day compressive strength. The results showed that the green concrete with the no-cement SFC binder can apparently enhance the bonding behavior on the basis of performance evaluation of the residual friction.

***Index Terms*— slag; fly ash; CFBC fly ash; no-cement; bonding behavior; residual friction.**

I. BACKGROUND

The excellent bonding stress between steel rebar and concrete surface is essential for reinforce concrete structure. The deformation of steel rebar and concrete must be the same when the structure gets outer force. It's necessary to avoid the discontinuity and separation in reinforce concrete section, in order to enhance the tensile resistance effectively for reinforce concrete Bonding stress between steel rebar and concrete surface is one of main topic for reinforced concrete design in order to increase the tensile resistance effectively [1]. In the past, many researchers investigated the bonding stress for ordinary Portland cement concrete [2, 3, 4, 5], pozzolanic cement concrete [6, 7], and alkali activated cement concrete [8].

According to [9], the addition of anhydrite 20-25% can increase the compressive strength of slag paste. The ingredient of circulating fluidized bed combustion fly ash (CFBC fly ash) include anhydrite and calcium oxide, especially the calcium oxide covered by anhydrite. After water reacts with anhydrite, the water will penetrate the anhydrite surface and reacts with calcium oxide. Calcium hydroxide will be created by calcium oxide and water after hydraulic reaction. In short-term period, calcium hydroxide will react with slag and increase the strength of concrete. In long-term period, fly ash will fill up the micro void and increase the strength of concrete as well [10, 11, 12].

The ingredients of cementitious materials for SFC concrete include the ground granulated blast furnace slag (S), low calcium Class F fly ash (F) and circulating fluidized bed combustion fly ash (CFBC fly ash). The pH value was 12.5 after the CFBC fly ash mixed with water and provides alkaline environment, which would accelerate the speed of producing C-S-H gel and C-A-H gel that was made by slag and water under the alkaline environment. In the past, many researches indicated that the fly ash could improve the workability, durability and volume stability of concrete, where the addition of fly ash 15 wt.% could gain excellent durability [12]. The concrete specimen using slag and CFBC fly ash with an optimum mixture of 80 wt.% slag and 20 wt.% CFBC fly ash could gain excellent mechanism properties [12, 13]. In this study, the experimental investigation of bonding stress, through the pull-out tests, between the reinforcing bar and the SFC concrete specimens being made by the green cementitious binder using the mixture of 80 wt.% slag, 15 wt.% fly ash and 20 wt.% CFBC fly ash was conducted. At the same time, the bonding stress with the OPC concrete with the grades of equivalent 28-day compressive strength was also studied. Then, the difference of effect of the water to cementitious binder ratio (w/cb) on the bonding stress between OPC concrete and SFC concrete will be discussed.

II. EXPERIMENTAL METHODS

A. Materials

This study employed Type Ⅰ Portland cement with a fineness of 3,450 cm2/g and specific gravity of 3.15. The fineness and specific gravity of the slag (S) were 6,000 cm2/g and 2.88, respectively. The specific gravity of the low calcium class F fly ash (F) was 2.26. The fineness and specific gravity of the circulating fluidized bed combustion fly ash (C) were 3,000 cm2/g and 2.70, respectively. The specific gravity in SSD condition and the maximum particle size of coarse aggregates were 2.58 and 19 mm, and respectively. The specific gravity in SSD condition and the fineness modulus (FM) of the fine aggregate were 2.73 and 3.00, respectively. The deformed bar of D13 (#4) of SD420W (fy = 420 MPa) in according with the standard of CNS 560 A2006 was used for the pull-out test.

B. Mix proportioning

Table 1 lists the six mix proportions used in this study, where the decimal values after the OPC/SFC in mixture ID denote the water to cementitious binder ratio (w/cb). Three kinds of 28-day compressive strength of 35 MPa, 45 MPa, and 55 MPa in the OPC and SFC specimens were conducted and designated as low, moderate and high compressive strength concretes, respectively. The volume percentage of coarse aggregate and fine aggregate were 30 % and 30 %, respectively. The no-cement binder using the mixture of 80 wt.% slag, 15 wt.% fly ash and 20 wt.% CFBC fly ash was used to produce the SFC concrete specimens for all the experimental study.

C. Specimens and Pull-out Test methods

Pull-out tests in accordance with RILEM/CEB/FIP-RC6 /83 were conducted in this study [14]. Fig. 1 displays the dimensions of the specimens used for pull-out tests, where the rebar of D13 (#4) was embedded in a 150×150×150 mm3 cubic concrete specimens with the embedded length of 65 mm (about 5 times the diameter of rebar). The width of cubical concrete specimen was ten times greater than the diameter of steel rebar in order to get the failure mode called as the pull-out destruction of the bond failure. A 200-ton universal servo-testing machine was used to pull out the embedded steel rebar with an LVDT to measure the slip at the end of steel rebar.

Bonding stress mainly includes the chemical adhesion, interlock and friction. By assuming the bonding test between the steel rebar and concrete surface being properly finished, i.e., the tensile force has been fully passed from steel rebar to concrete, a complete pull-out test curve includes the following three stages as shown in Fig. 2 [15]:

Stage 1: linear stage (micro-slip stage):

The first stage is called the linear stage or micro-slip stage, in which the slip is mainly be caused by the chemical adhesion failure between steel rebar and concrete surface.

Stage 2: bend-over curve stage (internal cracking stage):

The second stage is called the bend-over curve stage or internal cracking stage, in which the chemical adhesion disappear in this stage. The slip is mainly caused by the interlock which happened between the concrete and thread of deformed steel rebar. The maximum bonding stress will appear at this stage.

Stage 3: descending curve stage:

The third stage is called the descending curve stages, in which the bonding stress will decrease consecutively because of the cracking of concrete. The interlock stress disappears after the bonding stress approached to a steady state. The slip is mainly caused by the friction which happened between the concrete and steel rebar surface. The resulting friction in the steady part is specifically called the residual friction.

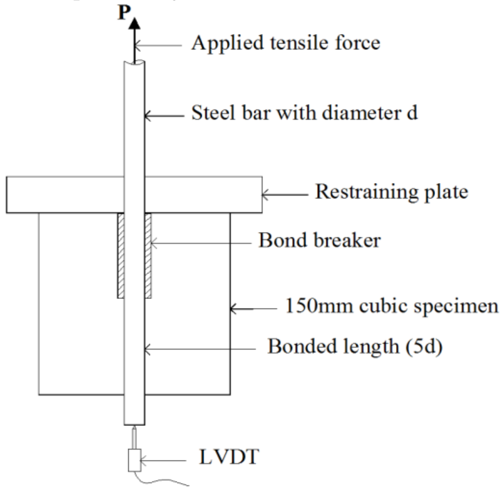

Fig. 1: Schematic diagram for the pull-out test in this study

Table 1: Mix proportioning of concrete (unit：kg/m^3)

Mixture ID	Water	Cement	Slag[a] (S)	Fly ash[b] (F)	CFBC[c] (C)	Coarse aggregate	Fine aggregate	f'_c [d] (MPa)
OPC-0.35	218.7	599.3	-	-	-	773.1	818.6	55
OPC-0.45	243.5	521.2	-	-	-	773.1	818.6	45
OPC-0.60	270.5	436.0	-	-	-	773.1	818.6	35
SFC-0.27	168.5	-	453.4	95.6	95.6	773.1	818.6	55
SFC-0.30	178.8	-	415.9	91.3	91.3	773.1	818.6	45
SFC-0.35	194.1	-	387.1	85.0	85.0	773.1	818.6	35

[a] Slag : Ground granulated blast furnace slag
[b] Fly ash : Low calcium Class F fly ash
[c] CFBC : Circulating fluidized bed combustion fly ash
[d] Compressive strength after 28 days of curing

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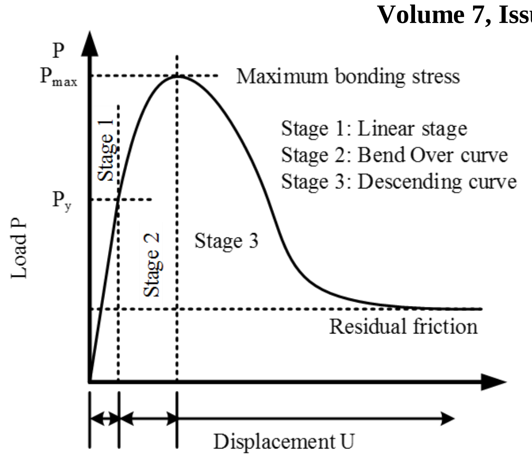

Fig. 2: Three stages of pull-out test [16]

III. RESULTS AND DISCUSSION

The experimental results indicate that the tendency of complete pull-out test curve for the SFC concrete was similar to that of the OPC concrete under low compressive strength as shown in Fig. 3. The maximum bonding stress of OPC concrete was higher than that of SFC concrete. The residual friction of OPC concrete which happened in the stable stage were similar to that of SFC concrete. In Fig. 4, the maximum bonding stress of SFC concrete was higher than that of OPC concrete under moderate compressive strength. The ingredients of CFBC fly ash can enhance the reactions of slag by anhydrite, and after 7 days, the fly ash will fill up the micro void and increase the bonding stress of concrete. The residual friction of SFC concrete was larger than that of OPC concrete. In Fig. 5, the maximum bonding stress of SFC concrete was higher than that of OPC concrete under high compressive strength. The maximum bonding stress of SFC concrete reached 31.29 MPa, and residual friction reached 16.01 MPa as shown in Table 2. Both of the stresses of SFC concrete were higher than those of OPC concrete obviously.

Fig. 6 indicated that there was a comprehensive increase in bonding stress and residual friction with the decrease of water to cementitious binder ratio of OPC concrete. The maximum bonding stress of OPC concrete reached 28.03 MPa, the corresponding slip reached 1.10 mm as shown in Table 2. The slip at maximum bonding stress increased with the decrease with the water to cementitious binder ratio (w/cb) of OPC concrete. Fig. 7 shows an increase in both the bonding stress and the residual friction with the decrease of water to cementitious binder ratio of SFC concrete. The maximum bonding stress and corresponding slip of SFC concrete were 31.29 MPa and 1.22 mm, respectively, as shown in Table 2. The slip at maximum bonding stress increased with the decrease of water to cementitious binder ratio of SFC concrete. The ratio of residual friction to maximum bonding stress to decreased with the increase of water to cementitious binder ratio. By comparing with OPC concrete as shown in Table 2, the residual friction of SFC concrete was greater than that of OPC concrete under both the moderate and high compressive strengths. The ratios of maximum bonding stress to residual friction of OPC and SFC concrete were 2.26 and 1.95, respectively. The ratios of residual friction to maximum bonding stress of SFC concrete were higher than those of OPC concrete under moderate and high compressive strengths. Therefore, the SFC concrete can retain more residual friction after descending stages under both the moderate and high compressive strengths.

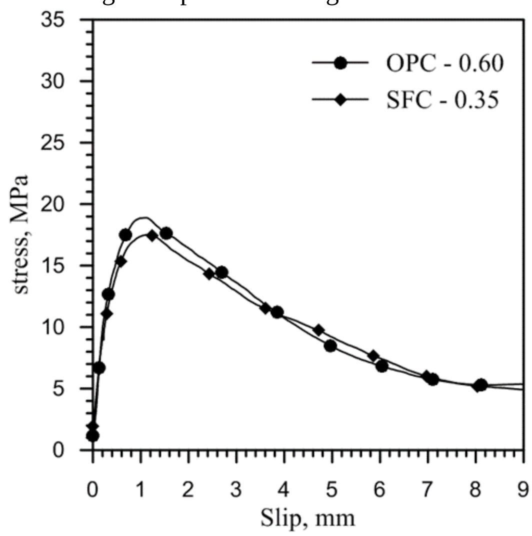

Fig. 3: Pull-out test of OPC concrete and SFC concrete under low compressive strength (35 MPa)

Table 2: The maximum bonding stress and residual friction

Mixture ID	Maximum bonding stress (MPa)	Slip at maximum bonding stress (mm)	Residual friction[a] (MPa)	R^b
OPC-0.35	28.03	1.10	12.39	0.442
OPC-0.45	22.48	0.95	7.63	0.339
OPC-0.60	18.89	0.92	5.36	0.284
SFC-0.27	31.29	1.22	16.01	0.513
SFC-0.30	25.57	1.14	10.69	0.418
SFC-0.35	17.51	1.11	4.91	0.280

[a] Residual friction at slip of 9 mm
[b] The ratio of residual friction to maximum bonding stress

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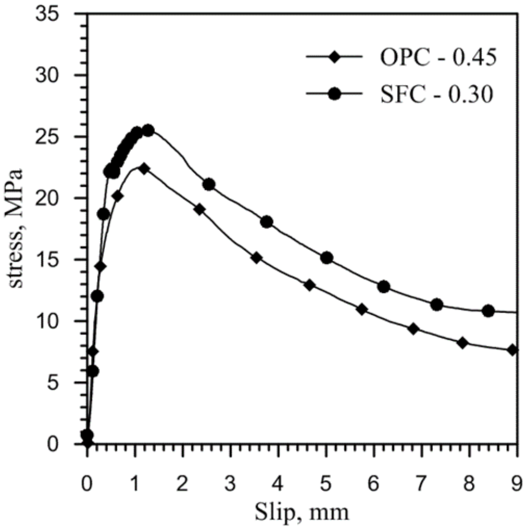

Fig. 4: Pull-out test of OPC concrete and SFC concrete under moderate compressive strength (45 MPa)

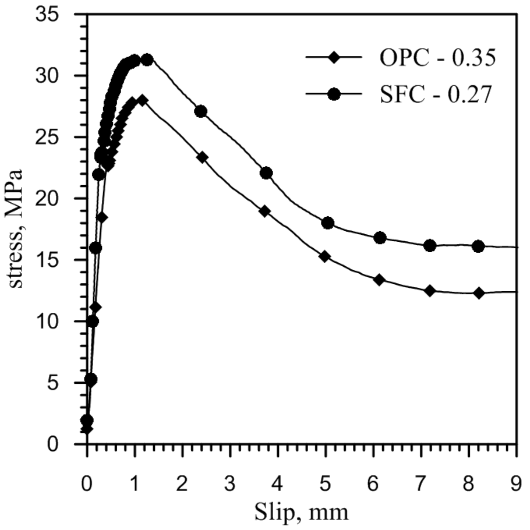

Fig. 5: Pull-out test of OPC concrete and SFC concrete under high compressive strength (55 MPa)

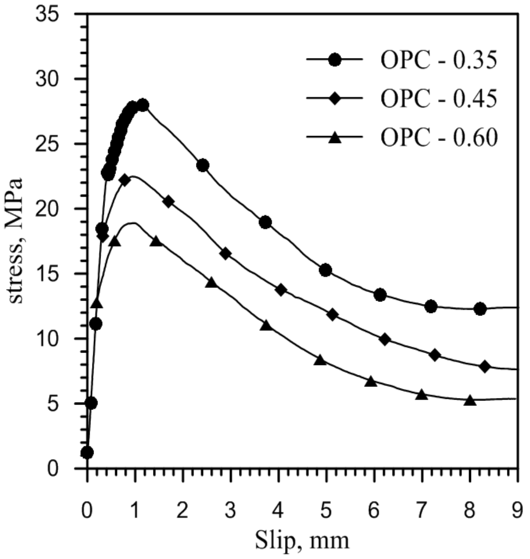

Fig. 6: Effect of water to cementitious binder ratio on pull-out test of OPC concrete

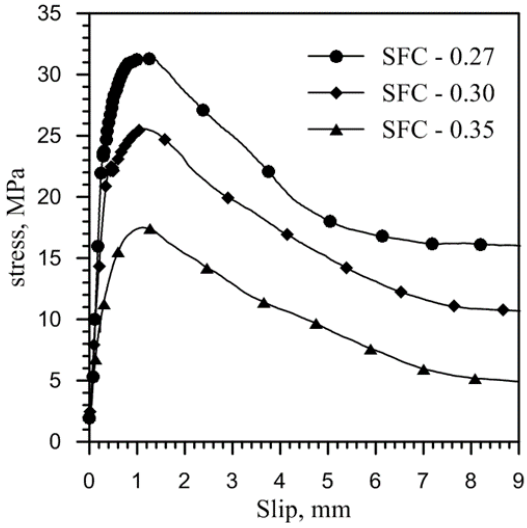

Fig. 7: Effect of water to cementitious binder ratio on pull-out test of SFC concrete

IV. RESULTS AND DISCUSSION

The experimental results indicate that the tendency of complete pull-out test curve for the SFC concrete was similar to that of the OPC concrete under low compressive strength as shown in Fig. 3. The maximum bonding stress of OPC concrete was higher than that of SFC concrete. The residual friction of OPC concrete which happened in the stable stage were similar to that of SFC concrete. In Fig. 4, the maximum bonding stress of SFC concrete was higher than that of OPC concrete under moderate compressive strength. The ingredients of CFBC fly ash can enhance the reactions of slag by anhydrite, and after 7 days, the fly ash will fill up the micro void and increase the bonding stress of concrete. The residual friction of SFC concrete was larger than that of OPC concrete. In Fig. 5, the maximum bonding stress of SFC concrete was higher than that of OPC concrete under high compressive strength. The maximum bonding stress of SFC concrete reached 31.29 MPa, and residual friction reached 16.01 MPa as shown in Table 2. Both of the stresses of SFC concrete were higher than those of OPC concrete obviously.

Fig. 6 indicated that there was a comprehensive increase in bonding stress and residual friction with the decrease of water to cementitious binder ratio of OPC concrete. The maximum bonding stress of OPC concrete reached 28.03 MPa, the corresponding slip reached 1.10 mm as shown in Table 2. The slip at maximum bonding stress increased with the decrease with the water to cementitious binder ratio (w/cb) of OPC concrete. Fig. 7 shows an increase in both the bonding stress and the residual friction with the decrease of water to cementitious binder ratio of SFC concrete. The maximum bonding stress and corresponding slip of SFC concrete were 31.29 MPa and 1.22 mm, respectively, as shown in Table 2. The slip at maximum bonding stress increased with the decrease of water to cementitious binder ratio of SFC concrete. The ratio of residual friction to maximum bonding stress to decreased with the increase of water to cementitious binder ratio. By comparing with OPC concrete as shown in

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Table 2, the residual friction of SFC concrete was greater than that of OPC concrete under both the moderate and high compressive strengths. The ratios of maximum bonding stress to residual friction of OPC and SFC concrete were 2.26 and 1.95, respectively. The ratios of residual friction to maximum bonding stress of SFC concrete were higher than those of OPC concrete under moderate and high compressive strengths. Therefore, the SFC concrete can retain more residual friction after descending stages under both the moderate and high compressive strengths.

V. CONCLUSION

The experimental results in this study demonstrate that both the bonding stress and residual friction of SFC concrete are higher than those of OPC concrete under both the moderate and high compressive strengths. By comparing with the OPC concrete, the higher values of ratio of residual friction to maximum bonding stress of SFC concrete indicates that the SFC concrete can retain more residual friction at the descending stages after peak value under both the moderate and high compressive strengths. In other words, the ductility of reinforced structures made with SFC concrete could be apparently enhanced comparing with those with OPC concrete.

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