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Bond Characteristics of High Strength Concrete with Recycled Aggregate and FRP Bar†

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In this study, to evaluate bond behaviour between high strength concrete with recycled aggregate and fiber reinforced polymer (FRP) bar, 36 specimens were manufactured using substitution rate of recycled aggregate, compressive strength of concrete, arrangement direction of CFRP or GFRP bar. Concrete cubes were manufactured by referring to the standards in KS F 2441, ASTM 234 and CAS-S802. Bond stress and slip of specimens did not show certain standards and bond stress had a decreasing trend with increase in substitution rate of recycled aggregate. Also for horizontal specimens with 30 % substitution rate of recycled aggregate, top specimen had higher bond strength than bottom specimen. For specimens with 100 % substitution rate of recycled aggregate, bottom specimen had higher bond strength than top specimen. This study suggests that the difference according to the settlement of an aggregate is not large.

Keywords: Fiber reinforced polymer, Bond characteristics, Recycled aggregate, High strength concrete.

INTRODUCTION

The construction industry is recognized as the main culprit of environmental destruction from extraction of natural aggregate and environmental load caused by landfill of construction wastes generated during the demolition of buildings. Recycled aggregate made by processing waste concrete during demolition of buildings is evaluated as an optimal alternative resource[1]. Nonetheless, KS F 2573 recommends that recycled aggregate be used at substitution rate of 30 % or below and concrete strength of 21 MPa or below with consideration on safety due to problems of reduced durability and strength. Durability of concrete can be improved using fiber reinforced polymer (FRP) bar, but this has not yet been practically applied as bond force between FRP bar and recycled aggregate concrete.There had been studies on bond characteristics of normal concrete and FRP bar[2-6], but there are no studies on recycled aggregate and FRP bar. In structures for active use of recycled aggregate concrete, studies on durability increase based on FRP bar are demanded in addition to experimenting on a structural member using existing rebar. Therefore as part of an evaluation on the applicability of recycled aggregate in structures, the aim of this study is to test the utility of recycled aggregate and applicability of FRP bar by experimentally examining the effect of recycled aggregate on high strength concrete and FRP bar.

Analysis of existing studies and building codes

Analysis of existing studies: According to existing studies[7,8], FRP bar was reported to show different bond characteristics than rebar, it has different surface form as deformed rebar. While deformed rebar with a rib or joint shows relatively high bond strength due to bearing pressure, FRP with smooth surface shows relatively low bond strength. Kang *et al.*[9] manufactured three types of fiber reinforced concrete to supplement low bond stress of FRP bar to evaluate bond performance according to surface form of FRP bar. As a result, mixture of fiber greatly increased slip in bond strength of FRP bar and sand blast FRP bar with low bond strength was reported to show improved bond performance with a mixture of fiber. Son *et al.*[10] studied bond strength between light weighted concrete and GFRP bar. As a result, they reported that the bond strength of GFRP bar is in the 40-67 % range of rebar depending on the concrete used and that bond strength was lower when light weighted concrete was used compared to normal concrete.

CEB-FIP model code[11]: In the bond model proposed by CEB-FIP code, maximum bond stress of constrained concrete with concrete covering depth over 5db and unconstrained concrete with depth under 5db for compressive strength of concrete is given as $2.5\sqrt{f_{ck}}$ and $2.0\sqrt{f_{ck}}$.

ACI code[12]: $\mu = 20.23\dfrac{\sqrt{f_{ck}}}{d_b}$

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TABLE-1
PARAMETERS OF SPECIMENS

Type	Replacement ratio (%)	Strength of concrete and FRP type					
		24 MPa		40 MPa		60 MPa	
		CFRP	GFRP	CFRP	GFRP	CFRP	GFRP
		Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
V	30	24C30V	24G30V	40C30V	40G30V	60C30V	60G30V
H(T)	30	24C30T	24G30T	40C30T	40G30T	60C30T	60G30T
H(B)	30	24C30B	24G30B	40C30B	40G30B	60C30B	60G30B
V	100	24C100V	24G100V	40C100V	40G100V	60C100V	60G100V
H(T)	100	24C100T	24G100T	40C100T	40G100T	60C100T	60G100T
H(B)	100	24C100B	24G100B	40C100B	40G100B	60C100B	60G100B

TABLE-2
PHYSICAL PROPERTIES OF AGGREGATES

Type	Specific gravity (g/cm^3)	Percentage of absolute volume (%)	Abrasion (%)	Water absorption (%)	Maximum diameter (mm)
Recycled aggregate	2.57	60	22.18	1.67	25

Design code of roman[13]: $\mu = 14.70\frac{\sqrt{f_{ck}}}{d_b}$

Here, μ is bond stress of reinforcing bar and f_{ck} is compressive strength of concrete.

EXPERIMENTAL

Experimental plan: In this study, to evaluate bond behaviour between high strength concrete with recycled aggregate and FRP bar, 36 specimens were manufactured using substitution rate of recycled aggregate, compressive strength of concrete, arrangement direction of FRP bar and type of FRP (CFRP D9, GFRP D13) as variables as shown in Table-1. Concrete cubes were manufactured as in Fig. 1 by referring to the standards in KS F 2441, ASTM 234 and CAS-S802[14].

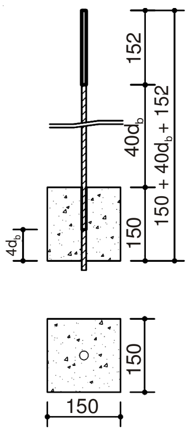


Fig. 1. Details of specimen

Materials used: Physical properties of the recycled aggregate and FRP used in this study are as shown inTables 2 and 3. Compressive strength of concrete according to the mix is shown in Table-4. Test process performed pursuant to KS code.

TABLE-3
MATERIAL DETAILS

Type	Tensile strength (MPa)	Elastic modulus (GPa)
GFRP	1,118	48
CFRP	1,655	103

Experimental method: A pull-out experiment was conducted pursuant to CSA S806-02 to evaluate bond performance of recycled aggregate concrete and FRP bar. Load was applied by load displacement control of 1mm/min using a 2,000 kN Universal Testing Machine (UTM). During the experiment, amount of slip in FRP bar and recycled aggregate concrete for each load step was measured as slip from free end measured at the embedded end of FRP bar. Slip was measured using linear variable differential transducer (LVDT).

RESULTS AND DISCUSSION

Failure mode: Bond failure modes are classified into splitting failure, where concrete is split in a horizontal direction by radial stress from deformed rebar rib to concrete and pull-out failure in which rebar is slowly pulled out due to shear failure of concrete between rebar ribs. Failure modes shown by specimens in this experiment are shown in Table-5. Specimens

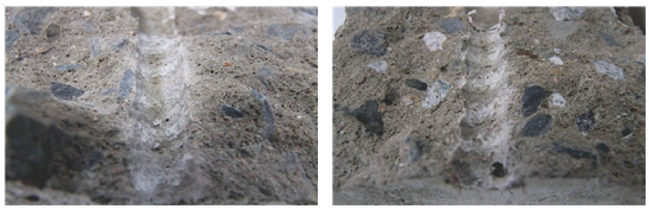
TABLE-4
MIX PROPORTIONS OF CONCRETE

	Replacement ratio (%)	Mixing ratio (kg/m^3)					W/C (%)	f_{ck}
		Cement	Sand	Aggregate	Water			
					Natural	Recycled		
24	30	286	845	633	271	175	61	27.42
	30			0	904			25.20
40	30	328	850	609	261	167	50	40.31
	100			0	870			41.34
60	30	487	733	569	244	169	35	67.77
	100			0	813			64.25

TABLE-5
DESTRUCTIVE PATTERNS

Type	Replacement ratio (%)	Strength of concrete and FRP type					
		24 MPa		40 MPa		60 MPa	
		CFRP	GFRP	CFRP	GFRP	CFRP	GFRP
		Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
V	30	Pull-Out	–	Pull-out	Splitting	Pull-out	Splitting
H(T)		Pull-Out	Pull-out	Pull-out	Pull-out	Pull-out	Pull-out
H(B)		Pull-Out	Pull-out	Pull-out	Splitting	Pull-out	Splitting
V	100	Pull-Out	–	Pull-out	Splitting	Pull-out	Splitting
H(T)		Pull-Out	Splitting	Pull-out	Pull-out	Pull-out	Pull-out
H(B)		Pull-Out	Splitting	Pull-out	Splitting	Pull-out	Splitting

were tested for bond strength of FRP bar and recycled aggregate concrete based on pull-out phenomenon under constraint of $5d_b$ or higher. As a result, all specimens using CFRP-D9 bar showed pull-out phenomenon. On the contrary, specimens using GFRP-D13 reinforced bar satisfied the condition of $5d_b$ or higher but showed splitting failure, except for top horizontal specimen with weak bond stress. Fig. 2 shows the cross sections of specimens with pull-out failure and splitting failure. Bond surface of FRP bar and concrete shown in the figure did not have a large difference. In the case of deformed rebar, bond surface of specimen with pull-out failure has a flat surface because rebar rib shaves off concrete. In contrast, bond surface of specimen using FRP bar showed similar shape as specimen with splitting failure. This phenomenon is caused by slip of FRP bar rib from than FRP surface above certain strength. Fig. 3 is a figure showing FRP bar of specimens with pull-out failure and splitting failure.



Pull-out failure Splitting failure

Fig. 2. Destroyed pattern specimen

Bond stress-slip relationship: For series 1 (CFRP) and series 2 (GFRP) made with concrete design strength of 24 MPa, all CFRP specimens had pull-out failure. As a result of the comparison with building codes and proposed equation, the 24C30V specimen exceeded CEB-FIP and 24C100V and 24C100B specimens exceeded the proposed equation of Roman. For GFRP specimens, 30 % substitution rate of recycled aggregate resulted in pull-out failure and 100 % substitution rate resulted in splitting failure. When each specimen was compared with building codes and proposed equation, all specimens were found to exceed the proposed equation of Roman. For Series 3 (CFRP) and Series 4 (GFRP) made with concrete design strength of 40MPa, CFRP specimens showed pull-out failure. All GFRP specimens showed splitting failure, except for top specimen of horizontal FRP bar with relatively weak bond stress. Although most of specimens showed bond stress higher than or equivalent to the proposed equation of Roman, bond stress of top specimen for horizontal FRP bar among specimens with 100 % substitution rate of recycled aggregate was relatively low. An additional experiment is deemed necessary on this. Series 5 (CFRP and Series 6 (GFRP) with concrete design strength of 60 MPa had similar failure modes as 40 MPa specimens, showing bond stress higher than or similar to the proposed equation of Roman. According to the bond stress-slip relationship of overall specimens, bond strength was reduced with increase in substitution rate of

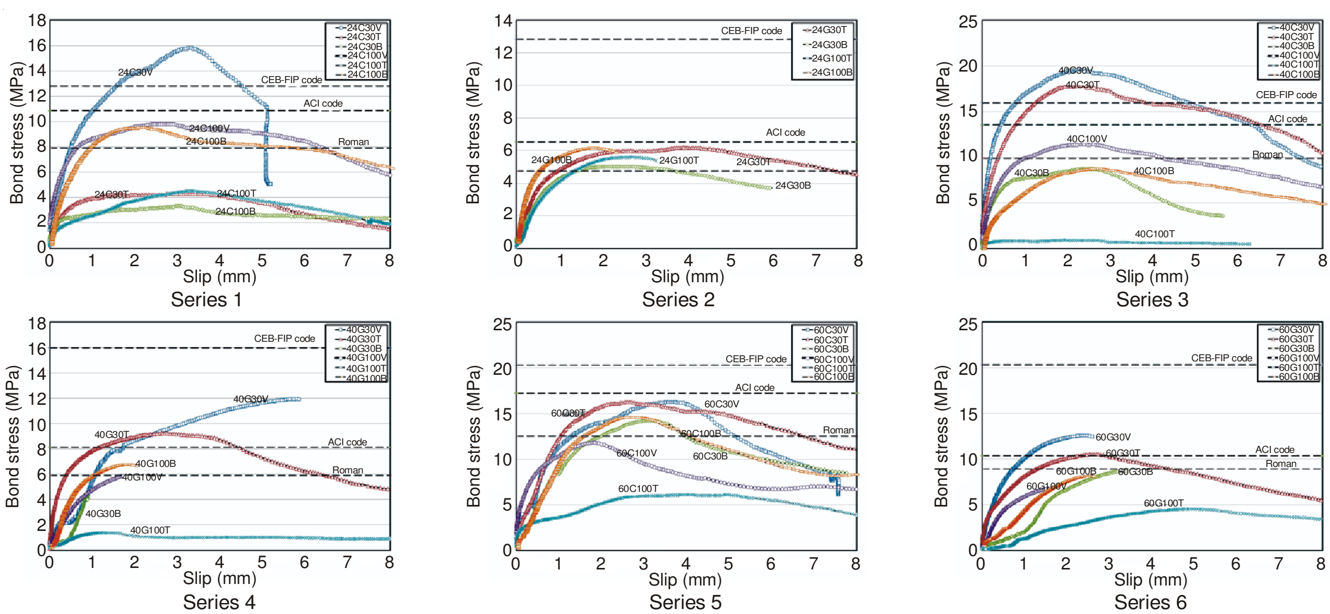


Fig. 3. Bond stress *versus* slip history

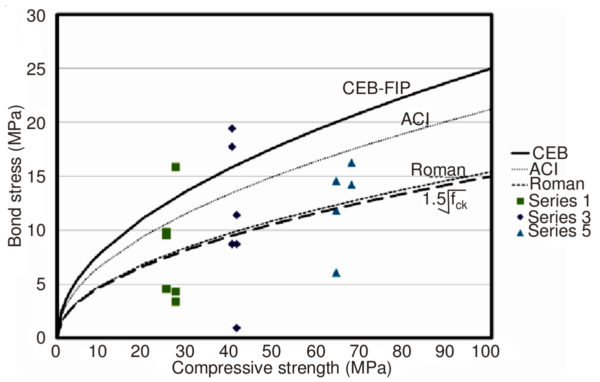
recycled aggregate. In addition, in case of horizontal specimens, specimens with 30 % substitution rate of recycled aggregate had higher bond strength in top specimen of horizontal FRP bar compared to bottom specimen. With 100 % substitution rate of recycled aggregate, bottom specimen of horizontal FRP bar had higher bond strength than top specimen. The difference in bond stress caused by settlement of aggregate is insignificant.

Comparison of experimental results with building codes/proposed equation: Bond strength of rebar and concrete in general is increased with increase in compressive strength of concrete. Such tendency is caused as higher resistance occurs between concrete and deformed rebars with increasing compressive strength of concrete. However, bond strength of FRP bar becomes relatively lower than rebar. While projecting rib of FRP bar resists during the early stage by bearing pressure, but rigidity of rib is lower than rebar in the later stage. Table-6 shows maximum bond stress of each specimen (τ_{max}) and value (τ_{ANA}) and the ratio (τ_{ANA}/τ_{max}) calculated using the proposed equation to compare bond stress of specimens with CEB-FIP, ACI and proposed equation of Roman. Bond performance of concrete with FRP bar according to substitution rate of recycled

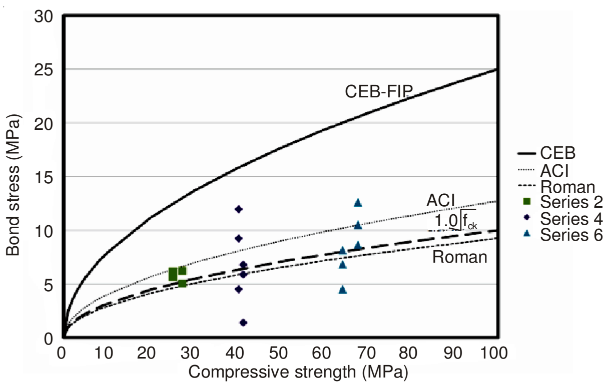
TABLE-6
TEST RESULTS AND COMPARISON WITH ANALYTICAL RESULT

Type	Replacement ratio (%)	f_{ck}	Series			Test results and comparison with analytical result					
			CFRP								
			Series 1	τ_{max} (Mpa) (1)	Slip (mm)	CEB-FIP(2)	(1)/(2)	ACI(3)	(1)/(3)	Roman(4)	(1)/(4)
V	30	27.42	24C30V	15.82	3.30	13.09	1.21	11.12	1.42	8.08	1.96
H(T)			24C30T	4.29	3.30	13.09	0.33	11.12	0.39	8.08	0.53
H(B)			24C30B	3.33	3.03	13.09	0.25	11.12	0.30	8.08	0.41
V	100	25.20	24C100V	9.80	2.91	12.55	0.78	10.65	0.92	7.74	1.27
H(T)			24C100T	4.53	3.41	12.55	0.36	10.65	0.43	7.74	0.59
H(B)			24C100B	9.51	2.23	12.55	0.76	10.65	0.89	7.74	1.23
			Series 3	τ_{max} (Mpa) (1)	Slip (mm)	CEB-FIP(2)	(1)/(2)	ACI(3)	(1)/(3)	Roman(4)	(1)/(4)
V	30	40.31	40C30V	19.44	2.45	15.87	1.22	13.48	1.44	9.79	1.99
H(T)			40C30T	17.72	2.42	15.87	1.12	13.48	1.31	9.79	1.81
H(B)			40C30B	8.71	2.62	15.87	0.55	13.48	0.65	9.79	0.89
V	100	41.34	40C100V	11.41	2.45	16.07	0.71	13.65	0.84	9.92	1.15
H(T)			40C100T	0.92	1.96	16.07	0.06	13.65	0.07	9.92	0.09
H(B)			40C100B	8.71	2.78	16.07	0.54	13.65	0.64	9.92	0.88
			Series 5	τ_{max} (Mpa) (1)	Slip (mm)	CEB-FIP(2)	(1)/(2)	ACI(3)	(1)/(3)	Roman(4)	(1)/(4)
V	30	67.77	60C30V	16.25	4.04	20.58	0.79	17.47	0.93	12.70	1.28
H(T)			60C30T	16.25	2.70	20.58	0.79	17.47	0.93	12.70	1.28
H(B)			60C30B	14.22	3.20	20.58	0.69	17.47	0.81	12.70	1.12
V	100	64.25	60C100V	11.81	1.85	20.04	0.59	17.01	0.69	12.36	0.96
H(T)			60C100T	6.08	4.19	20.04	0.30	17.01	0.36	12.36	0.49
H(B)			60C100B	14.56	2.87	20.04	0.73	17.01	0.86	12.36	1.18
			Series 2	τ_{max} (Mpa) (1)	Slip (mm)	CEB-FIP(2)	(1)/(2)	ACI(3)	(1)/(3)	Roman(4)	(1)/(4)
V	30	27.42	24G30V	-	-	13.09		6.67		4.85	
H(T)			24G30T	6.19	4.02	13.09	0.47	6.67	0.93	4.85	1.28
H(B)			24G30B	5.02	2.76	13.09	0.38	6.67	0.75	4.85	1.04
V	27.42	25.20	24G100V	-	-	12.55		6.40		4.65	
H(T)			24G100T	5.60	2.74	12.55	0.45	6.40	0.87	4.65	1.20
H(B)			24G100B	6.15	1.85	12.55	0.49	6.40	0.96	4.65	1.32
			Series 4	τ_{max} (Mpa) (1)	Slip (mm)	CEB-FIP(2)	(1)/(2)	ACI(3)	(1)/(3)	Roman(4)	(1)/(4)
V	30	40.31	40G30V	11.96	5.80	15.87	0.75	8.08	1.48	5.88	2.03
H(T)			40G30T	9.23	2.79	15.87	0.58	8.08	1.14	5.88	1.57
H(B)			40G30B	4.50	0.87	15.87	0.28	8.08	0.56	5.88	0.77
V	100	41.34	40G100V	5.86	1.71	16.07	0.36	8.19	0.72	5.95	0.99
H(T)			40G100T	1.38	1.27	16.07	0.09	8.19	0.17	5.95	0.23
H(B)			40G100B	6.77	1.85	16.07	0.42	8.19	0.83	5.95	1.14
			Series 6	τ_{max} (Mpa) (1)	Slip (mm)	CEB-FIP(2)	(1)/(2)	ACI(3)	(1)/(3)	Roman(4)	(1)/(4)
V	30	67.77	60G30V	12.57	2.46	20.58	0.61	10.48	1.20	7.62	1.65
H(T)			60G30T	10.50	2.73	20.58	0.51	10.48	1.00	7.62	1.38
H(B)			60G30B	8.61	3.37	20.58	0.42	10.48	0.82	7.62	1.13
V	100	64.25	60G100V	6.79	1.60	20.04	0.34	10.21	0.67	7.42	0.92
H(T)			60G100T	4.50	5.06	20.04	0.22	10.21	0.44	7.42	0.61
H(B)			60G100B	8.14	2.45	20.04	0.41	10.21	0.80	7.42	1.10

aggregate did not satisfy the standard in building codes, showing a problem in security of bond strength. Also, the ratio of an experimental value to each standard and proposed equation was 0.55 for CEB-FIP, 0.8 for ACI and 1.10 for Roman's equation. The experimental results of this study can be shown in terms of compressive strength as in Fig. 4. As shown in Fig. 4(a), CFRP bar partially showed specimens that exceeded CEB-FIP and Roman's proposed equation, but they failed to satisfy the standards of building codes and proposed equation. Expressed as a function of compressive strength of concrete ($\sqrt{f_{ck}}$), the experimental result of this study was found to be $1.5\sqrt{f_{ck}}$. This value is similar to the equation proposed by Roman. As shown in Fig. 4(a), most of GFRP bar specimens exceeded ACI and Roman's proposed equation, excluding top specimen of horizontal FRP reinforced bar. Concrete confining effect and strength were reduced in the top rebar due to leaning of coarse aggregate caused by vibrating compaction and gravity after casting of concrete. Expressed as a function of compressive strength ($\sqrt{f_{ck}}$), the experimental result for GFRP bar was *ca.* $1.0\sqrt{f_{ck}}$.



(a) CFRP



(b) GFRP

Fig. 4. Bond stress to compressive strength of concrete

Conclusion

This study was carried out to examine bond characteristics of high strength concrete with recycled aggregate and FRP bar. The difference in failure modes according to bond stress, strain rate and FRP bar was compared to existing reference equation to obtain the following conclusions. Bond stress and slip of specimens did not show certain standards and bond stress had a decreasing trend with increase in substitution rate of recycled aggregate. Also for horizontal specimens with 30 % substitution rate of recycled aggregate, top specimen had higher bond strength than bottom specimen. For specimens with 100 % substitution rate of recycled aggregate, bottom specimen had higher bond strength than top specimen. In this stuty suggests that the difference according to settlement of aggregate is not large. There was no large difference in bond stress of FRP bar according to increased strength of concrete. As a result of comparing the results of this study with CEB-FIP, ACI and Roman's proposed equation, there were specimens that satisfied and other specimens that failed to satisfy each building code and proposed equation. A newly proposed equation is required based on an additional experiment.

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