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FRP로 보강된 순환골재 고강도 철근콘크리트 보의 휨거동

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Flexural Behavior of High-Strength Reinforced Concrete Beam with Recycled Aggregate Strengthened by FRP Plate

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Abstract: As means to increase the use of concrete with recycled coarse aggregate (RCA), this study aims to evaluate the applicability for flexural strengthening of reinforced concrete beam with high-strength concretes and RCA on which FRP plates, used for repair and strengthening of old and low-durability reinforced concrete structures, is applied. In order to increase the adhesive force of epoxy and FRP plate, FRP plate was installed according to Near-Surface-Mounted (NSM) method. 12 specimens were manufactured using substitution rate of RCA (30%), concrete strengths (40MPa, 60MPa), diameters of deformed bar (D10, D13), and types of FRP plate (AFRP, CFRP) as variables to analyse flexural performance according to FRP plate and substitution rate of recycled aggregate. As a result, in all specimens, specimens strengthened by FRP plate showed a maximum of 17% increase in performance compared to specimens without FRP plate and strengthening performance of CFRP was found to be higher than AFRP. When modulus of rupture was used, the value of cracking moment was similar to that of the reference equation. As bending moment of some specimens strengthened by FRP plate failed to satisfy the criteria of KCI 2012 and ACI 440-2R, additional experiment is deemed as necessary.

Keywords: Fiber reinforced plastics plate, Flexural strength, Near surface mounted, Recycled aggregate

1. Introduction

Increasing number of buildings is being demolished due to aging, functional degeneration, and shortening of life span by structural problems. As reconstruction and redevelopment are becoming vitalized, demand for natural aggregate and generation of construction wastes are increasing (Ministry of Environment, 2010). Annual amount of construction wastes has reached 48.8(%) of total waste, which corresponds to 180,000 tons per day on average. Generation of construction wastes is expected to increase every year. As a solution to these problems, recycled coarse aggregate (RCA) made by processing waste concrete among construction wastes is evaluated as an optimal alternative. Most of existing researches on flexural member of reinforced concrete beam using RCA are merely assessing substitution rate of RCA and applicability of flexural member according to material characteristics, and these studies manufactured concrete based on the design strength regulated under KS F 2573. This fails to take into the account diverse variables of design strength for concrete used at construction sites, and limits practicability of RCA and applicability of structural member. Accordingly, strength assessment on flexural member about different designed strengths of RCA concrete used at construction sites is required to achieve practical use of RCA. Problems about reduced durability and strength during the use of RCA need to be supplemented. Therefore, as means to increase the use of concrete with RCA, the aim of this study is to evaluate the applicability for flexural strengthening of high strength reinforced concrete member with RCA by experimental works. For flexural strengthening, FRP plates (AFRP plate, CFRP plate) were applied. They are used to repair and reinforce old and low-durability concrete structures.

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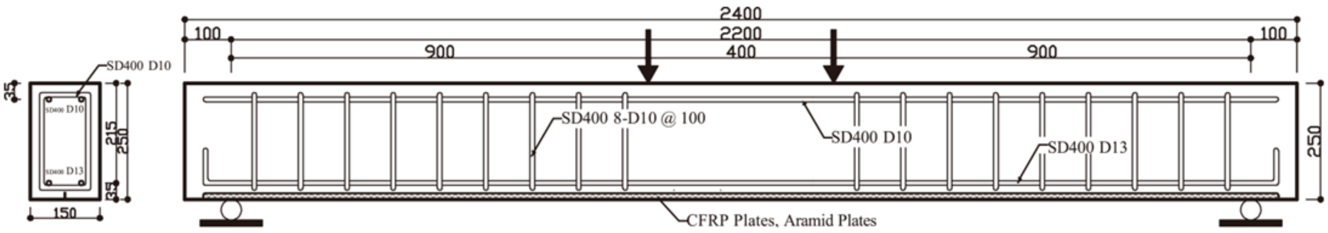

Fig. 1 Specimen details

2. Research Trends

Many recent studies have been conducted on flexural, shear, and bonding behaviours of concrete member strengthened by Near-Surface-Mounted (NSM) method (Rizkalla and EI-Hacha, 2004; D. J. Oehlers et al., 2007; R. Seracino et al., 2007; A. Nami, 2010; J. R. Yost et al., 2007; EI-Hacha and Rizkalla, 2004) but there is lack of existing research on RCA concrete strengthened by FRP. Seo conducted an experiment on the difference in strengthening effect between NSM and surface bonding, and bonding behaviour according to difference in bonding length of NSM (S. Y. Seo et al., 2012). As result of their study, surface mounting based on erection of FRP plate exhibited better strengthening performance compared to plate bonding method (S. Y. Seo et al., 2012). When the center was not bonded depending on flexural length, certain strengthening effect was exhibited. Lim performed a flexural experiment by manufacturing a T-shaped beam strengthened using FRP by NSM. The result verified 247% increase in strengthening effect (D. H. Lim, 2008). De Lorenzis carried out a flexural experiment on a T-shaped beam strengthened by NSM FRP, and they reported 44% increase in strengthening effect compared to unstrengthen specimen (L. De Lorenzis et al., 2000; L. Lorenzis and Teng, 2007). Existing research on RCA evaluated flexural behaviour of reinforced concrete beam with RCA using substitution rate of RCA and strength of high-strength concrete as variables (Y. T. Lee et al., 2014; S. H. Song et al., 2009; I. Maruyma et al., 2004). As a result, there was no difference in flexural performance of high-strength reinforced concrete beam according to substitution rate of RCA, and all specimens substituted with RCA concrete of 60MPa showed higher performance than specimens with 0% substitution of RCA. Song conducted experiment using material characteristics and substitution rate of recycled coarse aggregate and recycled fine aggregate as variables (S. H. Song et al., 2009). The result did not show larger difference in flexural performance according to substitution of RCA and fine aggregates. Maruyama carried out an experiment with substitution rate of RCA and W/C (water to cement ratio) as variables, reporting slight reduction in strength of specimens substituted 100% with RCA and fine aggregates according to W/C ratio and increase in maximum strength compared to the calculated value (I. Maruyma et al., 2004). Reduction of performance by use of RCA was reported as insignificant.

Table 1 Parameters of specimens

Series	Specimens name	R.R (%)	b×d (mm)	Net span (mm)	C.R	T.R	FRP
	N-D10-40						-
1	A-D10-40	30	150×215	2,400	D10-2	D10-2	AFRP
	C-D10-40						CFRP
	N-D13-40						-
2	A-D13-40	30	150×215	2,400	D10-2	D13-2	AFRP
	C-D13-40						CFRP
	N-D10-60						-
3	A-D10-60	30	150×215	2,400	D10-2	D10-2	AFRP
	C-D10-60						CFRP
	N-D13-60						-
4	A-D13-60	30	150×215	2,400	D10-2	D13-2	AFRP
	C-D13-60						CFRP

R.R: Replacement ratio
C.R: Compression rebar
T.R: Tension rebar

3. Experiments

Shapes of reinforced concrete beams strengthened by FRP plate and specimens are listed in Fig. 1 and Table 1. FRP plate was installed on the form prior to casting of concrete in this experiment in order to exclude bonding strength of epoxy and NSM FRP plate from consideration. To evaluate flexural behaviour of high strength reinforced concrete beam with RCA strengthened by FRP plate, Series 1-Series 4 were manufactured. Material properties of RCA, concrete, rebar, and FRP plate are shown in Table 2. Design strengths of concrete were 40MPa and 60MPa. Material test on rebar and FRP plate was performed pursuant to KS F 0802.

Table 2 Material properties of RCA, concrete, rebar and FRP plate

Recycled aggregate				
Specific gravity (g/cm^3)	P.A.V (%)	Abrasion (%)	Water absorption (%)	Maximum diameter (mm)
2.57	60	22.18	1.67	25

Reinforcing bars and FRP plate			
Type	Yield strength f_y (MPa)	Tensile strength f_u (MPa)	Elastic modulus (GPa)
D10	448	577	172
D13	497	603	178
AFRP	-	2,430	131
CFRP	-	3,125	195

Mix proportions of concrete								
Design strength f_{ck} (MPa)	R.R (%)	Mixing Ratio (kg/m^3)					W/C (%)	f_{cu} (MPa)
		C	S	Aggregate N	Aggregate R	W		
40	30	328	850	609	261	167	50	40.31
60	30	487	733	569	244	169	35	67.77

RCA: Recycled aggregate
P.A.V: Percentage of absolute volume
R.R: Replacement ratio
C: Cement, S: Sand, N: Natural, R: Recycled, W: Water

Force was applied in this experiment using a 2,000kN Universal Testing Machine (UTM). Load was applied as 4 points using displacement control. Also, displacement of reinforced concrete beam and strain rate of rebar and FRP plate were measured by linear variable displacement transformer (LVDT) and strain gauge.

4. Results and discussion

Final flexural destruction of high-strength recycled aggregate reinforced concrete beam strengthened by FRP plate is as shown in Fig. 2. All specimens showed new crack at both ends as flexural crack progressed to the top with increase in load after initial generation of flexural crack.

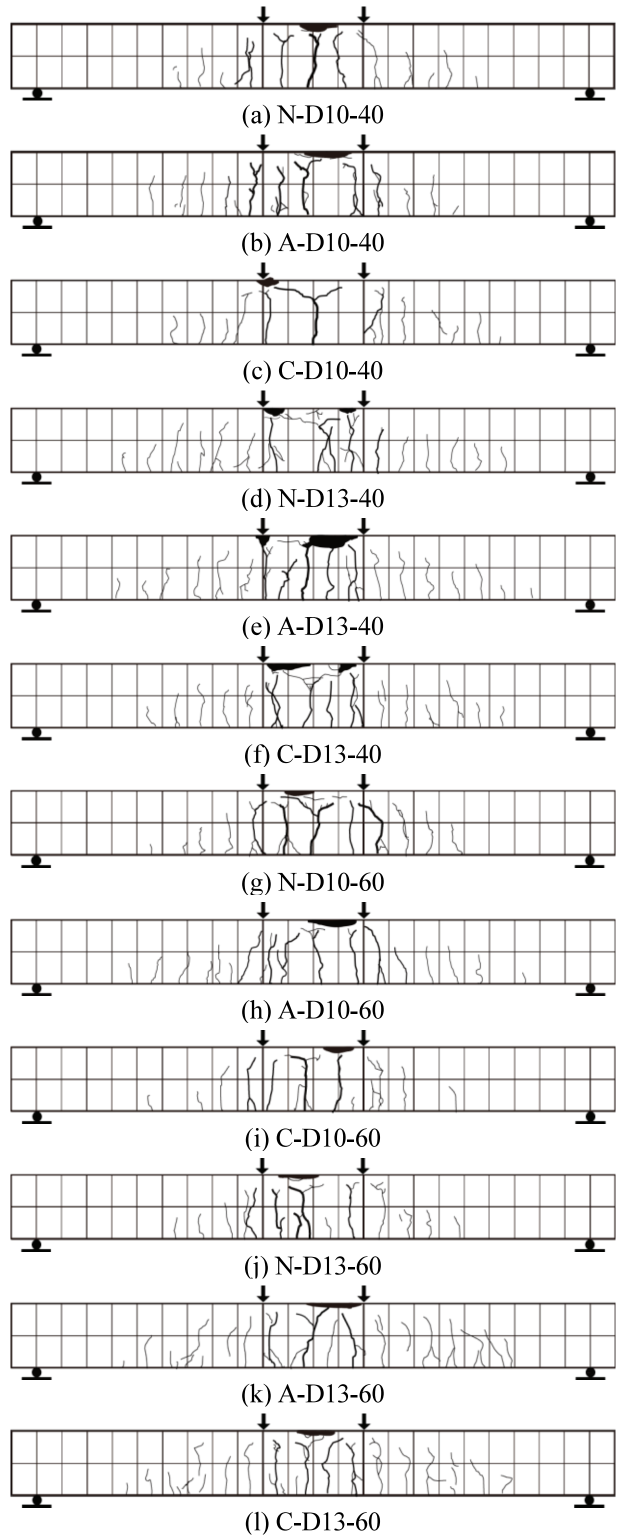

Fig. 2 Crack pattern of specimen

Deflection was rapidly increased after yielding of tensile rebar, and flexural destruction was shown by concrete crushing. In addition, a result of measuring the number of cracks generated after flexural destruction of concrete beam, there was no larger difference in the number of beam cracks caused by FRP plate. The number of cracks had an increasing trend according to diameter of rebar. Table 3 shows the number of cracks on reinforced concrete beam according to increasing displacement.

Table 3 Number of cracks

Series	Specimens name	Number of cracks	Series	Specimens name	Number of cracks	Growth (%)
1	N-D10-40	12	2	N-D13-40	22	45.45
	A-D10-40	13		A-D13-40	22	40.91
	C-D10-40	14		C-D13-40	17	17.65
3	N-D10-60	16	4	N-D13-60	17	5.88
	A-D10-60	11		A-D13-60	18	38.89
	C-D10-60	14		C-D13-60	16	12.50

Fig. 3, 4, 5, 6 are graph showing load-displacement curve of specimens according to Series. In Fig. 3, A-D10-40 specimen strengthened by AFRP showed 17.74% increase in maximum resistance compared to N-D10-40 specimen after the yield strength of rebar. C-D10-40 specimen strengthened by CFRP showed 12.24% increase. In addition, other specimens except for C-D10-40 specimen were found to have higher flexural resistance regulated by the current standards.

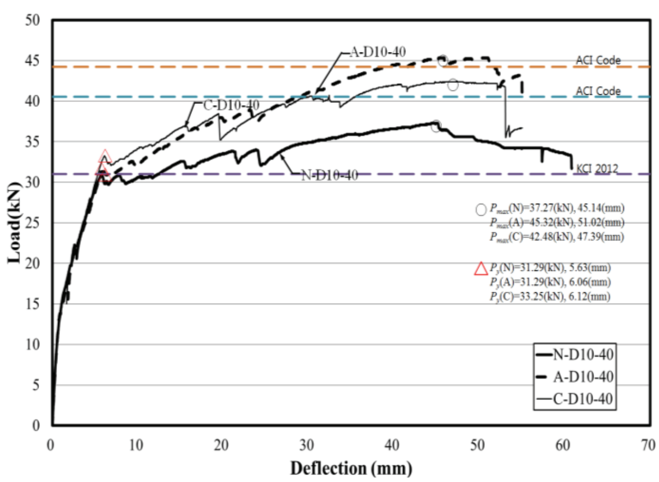

Fig. 3 Load displacement relationship: series 1

As shown in Fig. 4, load-displacement relationship of all Series 2 specimens had similar early strengths. Maximum resistance of specimen strengthened by FRP plate was increased by 5% compared to N-D13-40 specimen, but no larger difference was found. In addition, other specimens except for N-D13-40 specimen showed 6.63%-11.56% lower resistance than the current standards.

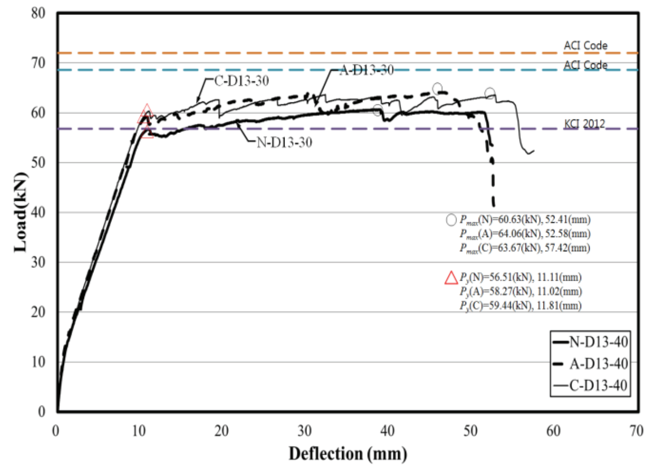

Fig. 4 Load displacement relationship: series 2

Early strengths were also similar in Series 3, and maximum resistance was increased by about 9% in the specimen strengthened by FRP plate.

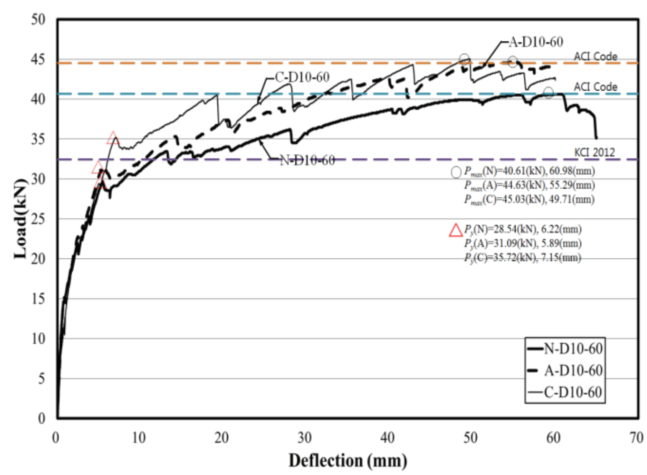

Fig. 5 Load displacement relationship: series 3

All specimens had higher resistance than the current standards as shown in Fig. 5. Series 4 specimens had slight difference in early flexural strength, but they were mostly similar. Maximum resistance was increased by 7.9% with AFRP plate (A-D13-60) and 10.32% with CFRP plate (C-D13-60) as shown in Fig. 6.

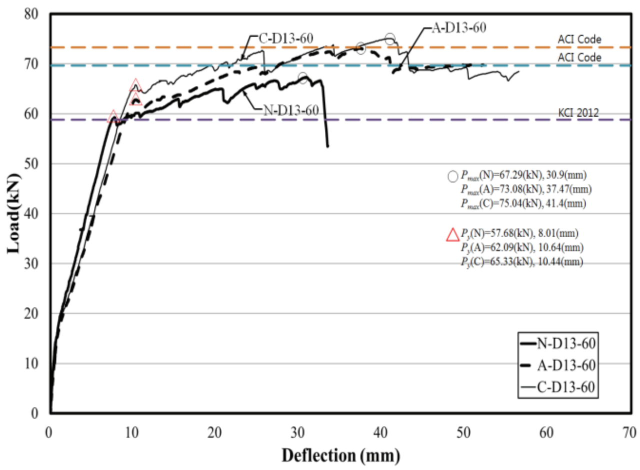

Fig. 6 Load displacement relationship: series 4

Strain rate of tensile rebar for each specimen had similar relationship among Series, and early strain rate prior to generation of concrete crack was similar. Strain rate of rebar for specimens not strengthened by FRP plate became higher after generation of crack. While specimens not strengthened by FRP plate had the rebar yield at $M_{\exp}/M_n$ value near 1, specimens strengthened by FRP plate showed a yield trend near $M_{\exp}/M_n$ value of 0.8. is the nominal bending moment in KCI 2012 or ACI 440-2R (American Concrete Institute, 2002), and is flexural moment from test.

Fig. 7 and Table 4 compare nominal bending moment (M_n) calculated using maximum flexural moment from flexural experiment (M_{n-test}) and the concept of rectangular stress provided in KCI2012, ACI 440-2R.

Table 4 shows test results. In case of Series 1 and Series 2, maximum load, $P_{\max}$, of specimens not strengthened by FRP plate was higher than load, P_n , at nominal moment strength, Mn ($P_{\max}/P_n$= 1.2~1.07). $P_{\max}/P_n$ was respectively 1.12 and 0.93 for specimens with AFRP plate and 0.96 and 0.88 for specimens with CFRP plate, failing to satisfy the reference equation. On the contrary, all Series 3 and Series 4 exceeded the reference equation, and specimens with CFRP plate showed values extremely similar with the reference values. Accordingly, while there seems to be no problem in flexural member performance of reinforced concrete using recycled aggregate, additional experiment needs to be conducted on increased durability as some specimens strengthened by FRP plate failed to satisfy the current standards.

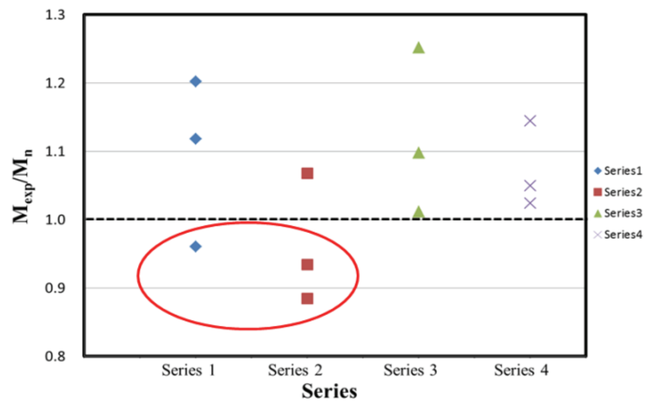

Fig. 7 Comparison with relative expression

Fig. 8 is a graph that compares existing research and the reference equation. As in the figure, existing research had unstrengthened specimens with recycled aggregate exceed the reference values, but C-D10-40, N-D13-40 and A-D13-40 specimens strengthened by FRP plate had lower values than the reference values.

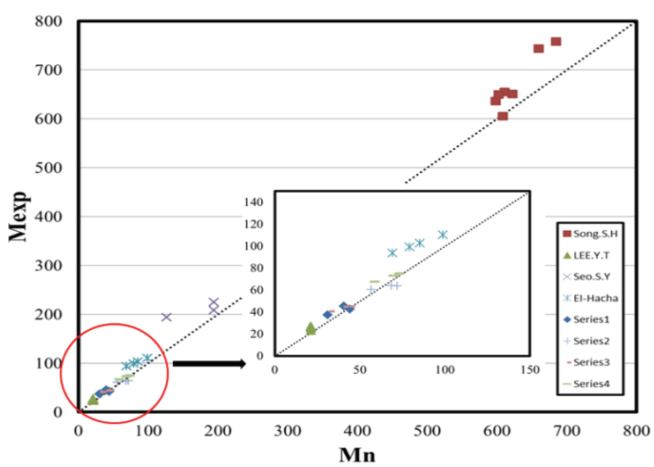

Fig. 8 Comparison with results of existing research

Table 4 shows loads, P_{cr}, at cracking moment (P_{cr}) calculated by cracking moment upon initial occurrence of flexural crack in the beam specimen (P_{cr-t}) and the current reference equation. Cracking moment according to the current reference equation can be calculated as shown in Eq. (1).

Table 4 shows loads, P_{cr}, at cracking moment (P_{cr}) calculated by cracking moment upon initial occurrence of flexural crack in the beam specimen (P_{cr-t}) and the current reference equation. Cracking moment according to the current reference equation can be calculated as shown in Eq. (1).

Table 4 Test results

Series	Specimens	Calculated results: Cracking load P_{cr} (kN) (1)	Calculated results: Maximum load P_n (kN) (2)	Test results: Cracking load P_{cr-t} (kN) (3)	Cracking load Deflection (mm)	(3)/(1)	Yield point P_y (kN)	Yield point Deflection (mm)	Maximum load P_{max} (kN) (4)	Maximum load Deflection (mm)	(4)/(2)
1	N-D10-40	13.83	31.01	14.22	0.98	1.03	30.21	8.33	37.28	45.14	1.20
	A-D10-40		40.54	14.72	1.18	1.06	31.29	6.06	45.32	51.02	1.12
	C-D10-40		44.23	15.69	1.10	1.13	33.25	6.12	42.48	47.39	0.96
2	N-D13-40	13.83	56.80	16.48	1.69	1.19	56.51	11.07	60.63	38.93	1.07
	A-D13-40		68.61	14.12	1.09	1.02	58.27	10.94	64.06	46.74	0.93
	C-D13-40		72.00	12.94	1.07	0.94	59.44	11.81	63.67	32.28	0.88
3	N-D10-60	17.90	32.45	15.99	1.08	0.95	28.54	6.22	40.61	60.98	1.25
	A-D10-60		40.67	16.08	1.26	0.95	30.99	5.89	44.63	55.29	1.10
	C-D10-60		44.52	16.28	1.35	0.96	33.94	8.07	45.03	49.71	1.01
4	N-D13-60	17.90	58.81	15.69	0.80	0.88	57.68	8.01	67.29	30.90	1.14
	A-D13-60		69.65	16.67	0.98	0.93	62.09	10.64	73.08	37.47	1.05
	C-D13-60		73.29	17.55	1.00	0.98	67.49	16.38	75.04	41.10	1.02

$$M_{cr} = \frac{f_r I_g}{y_t} (kN \cdot m) \quad (1)$$

Where $f_r = 0.63\sqrt{f_{ck}}$ modulus of rupture, I_g = geometrical moment of inertia, y_t= Distance from the neutral axis to tension end.

As result of comparing cracking moment measured by the experiment to the reference value in design, all specimens other than Series 3, Series 4 and C-D13-40 specimen showed higher cracking moment than the reference. Overall range of cracking moment was 0.83-1.19, showing similar distribution as the reference values. Therefore, cracking moment of high strength RCA reinforced concrete beam strengthened by FRP plate can be predicted using modulus of rupture ($0.63\sqrt{f_{ck}}$). Additional experiment is needed for a more accurate definition.

Ductility was calculated by the ratio of displacement at each load to displacement at rebar yielding. Ductility at maximum load was 2.5-9.8 and showed brittle tendency, and no difference was found according to strengthening with FRP plate. Ductility at 85% of maximum load showed brittle tendency of 1.2-4.14 in most of specimens, but Series 2 and Series 4 that used D13 rebar showed reduction of ductility to 0.58-0.93.

5. Conclusion

This study was an evaluation on flexural performance of high-strength reinforced concrete beam according to substitution rate of RCA strengthened by FRP plate. 12 specimens were manufactured to conduct an experiment on applicability of the current standards and practicality of RCA concrete. Conclusions obtained from the limited experiment above are as follows.

Destruction and cracking of high-strength reinforced concrete beam with RCA strengthened by FRP plate by simple force application were similar to beam not strengthened by FRP plate. The number of cracks was found to increase according to increase in diameter of rebar, regardless of FRP plate.

In all specimens, ductile behavior occurred to show increase of concrete displacement after maximum load. Specimens strengthened by FRP plate showed up to 17% increase compared to unstrengthen specimens and strengthening performance of CFRP plate was superior to AFRP plate.

Cracking moment measured by the experiment using modulus of rupture ($0.63\sqrt{f_{ck}}$) was similar with the reference equation and was found to be predictable.

As some specimens strengthened by FRP plate failed to satisfy the ACI 440-2R standard for flexural strength measured by the flexural experiment, an additional experiment is required.

Other specimens showed flexural strength higher than the KCI 2012 and ACI 440-2R standards.

No problem is expected in performance of reinforced concrete beam when flexural member is designed with recycled aggregate. Bonding strength between FRP plate and concrete must be verified in case of reinforced concrete beam with RCA applied with FRP plate.

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요 지 : 본 연구는 순환골재를 사용한 콘크리트의 활용증대 방안으로 철근콘크리트 구조물의 노후화와 내구성 저하 시 보수보강으로 사용되는 FRP (AFRP, CFRP) 판으로 보강된 순환골재 고강도콘크리트(40MPa, 60MPa) 보를 제작하여 순환골재 철근콘크리트 보의 휨 보강에 대한 적용성을 평가하고자 한다 기존의 표면매입보강에 따른 에폭시와 FRP 판의 부착력을 고려하지 않기 위해 콘크리트 타설 전 FRP 보강판을 거푸집에 미리 설치하였으며, 순환골재 치환율(30%), 콘크리트 강도(40MPa, 60MPa), 이형철근(D10, D13), FRP 판의 종류(AFRP 판, CFRP 판)를 변수로 12개 실험체를 제작하여, FRP 판과 순환골재 치환율에 따른 휨 성능을 분석하였다. 그 결과 FRP 판으로 보강한 실험체는 무보강 실험체에 비해 최대 17% 증가하는 경향을 나타내었으며 AFRP 판에 비해 CFRP 판의 보강 성능이 우수한 것으로 나타났다. 또한 순환골재 치환율에 따른 보강 성능의 차이는 없는 것으로 나타났다. 실험에 의해 측정된 균열모멘트는 파괴계수를 이용한 결과 기준식과 비슷한 값을 나타났으며 휨 모멘트는 FRP 판을 보강한 일부 시험체가 KCI 2012와 ACI 440-2R에서 제시한 기준을 만족하지 못하는 것으로 나타났다.

핵심용어 : FRP 플레이트, 휨강도, 표면매입, 순환골재