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Compressive performance of 50 MPa strength concrete-filled square and circular tube (CFT) columns using recycled aggregate

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Abstract

Recycled aggregate is an environmentally self-sustainable solution that can reduce construction waste and replace natural aggregates. However, there is a disadvantage in concrete such as initial strength drop and long-term strength development. Therefore, the interaction effect of the two materials can be expected by filling the cyclic aggregate concrete in the CFT column. In order to develop a concrete with compressive strength of 50 MPa as a recycled aggregate, we carried out a mixing experiment and fabricated 18 specimens to confirm the compressive behavior of a RCFT (Recycled Concrete Filled Tube) column that can be applied to actual buildings. Variable is the shape and thickness of steel pipe, concrete strength and mixing ratio, and coarse aggregate and fine aggregate are all used as recycled aggregate. The optimum mixing ratio for recycled aggregate concrete to be filled in the CFT filled steel pipe was found through three concrete preliminary mixing experiments. In addition, the compression test of the RCFT column was carried out to observe and analyze the buckling shape of the CFT column. Based on the analysis of the buckling configuration and the experimental data, the load-displacement curves of the specimens were drawn and the compressive behavior was analyzed.

Keywords: *Recycled aggregate; CFT column; concrete-filled tube; high-strength concrete.*

1. Introduction

1.1. Research background

As shown in Table 1, the construction industry has been increasing due to the social factors such as redevelopment and reconstruction, and the demolition and decommissioning of structures with more than 30 years of construction due to deterioration and deterioration of buildings. In the case of waste concrete, which constitutes the largest percentage of construction waste, the landfill shortage has increased due to the lack of landfill, and the problem of environmental pollution has been increasing due to waste concrete drainage. In addition, due to lack of natural aggregates, the aggregate supply and demand is getting worse and deeper, so the interest of recycled materials is increasing in terms of conservation of national resources and environmental preservation.

Table 1. Construction waste status.

	'12	'13	'14
Amount of waste (ton/day)	186,629	183,538	185,382
Increase rate compared to last year	0.1	-1.7	1.0

In addition, due to lack of natural aggregates, the aggregate supply and demand is getting worse and deeper, so the interest of recycled materials is increasing in terms of conservation of national resources and environmental preservation. Recycled aggregate is produced as aggregate suitable for the quality standard of recycled aggregate quality standards by wave, crushing, screening and separation processes. In particular, the cement paste attached to the surface of the aggregate causes low density and high water absorption rate, which causes low fluidity and creep and shrinkage due to low initial age compressive strength and high water absorption rate of concrete, and low recycling rate. As a method to overcome the disadvantages of concrete using such recycled aggregate and to use it structurally, a method of filling recycled aggregate concrete filled in a CFT steel pipe was devised. This is because the steel pipe enclosing the recycled aggregate receives the initial strength instead of the steel pipe, so that the inner concrete can be expressed and the external influence can be reduced to improve the long-term performance. Therefore, in order to apply the recycled aggregate concrete to the CFT, the target compounding strength was determined through preliminary mixing and the compressive behavior of the CFT column was confirmed.

1.2. Research content and scope

Two types of CFT steel pipes were used, square and circular. 100% recycled aggregate was used as the aggregate in the filled concrete, and the powder was divided into two types by using 100% ordinary Portland cement, silica fume and fly ash 20:10. The structural performance of the CFT column was analyzed based on the mixing ratio obtained through three concrete preliminary blending operations. The stub column test was carried out to minimize the buckling and to confirm the compressive behavior.

2. Prior research

2.1. Material characteristics of recycled aggregate concrete

In Korea, the law for promoting the recycling of construction waste was established in 2003 to establish the quality standard of recycled aggregate for each recycled application. As a result, KS F2573, recycled aggregate concrete (11, 2009) was added to the concrete standard specification through standardization of recycled aggregate KS, and there are a number of research papers for recycling recycled aggregate as a concrete material.

It was found from the 1998 experiment that the compressive strength was significantly increased when 20% of silica fume was incorporated. In 1999, the effect of fly ash content on the properties and mechanical properties of concrete was examined. Compressive and tensile strength of fly ash concrete decreased slightly from 7 days to 28 days in comparison with ordinary concrete. However, it was found that it was much better at the compressive strength [1].

In the study on the effect of recycled aggregate and fly ash on concrete fluidity and strength in 2013, the compressive strength and splitting tensile strength of concrete using recycled aggregate showed a tendency to decrease as the substitution rate increased, and recycled aggregate exceeded 30% in one case, this tendency was more pronounced. In addition, 30% replacement of recycled aggregate and concrete using fly ash were found to be helpful in improving long - term strength [2].

Meanwhile, there has been intensive research on recycled aggregate concrete (RAC) for mechanical properties in China and there has been much effort to clarify the performance and suitability of structural members made of RAC [3-6]. Li et al. [7] conducted an experiment on the compressive strength of RAC. As a result, the RCA content significantly affected the compressive strength of RAC. The compressive strength of RAC using 100% RCA was about 10% lower than the compressive strength of conventional concrete.

Based on these results, it was confirmed that it helps to improve the long - term compressive strength of recycled aggregate concrete containing fly ash and silica fume. Therefore, in this study, fly ash and silica fume were used in concrete formulations for long-term strength development.

2.2. Recycled aggregate concrete filled steel pipe CFT

The research on synthetic CFT columns using concrete using recycled aggregate has not yet been carried out in Korea. There are considerable reports on various mechanical properties and seismic performance of concrete CFT steel pipe columns using recycled aggregate in China.

Yang and Han [8] showed that the ultimate capacity of conventional concrete is 1.7 ~ 9.1% higher than that of RAC with 50% RCA because of the low strength of RAC. The dynamic model developed for general CFT columns is used for the calculation of CFT columns of recycled aggregate concrete and confirmed that it is appropriate.

Chen et al. [9] reported that the intensity of the RCAST column showed an increasing trend with increasing RCA replacement rates.

It was confirmed that the strength of most CFT concrete columns was evaluated with the same strength formula as that of general CFT column. It was confirmed that the strength of steel pipe (CFT) column increased with increasing the replacement ratio of recycled aggregate. Therefore, the steel pipe (CFT) column using only recycled aggregate without natural aggregate was fabricated and tested.

3. Theoretical considerations and analysis

3.1. Thickness limit and compressive strength equation

The structural performance of the composite section is shown in Table 2 in KBC2016 [10], where the width thickness ratio is dense / unconfined / triangular. Since the circular and square steel pipes to be used as test specimens in this experiment are dense sections (compressive strength), Eq. (1) is obtained.

Table 2. Width –Thickness ratio limits.

	Filled steel pipe		Unfilled steel pipe	
	Square, ***b*/*t***	Circle, ***D*/*t***	Square, ***b*/*t***	Circle, ***D*/*t***
λ_p	$2.26\cdot\sqrt{\frac{E}{f_y}}$	$0.15\cdot\sqrt{\frac{E}{f_y}}$	$1.12\cdot\sqrt{\frac{E}{f_y}}$	-
λ_r	$3.00\cdot\sqrt{\frac{E}{f_y}}$	$0.19\cdot\frac{E}{F_y}$	$1.40\cdot\sqrt{\frac{E}{f_y}}$	$0.11\cdot\sqrt{\frac{E}{f_y}}$

Compact section:

$$P_{n0} = P_p$$
$$P_p = F_u \cdot A_s + F_{ur} \cdot A_{sr} + C_2 \cdot f_{ck} \cdot A_s \qquad (1)$$

C_2 is equal to 0,85 in square cross section. In a circular cross section is calculated as:

$$0.85 \cdot \left(1 + 1.56 \cdot \frac{f_y \cdot t}{D_c \cdot f_{ck}}\right) \qquad (2)$$
$$D_c = D - 2 \cdot t$$

4. Design and experiment of recycled aggregate concrete suitable for CFT filled steel pipe

4.1. Experimental plan

In order to find the mixing ratio of recycled aggregate concrete suitable for CFT-filled steel pipes, an experimental plan was established as shown in Table 3 based on the results of the preliminary tests of the third stage. As the experimental parameters, the compressive strength of the recycled aggregate concrete was set to 30, 40, and 50 MPa, respectively. The experiment was divided into two stages according to the cement component. Table 4 shows the formulation design used in this experiment.

Table 3. Specimen parameters.

ID	f_{ck} (MPa)	**OPC:SP:FA**
Type 1	30	100:0:0
Type 2	30	100:0:0
Type 3	40	70:20:10
Type 4	50	70:20:10

* OPC = Ordinary Portland cement

* SP = Silica fume

* FA = Fly ash

4.2. Experimental method

In order to remove the recycled aggregate and the impurities contained in the aggregate, an aggregate washing operation was required in advance. After 2 to 3 washing operations, the surface yield of the aggregate had to be measured in order to modify the mixing ratio from the specific formulation to the in situ formulation. Aggregates were immersed in water to allow sufficient water to pass before the experiment. The water absorption rate was measured 12 hours before the experiment, and the difference was calculated. Since the recycled aggregate has a high water uptake and therefore has a large effect on the strength depending on the moisture content in the aggregate, the team measured the surface yield through three preliminary mixing experiments and found that the recycled aggregate concrete I found the mixing ratio. During the mixing process, the amount of high performance water reducing agent was observed and recorded in order to find the proper fluidity in the concrete placed in the CFT steel pipe. The liquidity was evaluated based on KS F 2402:2004 [11]. The blending was carried out by using a flow slump, not a general slump, as a target slump of 500 to 700 mm.

Recycled aggregate concrete specimens were 100 mm in diameter and 200 mm in height and were subjected to a mixing according to KS F 2403:2014 [12] as shown in Fig. 1 to produce specimens and underwater curing.

Fig. 1. Specimen curing.

The compressive strength was calculated by the average of three compressive tests at 3, 7, 14 and 28 days. The compressive strength of the recycled aggregate concrete specimens was tested at the rate of compression stress per second (0.6) MPa according to KS F 2405:2010 [13] as shown in Fig. 2.

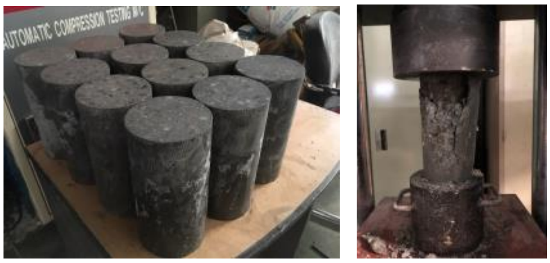


Fig. 2. Experiments of compressive strength of specimens.

Table 4. The mix proportions and properties if the new concrete.

Type	**Target strength** f_{ck} (MPa)	**Cement C** (kg/m^3)	**SP** (kg/m^3)	**FA** (kg/m^3)	**Recycled sand** (kg/m^3)	**Recycled coarse aggregate** (kg/m^3)	**Water W** (kg/m^3)	**W/C**	**28-day strength** f_{ck} (MPa)
1	30	22.4	0	0	61.2	69.3	3.7	52%	30.4
2	30	22.4	0	0	61.2	69.3	3.7	52%	26.9
3	40	15.9	4.5	2.3	60.4	68.4	3.8	51%	40.9
4	50	21.8	6.2	3.1	56.4	63.8	4.3	49%	54.9

Table 5. Specimen list.

Section type	**No.**	f_{ck} (MPa)	**Mix type**	λ_p	λ_r	λ	***D(b)* x *t*** (mm)	A_c (mm^2)	A_s (mm^2)	***L*** (mm)
Square	SA-1	X		95.2	120.6	37.5	□-150×4	20150.3	2336	450
	SB-1	30	OPC 100%	56.9	75.6	37.5				
	SB-2									
	SB-3									
	SB-4									
	SC-1	40	SP:FA = 20:10							
	SC-2									
	SD-1	50								
	SD-2									
Circle	CA-1	X			72.7	51.8	○-139.8×2.7	14179.7	1162.3	
	CB-1	30	OPC 100%	99.2	125.6	51.8				
	CB-2									
	CB-3									
	CB-4									
	CC-1	40	SP:FA = 20:10							
	CC-2									
	CD-1	50								
	CD-2									

4.3. Experimental results

Fig. 3 shows a comparison graph of compressive strength in this formulation. Two types of concrete with a design strength of 30 MPa, 30.4 MPa, 27 MPa and 40 MPa concrete with a design strength of 40 MPa and 54.9 MPa concrete with a design strength of 50 MPa, respectively.

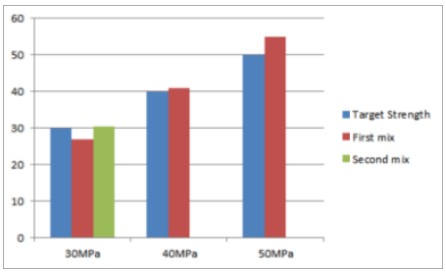


Fig. 3. Concrete mixture results.

5. Recycled aggregate concrete filled steel pipe CFT column experiment

5.1. Experimental result

18 specimens were produced. 4 mm steel plate (SPSR400 steel type) was used for rectangular steel pipe, and 2.7 mm steel plate of SPS260 steel type was used for round steel pipe (Fig 4). The rectangular steel pipe had a dimension of □ - 150 × 150 × 4, a circle of △ - 139.8 × 2.7, and a member length of 450 mm in both square and circular. Table 5 shows the summary of all the specimens. The experimental parameters were classified according to the type of steel pipe, the compressive strength of concrete, and the ratio of concrete powder. Fig. 5 is a photograph of curing after pouring concrete into a steel pipe.

Fig. 4. Steel pipe material

Fig. 5. RAC filling CFT.

5.2. Steel material experiment

According to KS B 0802:2003 [14], tensile test specimens of steel are to be numbered 5 for square steel pipes and 14B for round steel pipes according to KS B 0801:2007 [15] respectively. Table 6 shows the yield strength (f_y), tensile strength (f_u), yield ratio (f_y/f_u) and elongation (%) of the specimens.

Table 6. Results of coupon test.

Thickness (mm)	f_y (MPa)	f_u (MPa)	f_y/f_u (%)	Elongation (%)
4	260	359.61	72.3	30
2.7	310	471.92	65.8	21

5.3. CFT column compression experiment

The maximum load capacity of the specimen was checked and the yield behavior was investigated. All CFT columns were tested using 5,000 kN capacity UTM.

5.4. Experimental result

5.4.1 Structural performance test results

Table 7 Summarizes the maximum strength, displacement and initial stiffness of each specimen. The initial stiffness is defined as a quadrant connection the 45% point of maximum strength and the origin.

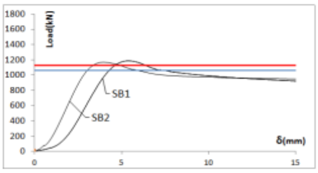
5.4.2 Load-displacement graph

The relationship between compressive load and column displacement is shown in Figs. The blue line is the expected strength at nominal strength (A in Table 6) and the red line is the expected strength (B in Table 6) using the material test values. It can be confirmed that most of the test specimens of round and square steel pipes have reached the maximum load exceeding the expected strength. Fig. 7 is a load-displacement graph of square and circular steel tubes for unfilled steel tubes.

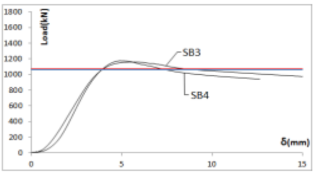
Table 7. Experimental result.

Specimen	**Maximum load** (kN) **[C]**	**Axial displacement** (mm)	**Initial stiffness** (kN/mm)
SA-1	699.1	2.9	276
SB-1	1187.3	5.4	191.5
SB-2	1169.5	3.9	302.3
SB-3	1161.2	5.7	241.9

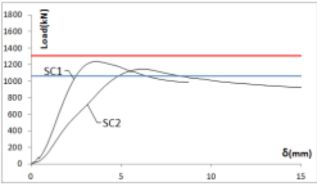
SB-4	1176.6	4.9	221.5
SC-1	1145	6.1	237.5
SC-2	1237.1	3.6	381.8
SD-1	1248.5	5.9	267.4
SD-2	1525.7	4.1	361.4
CA-1	436.4	5.6	180.2
CB-1	900.6	16.1	210
CB-2	865.6	15.6	186.4
CB-3	914	14.5	321
CB-4	788.1	12.7	257
CC-1	789.6	7.4	306.8
CC-2	906.5	12.9	259.8
CD-1	1127.9	6.3	307.6
CD-2	1078.1	5.1	303.6



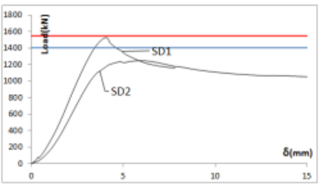
(a) SB-1, SB-2.



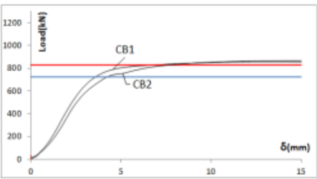
(b) SB-3, SB-4.



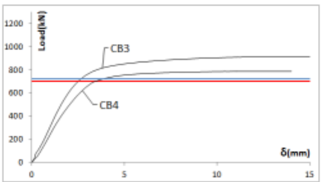
(c) SC-1, SC-2.



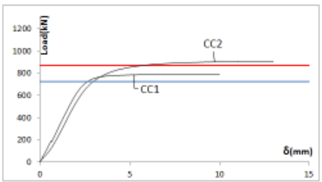
(d) SD-1, SD-2.



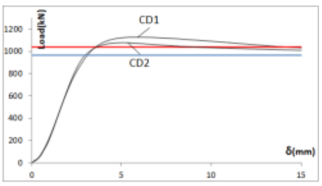
(e) CB-1, CB -2.



(f) CB-3, CB-4.



(g) CC-1, CC -2.



(h) CD-1, CD-2.

Fig. 6. CFT column load-displacement curve graph.

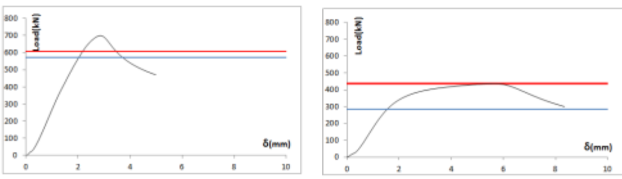


Fig. 7. Unfilled steel pipe load-displacement curve graph.

5.4.3 Failure mode of specimens

Fig. 8 shows the comparison of the fracture behavior of all specimens after the test. Most of them buckled after reaching the maximum compressive load. Experiments were carried out until the load reached 80% of the maximum load. It can be confirmed that buckling occurred at the upper part of all columns of the filled steel pipe columns. The test specimens with several buckling showed the tendency of the load to drop after reaching the maximum load.


(a) Square type.


(b) Circular type.

Fig. 8. Compressive failure mode of CFT column.

5.4.4 Comparison with existing design formula

The experimental results are compared with the current design formulas to confirm the suitability of the design formulas. Table 7 shows the comparison of the predicted loads calculated by applying the nominal strength with the experimental data and the expected load calculated by applying the nominal strength to the existing standard. The results were much similar to the predicted loads calculated by the design equation when compared with the experimental results.

6. Analysis and discussion

6.1. High strength concrete using recycled aggregate for filling steel pipe

In this experiment, the natural aggregate was replaced with 100% recycled aggregate. In order to reach the target strength, three preparations were made using a high performance water reducing agent. In this formulation, compressive strength was confirmed through specimens made of four types of blends Table 8 summarizes the results. In the case of 30 MPa, the experiment was carried out by dividing into two types. In the first type, an error of 1% was generated, resulting in an error of 30.4 MPa and in the second type, an error of about 10% occurred. 40 MPa had an error of 2%, which was 40.9 MPa, and 50 MPa had an error of 9%, indicating a strength of 54.9 MPa. Except for the second type of 30 MPa, it was confirmed that the remaining composition had a strength very close to the design strength.

Table 8. Strength properties of recycled aggregate concrete.

Specified concrete strength	**30 MPa**		**40 MPa**	**50 MPa**
28 days compressive Strength	30.4	27	40.9	54.9
Accuracy of Concrete	(101%)	(90%)	(102%)	(109%)

6.2. Strength development patterns by concrete components

As a result of checking the strength by date, we could confirm the characteristics of specimens according to the ratio of powder. The strength of the concrete was estimated using ACI 209R-92 [16] according to Eq. (3). Portland cement was usually used. For wet curing, *a* was 4.0 and *b* was 0.85.

$$\left(f_c'\right)_t = \frac{t}{a+b+c}\cdot\left(f_c'\right)_{28} \tag{3}$$

Table 9 shows the estimated strength of the recycled aggregate and the results of the compression test of the recycled aggregate concrete, calculated using Eq. (3). At 30 MPa, which is a mixture of powders using only ordinary Portland cement, it was confirmed that the estimated strength by the estimation formula of strength and strength at 7 and 28 days has an error of about 11%. However, in the case of mixing silica fume and fly ash at a ratio of 20:10, the intensities calculated by the strength and strength estimation equations at 7 and 28 days were 43% and 23%, respectively.

6.3. Comparison of compressive strength of RCFT column with existing design formula

Table 10 summarizes the table to compare the expected maximum yield strength due to the nominal strength of the specimen, the expected maximum yield strength after the material test, and the maximum load. In addition, the ratio of load-to-load is compared with each other. C / B shows that most of the specimens show compressive strength similar to expected strength.

Table 9. Strength properties of recycled aggregate concrete.

Concrete			**7 days**	**28 days**
30 MPa	estimated strength		21	30
	OPC 100%	Type1	18.99 (90.0%)	30.36 (101%)
		Type2	16.68 (79.4%)	26.99 (90%)
40 MPa	estimated strength		28	40
	SP:FA= 20:10	Type3	16.75 (59.8%)	40.90 (102%)
50 MPa	estimated strength		35	50
	SP:FA= 20:10	Type4	30.35 (86.7%)	54.86 (109%)

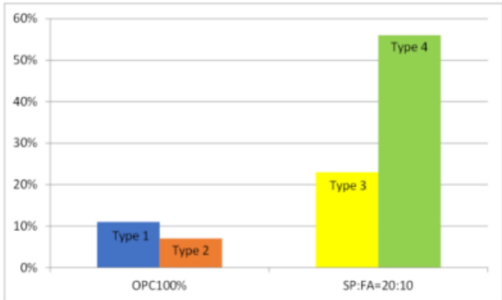


Fig. 9. Changes in the compressive strength accuracy of concrete mixtures at 7th and 28th days.

Table 10. Experiment results.

Specimen	**Expected maximum strength calculated by nominal strength** (kN) **[A]**	**Maximum expected strength after material test** (kN) **[B]**	**Ma-ximum load** (kN) **[C]**	**C/B**
SA-1	572.3	607.4	699.1	1.15
SB-1	1062.8	1127.4	1187.3	1.05
SB-2	1062.8	1127.4	1169.5	1.04
SB-3	1062.8	1069.6	1161.2	1.09
SB-4	1062.8	1069.6	1176.6	1.10
SC-1	1062.8	1307.9	1145	0.88
SC-2	1062.8	1307.9	1237.1	0.95

SD-1	1405.3	1547	1248.5	0.81
SD-2	1405.3	1547	1525.7	0.99
CA-1	284	348.7	436.4	1.25
CB-1	723.5	827.9	900.6	1.09
CB-2	723.5	827.9	865.6	1.05
CB-3	723.5	787.3	914	1.16
CB-4	723.5	787.3	788.1	1.00
CC-1	723.5	955	789.6	0.83
CC-2	723.5	955	906.5	0.95
CD-1	964.6	1123.2	1127.9	1.00
CD-2	964.6	1123.2	1078.1	0.96

6.4. Confinement effect of square/circular RCFT columns

It is known that when triaxial compression is applied to the concrete specimen, it increases more than uniaxial compressive strength and increases ductility after maximum strength. Therefore, the experimental results are summarized as Table 11 to analyze the restraint effect according to the cross-sectional shapes of square and circular steel pipes applied as variables. The nominal strength of the steel pipe and the internally recycled aggregate concrete of the specimen and the strength obtained from the material test were applied to Eq. (1), respectively. As a result of comparing the two values by a ratio and comparing the averages, the circular steel pipe showed a larger value of about 10%. It is considered that the circular steel pipe is more effective in restraining effect than square steel pipe. In addition, it was confirmed that there is no significant effect on the strength of the concrete filled in the steel pipe.

Table 11. Calculation and analysis of expected strength formula and empirical formula.

Specimen	Expected maximum strength calculated by nominal strength (kN) [A]	Maximum load (kN) [C]	C/A
SB-1	1062.8	1187.3	1.12
SB-2	1062.8	1169.5	1.10
SB-3	1062.8	1161.2	1.09
SB-4	1062.8	1176.6	1.11
SC-1	1062.8	1145	1.08
SC-2	1062.8	1237.1	1.16
SD-1	1405.3	1248.5	0.89
SD-2	1405.3	1525.7	1.09
	average		1.08
CB-1	723.5	900.6	1.24
CB-2	723.5	865.6	1.20
CB-3	723.5	914	1.26
CB-4	723.5	788.1	1.09
CC-1	723.5	789.6	1.09
CC-2	723.5	906.5	1.25
CD-1	964.6	1127.9	1.17
CD-2	964.6	1078.1	1.12
	average		1.18

7. Conclusion

In order to evaluate the performance of recycled aggregate concrete and the compressive strength of CFT steel pipe columns filled with concrete using recycled aggregate, four concrete mixes and 18 unconfined compression tests were carried out and the following conclusions were drawn:

1. RAC test results. It was confirmed that the recycled aggregate was able to develop strength up to 50 MPa without using natural aggregate.
2. In the case of concrete using recycled aggregate as well as concrete using ordinary aggregate, the difference in the difference between the estimated strength and the actual experimental compressive strength was 11% in the case of using silica fume and fly ash, 23% And 43%, respectively.
3. The evaluation of compressive capacity of the CFT columns shows that the compressive strength is similar to the predicted compressive strength calculated by the conventional compressive strength equation.
4. The predicted yield strength of the test specimens calculated from the nominal strength was compared with the experimental maximum load, and the constraint effect was analyzed. Because of checking the average value, the circular steel pipe showed about 10% larger value, confirming that it is more advantageous in confinement effect.

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