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Structural Performance of Recycled Aggregate Concrete Confined by Spiral Reinforcement

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Abstract

This paper estimates the structural behavior of recycled aggregate concrete confined by spiral reinforcement. The main test parameters are designed to be the type of aggregates, replacement ratio of recycled aggregates, steel ratio and yield strength of spirals. Specimens subjected to concentrated axial load can be divided into two groups, natural and recycled aggregate specimens, based on the type of coarse aggregate used. The recycled aggregates are designed to be used from 0% to 100% in the specimens. Spiral reinforcement is varied up to 1.75% and 1,430 MPa for the steel ratio and yield strength of spiral, respectively. Furthermore, cover concrete and longitudinal reinforcement are neglected to estimate the pure capacity of recycled aggregate concrete confined by spiral reinforcement only. Test results showed that the structural performance of recycled aggregate concrete specimens confined by steel spirals was similar to that of natural aggregate concrete specimens, regardless of the replacement ratio of recycled aggregates, the steel ratio and the yield strength of the spirals.

Keywords: recycled aggregate; confined concrete; spiral reinforcement; stress-strain relationship; ultra-high-strength reinforcement

1. Introduction

Architectural activities have become more widespread with human development, and the number of deteriorated buildings has increased in proportion. When such buildings are demolished, vast amounts of construction waste are produced, and the quantity of this waste continues to rise each year. The burial of waste concrete, which accounts for the largest portion of construction waste, has adverse effects on the environment. An adequate solution, therefore, should be devised to recycle waste concrete.

The recent shortage of natural aggregates has resulted in growing interest in alternative aggregates. Recycled aggregates can be obtained from the waste concrete through crushing and abrasion processes. Many studies have been conducted on the quality control and manufacturing process of recycled aggregates to achieve environmental-friendly and higher value-added recycled aggregates. However, due to a lack of social recognition concerning their safety, recycled aggregates have only been utilized as non-structural materials.

For recycled aggregates to be utilized as a structural material, the structural performance of concrete with recycled aggregates must be verified, but the existing studies on recycled aggregates have focused on material properties. Recently, a few studies (Fathifazl *et al*. 2012; Kim *et al*. 2013; Rahal and Al-Khaleefi 2015) have been carried out on the flexural, shear, and shear-friction behaviors of reinforced recycled aggregate concrete members. However, such studies on structural members are still scarce.

In general, to prevent the collapse of a whole building, building codes demand high safety for reinforced concrete columns, which are structural members subjected to high axial force. Columns without transverse reinforcement exhibit brittle failure after peak load, showing excessive lateral expansion and cracks. Since the brittle failure of reinforced concrete columns can be avoided through the use of transverse reinforcement, it is necessary to estimate the structural performance of recycled aggregate concrete confined by transverse reinforcement. This research performs an experimental and analytical study to provide a fundamental resource on the structural performance of recycled aggregate concrete confined by spiral reinforcement.

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Table 1. Physical Properties of Aggregates Used in this Study

Aggregates		Maximum size (mm)	Specific gravity (g/cm^3)	Absorption rate (%)	Fineness modulus
Coarse aggregate	Natural	25	2.61	0.68	6.60
	Recycled	25	2.53	2.55	6.58
Fine aggregate		5	0.64	2.39	2.94

Table 2. Concrete Mix Proportions

Concrete	Design strength (MPa)	W/C (%)	S/a (%)	Unit weight (kg/m^3)				
				W	C	S	G	AD
NA-series	25	61.9	50	177	257	891	898	2.00
R50-series		60.2			265	888	895	1.91
R75-series		60.2			265	888	895	1.91
R100-series		59.0			270	885	892	1.80

2. Experimental Program

2.1 Materials

Type 1 Portland cement was used to make ready-mixed concrete. This study used two types of coarse aggregates, natural and recycled, as described in Table 1. The recycled coarse aggregate used in this study obtained from waste concrete. The production process of recycled coarse aggregate is (1) the crushing of the waste concrete using jaw crusher, (2) the exclusion of impurities, (3) second crushing using cone crusher, impact crusher, and double log washer, and (4) the separation of crushed aggregates by size.

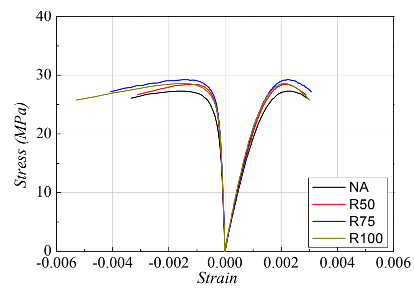
Natural crushed coarse aggregates used in this test had a nominal maximum size of 25 mm, a specific gravity of 2.61 g/cm^3, and an absorption rate of 2.55%. Natural fine aggregates were used in all of specimens and their physical properties are presented in Table 1. As can be seen in Table 2., four types of concrete were used in this study according to the replacement ratio of recycled aggregates. The concrete was designed to have a design strength of 25 MPa, a water-to-cement ratio of approximately 60%, and a sand percentage of 50%. The concrete used in this study showed similar slumps of 160~170 mm.

Compression tests for cylindrical plain concrete specimens with a diameter of 150 mm and a height of 300 mm were performed to estimate the properties of the concrete. The compressive strengths of the concrete were measured from 26.1 to 29.7 MPa. The compressive strength and axial strain at peak stress (peak axial strain) of each concrete are presented in Table 3. Fig.1.(a) shows the stress-strain relationships of the concrete used in this study.

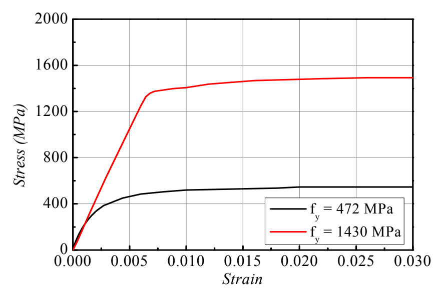
This study used normal- and ultra-high-strength round bars with a diameter of 4.5 mm. Based on the 0.2% off-set method, yield strengths of round bars were found to be 472 MPa and 1,430 MPa. All reinforcement showed the same elastic modulus of 2.0×10^5 MPa. The tensile stress-strain relationships of the steel reinforcement are presented in Fig.1.(b).

2.2 Specimen Details

A total of 12 unconfined specimens and 30 spirally confined specimens, with a diameter of 150 mm and a height of 300 mm, were designed to investigate the confined behavior of recycled aggregate concrete with spiral reinforcement. As seen in Table 3., the main test variables were the type of aggregate, the replacement ratio of recycled aggregate, the yield strength and the steel ratio of the spirals. The replacement ratios of recycled aggregates were designed to be 0% and 50% as well as 75% and 100%. In the names of the specimens, NA and R refer to natural and recycled aggregates, respectively. The normal- and ultra-high-strength steel bars had yield strengths of 472 MPa and 1,430 MPa, respectively. The steel ratios of the spirals were designed to be 1.75% and 1.0%, named S and M, respectively, as seen in Fig.2.

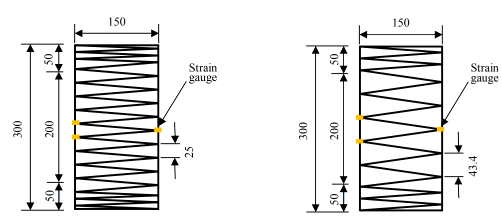


(a) Concrete



(b) Steel bars

Fig.1. Stress Versus Strain Relationships of Materials



(a) S-series (ρ_s = 1.75%) (b) M-series (ρ_s = 1.00%)

Fig.2. Details of Specimens (Unit: mm)

To obtain the reliability of the experimental results, the same three specimens were designed for each series. Cover concrete and longitudinal reinforcement were neglected to estimate the pure effect of spiral reinforcement. Fig.2. shows the positions of strain gauges attached to steel spirals with intervals 120 degrees at mid-height of the specimen.

2.3 Test Setup of Specimens

The test setup of the specimens is presented in Fig.3. Three linear variable differential transformers (LVDTs) for longitudinal direction were installed between upper and lower circular steel frames fixed at a distance of 50 mm from the top and bottom of the specimen, respectively. Furthermore, three transverse LVDTs were installed at the mid-height of each specimen to measure the transverse deformation of specimens. A universal machine with a capacity of 2,000 kN was used for loading specimens.

3. Experimental Results and Discussion

3.1 General Behavior

Table 3. provides the experimental results for the peak stress, axial and lateral strains at peak stress, and the yielding point of the spiral reinforcement. Figs.4. and 5. show the crack patterns and stress versus strain relations of tested specimens. As shown in Table 3., plain concrete specimens had similar average peak stresses, f'_{co}, of 26.9~29.4 MPa and average peak axial strains of 0.0021~0.0023. In this study, axial strain was measured using the longitudinal LVDTs. The lateral strain of unconfined specimens was obtained from the transverse LVDTs, and that of spirally confined specimens from strain gauges.

The unconfined concrete specimens showed brittle failure after peak stress. On the other hand, spirally confined specimens showed ductile behavior after peak load, exhibiting increasing peak axial strain and lateral strain at peak stress (peak lateral strain) as the yield strength and reinforcement ratio of the spirals increased. This tendency was similar to that of other spirally confined specimens regardless of the aggregate type and replacement ratio. As presented in Table 3., the spiral reinforcement of all specimens reached their yield strain before peak stress. This implies that the concrete can be fully confined by spiral reinforcement even if the ratio of recycled aggregates is increased to 100%.

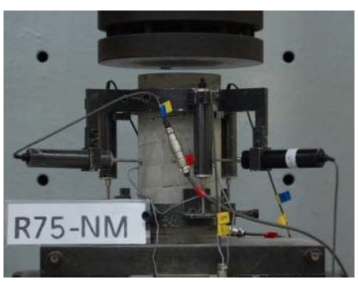
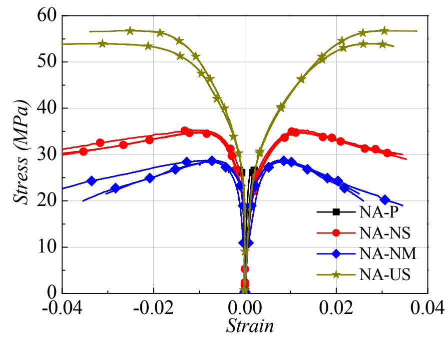


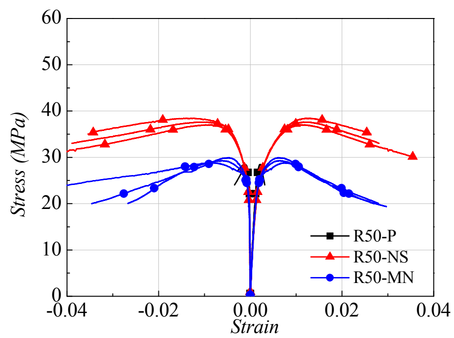
Fig.3. Test Setup of Specimen

(a) R100-NS (b) R100-NM (c) R100-US

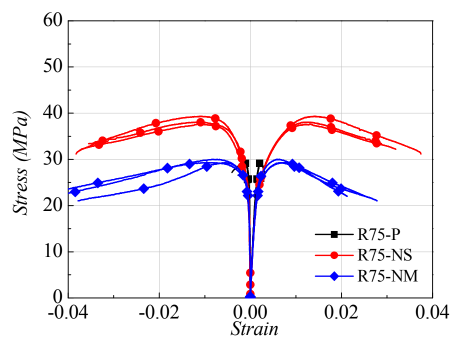
Fig.4. Crack Patterns of Typical Specimens After Failure



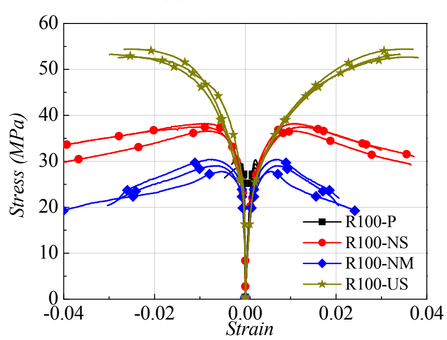
(a) NA-series



(b) R50-series



(c) R75-series



(d) R100-series

Fig.5. Experimental Results of Specimens

Table 3. Specimen Details and Experimental Results of Tested Specimens

Specimens		f'_{co} (MPa)	ε'_{co}	f_y (MPa)	ρ_s (%)	Experimental results			
						f'_{cc} (MPa)	Axial strain at peak load	Axial strain at yielding	Spiral yielding
NA-NS*	1	26.9	0.0021	472	1.75	35.3	0.0116	0.0061	pre-peak
	2	26.9	0.0021	472	1.75	34.8	0.0118	0.0060	pre-peak
	3	26.9	0.0021	472	1.75	34.7	0.0120	0.0069	pre-peak
NA-NM*	1	26.9	0.0021	472	1.01	28.4	0.0078	0.0041	pre-peak
	2	26.9	0.0021	472	1.01	28.7	0.0084	0.0047	pre-peak
	3	26.9	0.0021	472	1.01	28.7	0.0073	0.0057	pre-peak
NA-US	1	26.9	0.0021	1430	1.75	53.9	0.0271	-	-
	2	26.9	0.0021	1430	1.75	56.8	0.0303	0.0161	pre-peak
	3	26.9	0.0021	1430	1.75	54.0	0.0277	0.0171	pre-peak
R50-NS*	1	28.3	0.0022	472	1.75	37.0	0.0108	0.0052	pre-peak
	2	28.3	0.0022	472	1.75	37.6	0.0116	0.0057	pre-peak
	3	28.3	0.0022	472	1.75	38.5	0.0129	0.0053	pre-peak
R50-NM*	1	28.3	0.0022	472	1.01	29.3	0.0064	0.0044	pre-peak
	2	28.3	0.0022	472	1.01	29.9	0.0061	0.0049	pre-peak
	3	28.3	0.0022	472	1.01	28.8	0.0080	0.0054	pre-peak
R75-NS	1	28.4	0.0023	472	1.75	38.1	0.0127	0.0052	pre-peak
	2	28.4	0.0023	472	1.75	39.3	0.0141	0.0057	pre-peak
	3	28.4	0.0023	472	1.75	37.6	0.0132	0.0053	pre-peak
R75-NM	1	28.4	0.0023	472	1.01	29.3	0.0068	0.0044	pre-peak
	2	28.4	0.0023	472	1.01	30.0	0.0064	0.0049	pre-peak
	3	28.4	0.0023	472	1.01	29.3	0.0077	0.0054	pre-peak
R100-NS	1	29.4	0.0022	472	1.75	38.2	0.0103	0.0051	pre-peak
	2	29.4	0.0022	472	1.75	37.5	0.0121	0.0057	pre-peak
	3	29.4	0.0022	472	1.75	36.6	0.0107	0.0053	pre-peak
R100-NM	1	29.4	0.0022	472	1.01	30.4	0.0067	0.0043	pre-peak
	2	29.4	0.0022	472	1.01	29.0	0.0067	0.0053	pre-peak
	3	29.4	0.0022	472	1.01	27.8	0.0056	0.0045	pre-peak
R100-US	1	29.4	0.0022	1430	1.75	52.7	0.0358	0.0222	pre-peak
	2	29.4	0.0022	1430	1.75	53.3	0.0340	0.0174	pre-peak
	3	29.4	0.0022	1430	1.75	54.4	0.0356	0.0195	pre-peak

* Specimens previously tested by authors (Kim *et al.* 2011)

The specimens failed with spalling of the concrete between the spiral reinforcement. This spalling increased with higher yield strength of spiral reinforcement due to the increasing lateral expansion of concrete at failure. The concrete spalling after failure was remarkable as the steel ratio of spirals decreased because of the smaller effective areas of lateral confinement, as seen in Fig.4. Based on the experimental results, no differences were observed in crack patterns in relation to the replacement ratio of recycled aggregates. This demonstrates that recycled aggregates do not deteriorate the structural performance of spirally confined concrete. Further research, however, is needed on recycled aggregates with adsorption rates higher than 2.55%.

3.2 Strength and Ductility Enhancement

The strength and ductility enhancements of specimens are shown in Figs.6. and 7., respectively. In this study, the ductility enhancement ratio was defined as the enhancement ratio of the peak axial strain of specimens. The strength and peak axial strain of NA-NS specimens, with natural aggregates and a spiral reinforcement ratio of 1.75%, improved 1.3 times and 5.6 times compared to those of unconfined specimens. These results show that a superior lateral confinement effect is achieved by using spiral reinforcement. As shown in Figs.6. and 7., the R50-, R75-, and R100-NS specimens, having the same spiral reinforcement but different replacement ratios, improved 1.27~1.35 times and 5~5.8 times in strength and peak axial strain, respectively. For the NS-series specimens, there was no deterioration in strength with increasing replacement ratio of recycled aggregates, as seen in Fig.6.

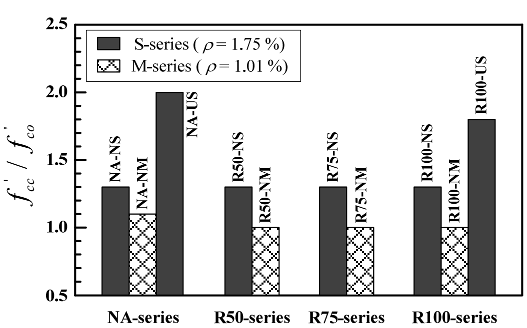


Fig.6. Strength Enhancement of Specimens

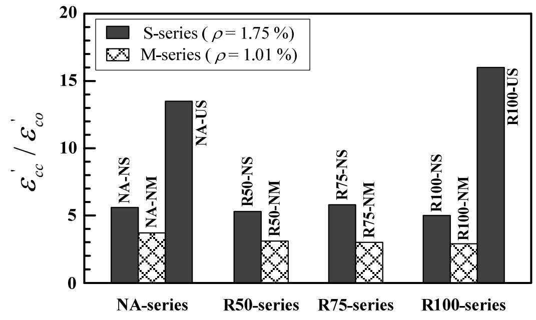


Fig.7. Axial Strain Enhancement of Specimens

In the case of the NM-series specimens, with a yield strength of 472 MPa and a steel ratio of 1.0%, NA-NM specimens with natural aggregates had only a 6% improvement in peak stress compared to unconfined concrete due to their low lateral reinforcement ratio. In terms of ductility, however, the peak axial strain increased by 3.7 times compared to that of unconfined specimens. This tendency was also observed in the specimens with recycled aggregates.

When high-strength spiral reinforcement was used, the peak stress and ductility of NA-US specimens with natural aggregates improved 2.04 times and 13.5 times, respectively, compared to the unconfined specimens. As shown in Figs.6. and 7., the strength and ductility of the NA-US specimens are 1.57 and 2.4 times better, respectively, than those of the NA-NS specimens. In other words, improvements in strength and ductility of spirally confined specimens can be achieved by having higher yield strength of spiral reinforcement. Since the lateral confinement performance of spiral reinforcement decreases with increasing the compressive strength of concrete (Martinez *et al.* 1984; Sheikh *et al.* 1994), further research should be conducted on the lateral confinement performance of the recycled aggregate concrete with varying levels of the compressive strength of concrete.

The strength of R100-US specimens with ultra-high-strength spirals and 100% replacement ratio of recycled aggregates was 1.82 times better than that of unconfined specimens, and 1.43 times better than that of R100-NS specimens with normal-strength spiral reinforcement. This was somewhat lower than NA-US specimens having natural aggregates, but the structural performance is comparable considering the 10% higher concrete compressive strength of R100-US. In particular, as shown in Fig.7., the ductility of R100-US specimens was 16 times and 3.2 times higher than those of unconfined specimens and R100-NS specimens with normal-strength spiral reinforcement, respectively. These results were superior to those for NA-US specimens.

3.3 Lateral Expansion Behavior

Fig.8. shows the relationship between axial strain and lateral expansion ratio of tested specimens. In this study, the lateral expansion ratio refers to the ratio of the lateral-to-axial strains of specimens. The lateral strain of unconfined specimens was obtained from transverse LVDTs, while those of the remaining specimens were obtained from strain gauges attached to the spiral reinforcement. As shown in Fig.8.(a), the lateral expansion ratio of unconfined specimens begins at approximately 0.15 and exceeds approximately 0.5 at peak stress. After peak load, the specimens exhibited brittle failure with rapid lateral expansion. It can be seen in Fig.8.(a) that lateral expansion behavior is hardly influenced by the aggregate type and the replacement ratio of recycled aggregates.

Fig.8. shows that spirally confined specimens have less lateral expansion compared to unconfined P-series specimens. Spirally confined specimens exhibited an increase in lateral expansion after yielding of spirals, and the decrease in lateral expansion became more pronounced with increasing steel ratio and yield strength of spiral reinforcement. In particular, the lateral expansion ratio significantly decreased when the yield strength of spiral reinforcement rose from normal- to ultra-high-strength. These experimental results indicate that the lateral expansion characteristics of specimens are unaffected by the use of recycled aggregates, and that the lateral expansion ratio decreases with the increasing lateral confinement performance of spiral reinforcement.

4. Prediction of Stress Versus Axial Strain Relationship

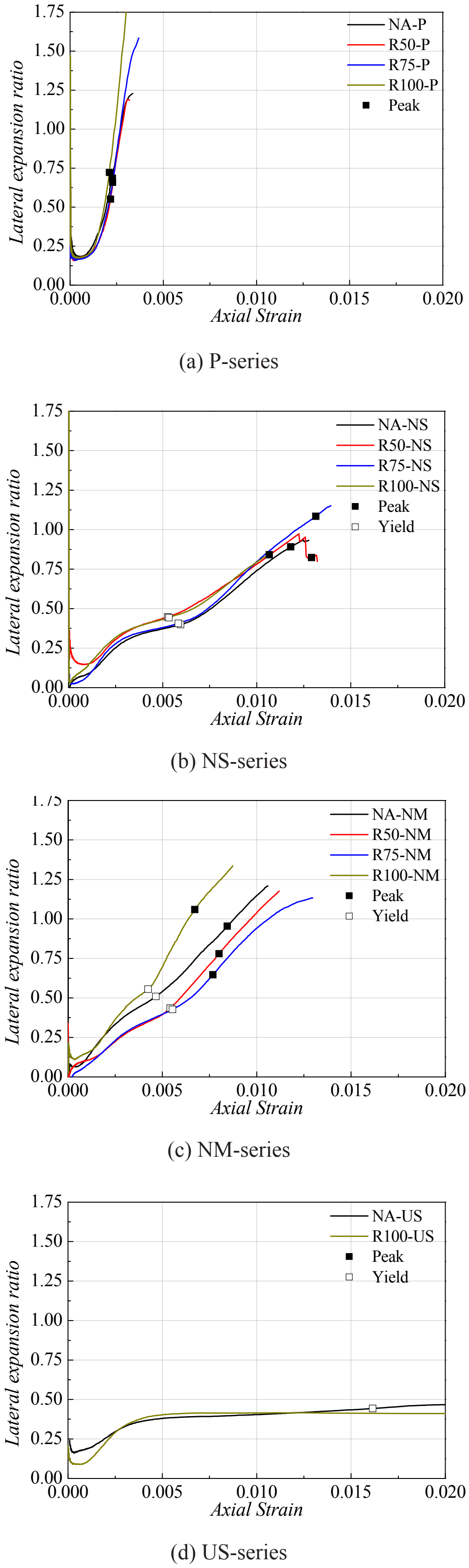
4.1 Analytical Model

In this study, experimental results for confined concrete specimens with up to 100% replacement ratio of recycled aggregates are predicted using the analytical model proposed by Kim *et al.* (2016), which predicts the stress versus axial strain relationship of confined concrete with spiral reinforcement using the relationship between axial and lateral strains at peak load. This model is able to consider the confinement effect of high-strength materials for strength and ductility enhancement of spirally confined concrete. Analytical results obtained from the model proposed by Kim *et al.* were shown to be in good agreement with test results (Assa *et al.* 2001; Desayi *et al.* 1978; JICE 1990; Kim 2010; Muguruma *et al.* 1978) with the concrete compressive strengths of 18.9~120 MPa, spiral yield strengths of 164~1,430 MPa, and spiral ratios of 0.29~2.33%.

The model proposed by Kim *et al.* (2016) uses the following equation proposed by Popovics (1973) for the stress-axial strain relationship of spirally confined concrete.

$$\frac{f_c}{f_{cc}^{'}} = \frac{n(\varepsilon_c / \varepsilon_{cc}^{'})}{n-1+(\varepsilon_c / \varepsilon_{cc}^{'})^n} \quad (1)$$

where f_c and $f^{'}_{cc}$ are the stress and peak stress of confined concrete, respectively, ε_c and $\varepsilon^{'}_{cc}$ are the axial strain and peak axial strain of confined concrete,



(a) P-series

(b) NS-series

(c) NM-series

(d) US-series

Fig.8. Lateral Expansion Characteristics of Tested Specimens

respectively, and n is a coefficient affecting ascent and decent curves and is defined as follows:

$$n = E_c / (E_c - E'_{cc}) \tag{2}$$

$$E'_{cc} = f'_{cc} / \varepsilon'_{cc} \tag{3}$$

where E_c is the elastic modulus of concrete, taken as the following equation proposed by Carrasquillo *et al.* (1981).

$$E_c = 3320\sqrt{f'_{co}(MPa)} + 6900 \tag{4}$$

Kim *et al.* proposed the following relationship between the axial and lateral strains at peak load to estimate the peak stress and strain state of spiral reinforcement.

$$\frac{\varepsilon'_l}{\varepsilon'_{cc}} = 0.75 - 0.0035 f'_{co} \le 0.6 \tag{5}$$

where ε'_{cc} and ε'_l are the axial and lateral strains at peak stress, respectively, and f'_{co} is the compressive strength of plain concrete. Once the peak axial strain ε'_{cc} is determined, the peak lateral strain ε'_l can be calculated using Eq. (5). As the peak lateral strain represents the spiral stress and the lateral confinement pressure at peak stress, f'_{sp} and f'_l, the peak stress of confined concrete can be obtained.

Kim *et al.* modified the formulas proposed by El-Dash and Ahmad (1995) to calculate the peak axial strain and peak stress of spirally confined concrete as follows:

$$\varepsilon'_{cc} = \varepsilon'_{co} + \varepsilon'_{ce} \tag{6}$$

$$\varepsilon'_{ce} = \left(\frac{6.0}{(s/d_s)^{0.11}(f'_{co})^{1.15}}\right)\left(\frac{f'_l}{f'_{co}}\right) \tag{7}$$

$$f'_l = \frac{1}{2}\rho_s f'_{sp}\left(1 - \sqrt{\frac{s}{1.25D_s}}\right) \tag{8}$$

$$f'_{cc} = f'_{co} + f'_{ce} \tag{9}$$

$$f'_{ce} = \left[5.1\left(\frac{f'_{co}}{f'_{sp}}\right)^{0.5}\left(\frac{d_s}{\rho_s}\right)^{0.25}\right] f'_l \tag{10}$$

where ε'_{co} is the peak axial strain of plain concrete, taken as $0.001648+0.000016f'_{co}$, ε'_{ce} and f'_{ce} are the enhanced axial strain and stress at peak, s is the vertical spacing of spiral reinforcement, d_s is the diameter of a spiral, ρ_s is the steel ratio of spirals, f'_{sp} is the stress of spiral reinforcement at peak load, and D_s is the diameter of spiral between bar centers.

Table 4. Comparison between Experimental and Analytical Results

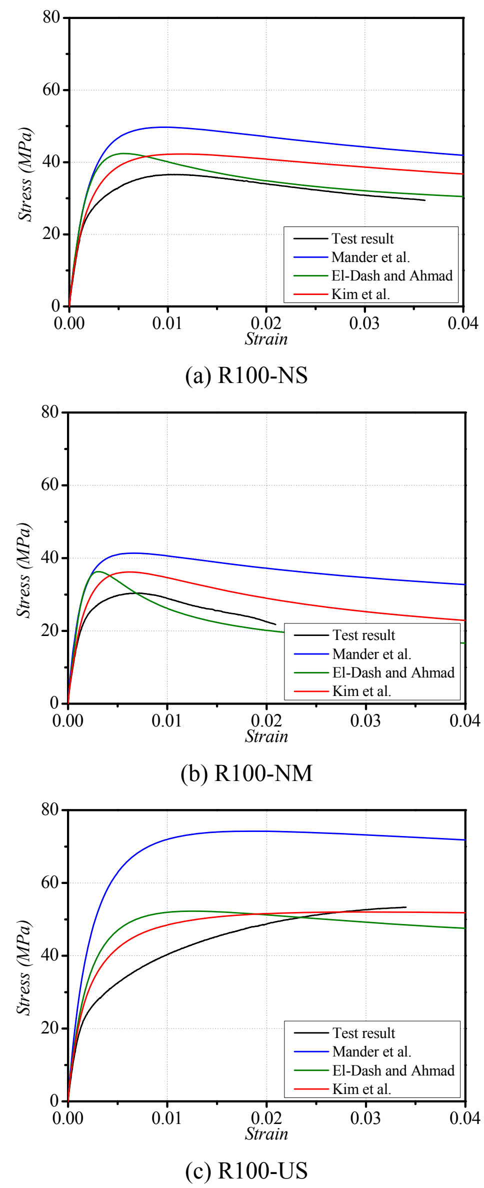
Specimens	Experimental results (average)			Experimental/Analytical					
				Mander *et al.* (1988)		El-Dash and Ahmad (1995)		Kim *et al.* (2016)	
	f'_{co} (MPa)	f'_{cc} (MPa)	ε'_{cc}	$\frac{f'_{cc,exp.}}{f'_{cc,ana.}}$	$\frac{\varepsilon'_{cc,exp.}}{\varepsilon'_{cc,ana.}}$	$\frac{f'_{cc,exp.}}{f'_{cc,ana.}}$	$\frac{\varepsilon'_{cc,exp.}}{\varepsilon'_{cc,ana.}}$	$\frac{f'_{cc,exp.}}{f'_{cc,ana.}}$	$\frac{\varepsilon'_{cc,exp.}}{\varepsilon'_{cc,ana.}}$
NA-NS	26.9	34.9	0.0118	0.74	1.19	0.89	1.83	0.89	0.90
NA-NM		28.6	0.0078	0.74	1.15	0.85	2.40	0.85	1.13
NA-US		54.9	0.0284	0.78	1.49	1.12	1.85	1.13	0.80
R50-NS	28.3	37.7	0.0118	0.78	1.21	0.92	1.99	0.92	0.98
R50-NM		29.4	0.0070	0.73	1.03	0.83	2.18	0.84	1.05
R75-NS	28.4	38.3	0.0133	0.79	1.37	0.93	2.26	0.93	1.11
R75-NM		29.5	0.0070	0.73	1.05	0.84	2.22	0.84	1.08
R100-NS	29.4	37.4	0.0110	0.75	1.15	0.88	1.98	0.89	0.98
R100-NM		29.1	0.0063	0.70	0.96	0.80	2.07	0.80	1.03
R100-US		53.5	0.0351	0.72	1.90	1.02	2.78	1.03	1.17
			Mean	0.75	1.25	0.91	2.16	0.91	1.02
			COV	3.6%	21.0%	10.2%	12.6%	10.3%	10.5%

4.2 Comparison of Experimental and Analytical Results

Table 4. and Fig.9. provide a comparison of experimental and analytical results. In this study, existing models proposed by Mander *et al.* (1988) and El-dash and Ahmad (1995) are used in this study to verify the accuracy of the model by Kim *et al.* (2016). As seen in Table 4., the model proposed by Mander *et al.* overestimates the test results for peak stress with a mean experimental-to-analytical ratio of 0.75, whereas it underestimates the peak axial stress with an average of 1.25. The prediction results obtained using the model by Mander *et al.* for the peak stress had no significant effect on spiral properties, but the peak axial strain greatly deteriorated as the yield strength of the steel spirals increased.

In the case of peak stress, Kim *et al.* modified the original equations proposed by El-Dash and Ahmad to consider the decrease of strength enhancement with lower peak stress of spiral reinforcement. In this test, all specimens with spiral reinforcement yielded before peak load, because normal-strength concrete was used. As seen in Table 4., therefore, models proposed by Kim *et al.* and El-Dash and Ahmad equally predict the real peak stress with a mean of 0.91 and a coefficient of variation (COV) of 10.3%. In addition, the prediction results show that neither model is affected by changing the spiral properties.

In the case of peak axial strain, the model proposed by El-Dash and Ahmad greatly underestimated the experimental results by an average of 2.16 times. On the other hand, the model by Kim *et al.* provided good accuracy for the real peak axial strain with an average of 1.02 and a COV of 10.5%. Furthermore, as seen in Fig.9. for R100 series specimens, the model by Kim *et al.* can successfully trace the stress versus axial strain of natural and recycled aggregate concrete specimens with spiral reinforcement. Comparison between



(a) R100-NS

(b) R100-NM

(c) R100-US

Fig.9. Comparison of Analytical and Experimental Results

analytical and experimental results showed that the model proposed by Kim *et al.* can be reasonably used for the prediction of the behavior of spirally confined concrete, regardless of the replacement ratio of recycled aggregates.

5. Conclusions

This study evaluated the behavior of spirally confined recycled aggregate concrete with test variables of the replacement ratio of recycled aggregate, yield strength and steel ratio of spiral reinforcement. Based on this study, the following conclusions are drawn:

(1) The lateral confinement performance of spirally confined concrete with recycled aggregates improved as the yield strength and steel ratio of the spiral reinforcement increased. This tendency was observed regardless of the aggregate type and replacement ratio of recycled aggregates. Furthermore, the use of 100% recycled aggregates with absorption rate of 2.55% did not cause any deterioration of the strength and ductility of the spirally confined specimens.

(2) These experimental results for normal-strength concrete demonstrated that all specimens, regardless of aggregate type, showed the yielding of spirals before peak stress and had similar lateral expansion characteristics. This implies that steel spirals exhibit their full performance before peak stress, and that lateral confinement performance is unaffected by the use of recycled aggregates.

(3) Spirally confined specimens showed greater spalling of concrete with an increase in the yield strength of spiral reinforcement due to the increase in lateral expansion at failure. The spalling of concrete also increased with decreasing spiral reinforcement ratio because of the smaller effective areas of lateral confinement. The crack patterns of specimens with recycled aggregates were similar to those of specimens with natural aggregates, regardless of aggregate type and the replacement ratio of recycled aggregates.

(4) From a comparison of experimental and analytical results, it is shown that the analytical model proposed by Kim *et al.* has sufficient accuracy in predicting the behavior of spirally confined concrete with recycled aggregates.

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