STUDY OF FEASIBILITY AND MECHANICAL PROPERTIES FOR PRODUCING HIGH-FLOWING CONCRETE WITH RECYCLED COARSE AGGREGATES

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Abstract

This study uses crushed waste concrete with compressive strength ranged from 210 to 350 kgf/cm^2, as recycled aggregates to produce high-flowing concrete. Proper amount of fly ash (25%, 30%) and superplasticizer is added. The water-to-cementitious material ratio (w/cm) was 0.50, 0.55, and 0.60. The engineering properties including compressive strength, splitting tensile strength and bond strength were tested. Meanwhile, the results were compared with those from specimens made of natural-aggregate with same mix proportions.

The physical properties of recycled aggregates obtained from crushed waste concrete of this experiment meet CNS1240 (equivalent to ASTM C33) specifications and requirements. The engineering properties of concretes made from natural and recycled aggregates showed only slight differences. The utilization of recycled aggregates for high flowing concrete is confirmed and is an environment friendly material.

1. Introduction

1.1. Definition of high flowing concrete

High-flowing concrete is defined as concrete with high workability and enough cohesiveness without causing segregation and bleeding. For local needs the strength are set between 280 and 350 kgf/cm^2, cement efficiency ≥1.1 kgf/cm^2 per kg, amount of cement less than 300 kg/m^3, initial slump 220±20 mm, slump flow 500±100 mm, 45-minute slump larger than 200 mm, slump flow above 400 mm, w/c = 0.42, and pozzolan material = 30% [1].

1.2. Basic property of recycled aggregate (RA)

1) Aggregate shape and surface structure

RAs obtained from crushed waste concrete have more angles. The surface is highly porous and rough. Its length-to-width ratio is between that of gravel stones and crushed stones, and its shape is similar to that of gravel stone which meets the shape of aggregates [2].

2) Density and absorption rate of aggregates

According to the research of Hansen and Narud [3], if the weight of per unit of waste concrete ranges from 2380 to 2410 kg/m^3 (the specific weight of natural aggregate is from 2.50 to 2.61), SSD specific weight of recycled aggregate ranges from 2.34 to 2.49 (its aggregate diameter is from 16 to 32 mm) and is not affected by the source of waste concrete.

The absorption rate (AR) of recycled aggregate is higher than that of natural one. The research of Hansen and Narud [3] points out that the AR of recycled aggregate is 8.7% for diameter from 4 to 8 mm, 3.7% for diameter from 16 to 32 mm. The AR of natural aggregate is only from 0.8% to 3.7%. It is obvious that the AR of recycled aggregate is higher. It is generally suggested to wet the RA before it is used.

1.3. Property of high flowing concrete made with RA (CRA)

1) Amount of water and workability

When the aggregate is under the condition of saturated surface dry (SSD), the consistency of CRA is very similar to that of high flowing concrete made with natural aggregates (CNA), but its rate of slump and slump flow loss is higher. According to Mukai [4], to produce CRA (recycled aggregate plus natural sand) and CNA of same slump, the amount of water is increased by 10 kg/m^3 or 5% for CRA as compared to same mix proportion of CNA.

2) Water to cementitious materials ratio (w/c) and amount of cement

From literature, it is found that the relationship between compressive strength and w/c of concrete is approximately linear for both CRA and CNA. However, the strength of CRA is not as high as that of CNA. At same w/c, to produce CRA with the same workability as CNA, the amount of water is increased by 5%. The cement must be increased by 5% to keep w/c constant [2, 3].

3) Mix proportioning design

Mix proportioning design of CRA is generally similar to that of normal one, and ACI mix proportioning design method is suitable.

4) Compressive strength and strength development

According to literature [2], it is found that the strength of CRA is lower than that of CNA by 10%. If the w/c of old concrete is less than w/c of newly made CRA, the strength of the new CRA will be able to match or even exceed the strength of CNA with the same mix proportion.

5) According to Tsong, Yen [5], the variability of bond strength of CRA is higher and the strength is less than that of CNA at the same mix proportion.

2. Experimental Design

2.1. Testing materials

1) Water

This experiment chooses tap water as mixing water of concrete.

2) Cement

Type I portland cement, with fineness 3400 cm^2/g and specific weight 3.15.

3) Fly ash

The fly ash for this experiment was from Linko Plant of Taiwan Power Company and with fineness 3050 cm^2/g, specific weight with 2.3 and ignition loss 4.2%.

4) Recycled aggregate

The recycled aggregates are from concrete with compressive strength from 210 to 350 kgf/cm^2. The waste concrete was crushed by the crushers of a modern aggregate processing plant. The maximum diameter of recycled aggregate is 19 mm. The specific weight, AR, and FM are listed in Table 1, and the results of sieve analysis are shown in Fig. 1, which meet the specification of CNS 1240. Meanwhile, before mixing, the fines smaller than 75-μm sieve in recycled aggregates should be washed out to less than 1% per CNS 1240. The waste concrete of this experiment does not include other materials of constructions like paints, glasses, plastics, and bricks.

5) Natural aggregate

The maximum diameter of natural aggregate of this experiment is 19 mm. Its property analysis is in Table 1, and sieve analysis is illustrated as Fig. 1, which meet the specification of CNS 1240.

6) Fine aggregate

The fine aggregate of this experiment is natural river sand; its property analysis is shown in Table 1. The sieve analysis is illustrated as Fig. 1, which meets the specification of CNS 1240.

7) Reinforcing bar

SD42 reinforcing bar with yielding stress of 5438 kgf/cm^2 is used. The elongation is 17.5% (>12%), which meets the specification of CNS 560 (equivalent to ASTM A615).

8) Superplasticizer

Superplasticizer (SP) of G Type with sulphonated naphthalene formaldehyde condensates (SNF) as main constituents is used. The superplasticizer has a solid content 41.40% and specific weight 1.21, which meets the specification of ASTM C494.

Table 1: Physical properties of coarse and fine aggregates

Type / Property	Recycled coarse aggregate	Natural coarse aggregate	Natural fine aggregate
SSD specific weight	2.41	2.63	2.66
OD specific weight	2.29	2.61	2.63
AR (%)	5.26	0.80	1.09
FM	6.38	6.56	2.91

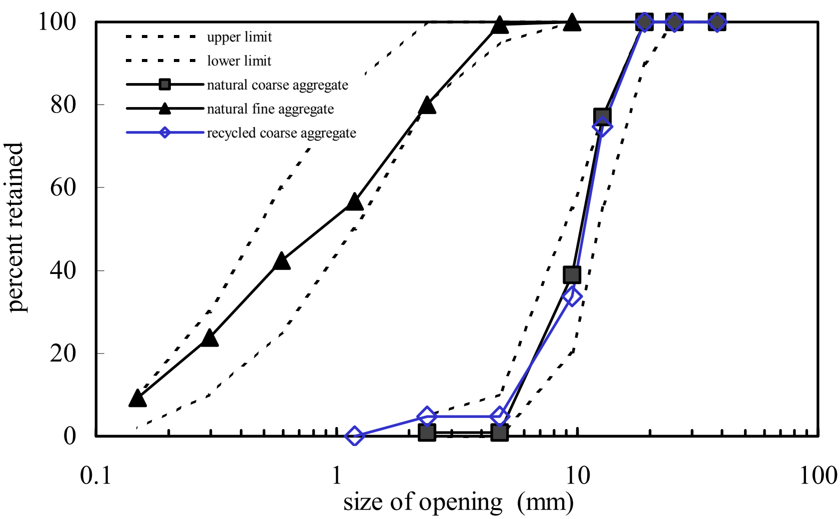

Fig. 1: Grading curve for aggregates

2.2. Mix proportioning design

This research is mainly to explore the differences between recycled-aggregate made high flowing concrete and natural-aggregate made high flowing concrete. The mix proportioning design uses ACI absolute volume method. The variables include water to cementitious ratio (w/c=0.50, 0.55, 0.60), superplasticizer (SP = 1.3%, 1.4%, 1.5%), fly ash (25%, 30%), and the value of S/A (0.40, 0.45, 0.50, 0.55), as shown in Table 2.

2.3. Tests

1) Workability

Slump and slump flow of all mix proportions were tested; the slump test is based on CNS1176 (equivalent to ASTM C143) [6] and slump flow test is based on JASS 5 T-503.

2) Curing and testing
   Specimens were made and cured according to relevant standards until the age of 28 days. Compressive strength and splitting tensile strength were then tested to find the best mix proportion for middle-and-low-strength concrete.
3) Test of bond strength
   According to CNS 11152 (equivalent to ASTM C234), each mix proportion respectively produces three cubes with sizes of 15×15×15 cm and 15×15×30 cm. Reinforcing bars were placed concrete were cast as shown in Fig. 2. When the specimens are between 7 and 14 days of age the 15×15×30-cm prisms were broken into half in flexure to form two 15×15×15 cubes.

Table 2: Mix proportion of concrete

No.	Mix proportioning no.	w/c	S/A (%)	Amount of water (kg)	SP (kg)	Cement (kg)	Fly ash (kg)	Coarse aggregate (kg)		Fine aggregate (kg)
								Natural	Recycled	
1	R50F25SP14	0.5	50	184.7	5.32	285	95	0	804	887
2	N50F25SP14			184.7	5.32	285	95	877	0	887
3	R50F30SP15			184.3	5.70	266	114	0	801	884
4	N50F30SP15			184.3	5.70	266	114	874	0	884
5	R55F25SP13	0.55	50	204.0	4.94	285	95	0	781	862
6	N55F25SP13			204.0	4.94	285	95	852	0	862
7	R55F30SP13			204.0	4.94	266	114	0	778	858
8	N55F30SP13			204.0	4.94	266	114	849	0	858
9	R55F30SP13(S40)		40	204.0	4.94	266	114	0	934	687
10	R55F30SP13(S45)		45	204.0	4.94	266	114	0	856	773
11	R55F30SP13(S55)		55	204.0	4.94	266	114	0	700	945
12	R60F25SP13	0.60	50	205.5	4.55	262.5	87.5	0	793	875
13	N60F25SP13			205.5	4.55	262.5	87.5	865	0	875
14	R60F30SP13			205.5	4.55	245	105	0	790	872
15	N60F30SP13			205.5	4.55	245	105	862	0	872
16	R60F30SP13(S40)		40	205.5	4.55	245	105	0	948	697
17	R60F30SP13(S45)		45	205.5	4.55	245	105	0	869	784
18	R60F30SP13(S55)		55	205.5	4.55	245	105	0	711	959

Note: R = recycled aggregate concrete; N= normal concrete; F = fly ash; SP = superplasticizer; S = S/A.

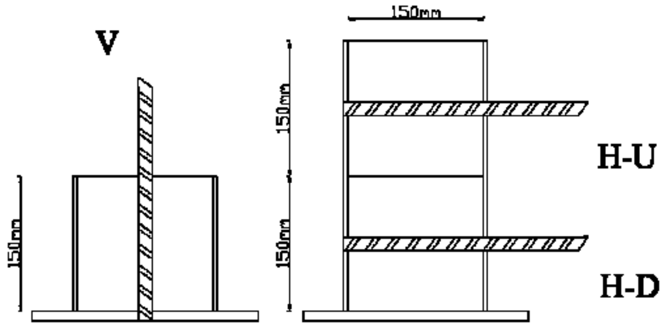

Fig. 2: Reinforcing bar position of bond strength test

3. Testing Result and Discussion

3.1. Coarse aggregate of waste concrete

The surface of the recycled aggregates is highly porous and rough, and is covered with cement mortar, whose volume makes up 34.94% of the recycled aggregates, which corresponds to other research results [3]. The SSD specific weight of recycled coarse aggregate is less than that of natural by 8.4%; its AR is much higher than natural one (as Table 1).

3.2. Workability of fresh concrete

The tested results of slump and slump flow of each fresh concrete is listed in Table 3.

1) Recycled-aggregate or natural-aggregate high flowing concrete generally meets high flowing concrete requirements at the same mix proportion, the slump loss at 45 minute of CRA is about 2.04% to 8.7% higher than that of CNA. The loss of 45-minute slump flow of CRA is about 0.7% to 10.0% higher than that of CNA. It is inferred that this phenomenon results from the re-hydration of old mortar on the surface of recycled aggregates, which consumes water and is also because of high AR of RA.
2) For both recycled-aggregate high flowing concrete or natural-aggregate one, the concrete with 25% replacement rate of fly ash showed a higher loss of slump and slump flow than that with 30% replacement rate.
3) For specimens with w/c of 0.55 or 0.60 and the S/A of 40% and 45%, the initial slump is lower and the concrete segregates. It is because that the fine aggregates are not sufficient and coarse aggregate contents are too high. The loss of slump and slump flow with 50% S/A is lower than that with 55% S/A. The loss of slump and slump flow is also lower for w/c = 0.55 specimens than that of w/c = 0.60.

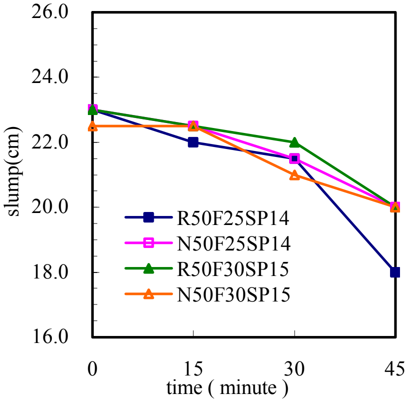

Fig. 3: Development of slump (w/c=0.50)

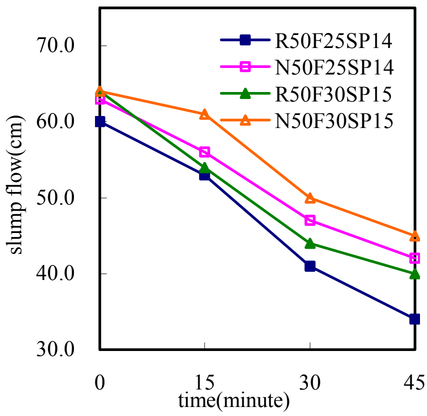

Fig. 4: Development of slump flow (w/c=0.50)

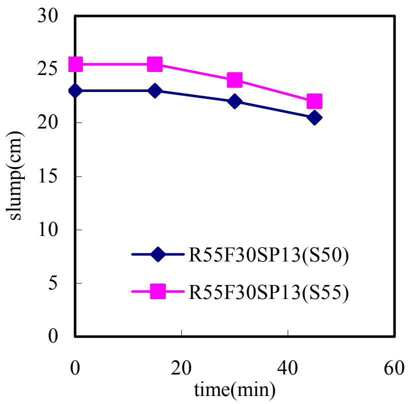

Fig. 5: Development of slump loss of recycled concrete with w/c=0.55, s/a=50%, 55%

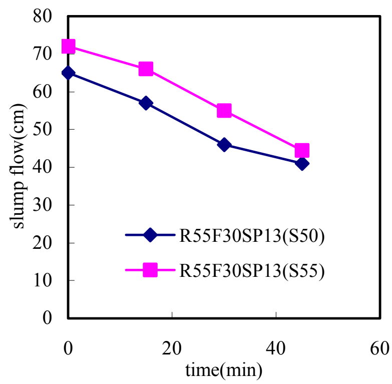

Fig. 6: Development of slump flow loss of recycled concrete with w/c=0.55, s/a=50%, 55%

Table 3: Comparison of slump and slump flow

No.	Mix proportioning no.	Slump (cm)					Slump flow (cm)				
		0 min.	15 min.	30 min.	45 min.	45-min loss rate	0 min.	15 min.	30 min.	45 min.	45-min loss rate
1	R50F25SP14	23.0	22.0	21.5	18.0	21.74 %	60.0	53.0	41.0	34.0	43.33 %
2	N50F25SP14	23.0	22.5	21.5	20.0	13.04 %	63.0	56.0	47.0	42.0	33.33 %
3	R50F30SP15	23.0	22.5	22.0	20.0	13.04 %	64.0	54.0	44.0	40.0	37.50 %
4	N50F30SP15	22.5	22.5	21.0	20.0	11.11 %	64.0	61.0	50.0	45.0	29.69 %
5	R55F25SP13	23.5	22.5	22.0	21.0	10.64 %	69.0	59.0	50.0	42.0	39.13 %
6	N55F25SP13	22.0	22.0	20.5	20.5	06.82 %	69.0	63.0	54.0	44.0	36.23 %
7	R55F30SP13	23.0	23.0	22.0	20.5	10.87 %	65.0	57.0	46.0	41.0	36.92 %
8	N55F30SP13	21.5	21.5	21.5	20.5	4.65 %	63.5	57.0	47.5	40.5	36.22 %
9	R55F30SP13(S40)	16.0	Segregation								
10	R55F30SP13(S45)	17.5	Segregation								
11	R55F30SP13(S55)	25.5	25.5	24.0	22.0	15.56%	72.0	66.0	55.0	44.5	38.19%
12	R60F25SP13	26.0	24.0	22.5	20.5	21.15 %	70.0	59.0	52.0	41.5	40.71 %
13	N60F25SP13	24.5	23.0	20.5	20.0	18.37 %	71.5	60.5	52.0	44.0	38.46 %
14	R60F30SP13	24.5	24.0	22.5	21.5	12.24 %	69.0	64.5	52.0	42.5	38.41 %
15	N60F30SP13	24.5	24.0	23.5	22.0	10.20 %	70.0	63.0	57.0	49.0	30.00 %
16	R60F30SP13(S40)	23.5	Segregation								
17	R60F30SP13(S45)	19.5	Segregation								
18	R60F30SP13(S55)	24.5	24.0	20.5	19.0	22.45%	62.0	55.5	43.0	37.5	39.52%

3.3. Compressive strength

Compressive strength of this study is shown in Table 4. The following results can be obtained.

1) For both CRA and CNA, it is helpful for workability of concrete when the amount of replacement of fly ash is high (as 30% in this research). But it has a negative influence on the strength of concrete. This is similar to other research results [7].
2) Compressive strength of recycled-aggregate high flowing concrete with 25% of the amount of replacement of fly ash is generally higher than that of CNA, which is illustrated as Figs. 7–9. However, its late strength develops slowly, and even slower than that of natural-aggregate high flowing concrete (as R50F25, R55F25). Besides, this phenomenon is more obvious when w/c is lower. It is inferred that this phenomenon results from the re-hydration of cement in the mortar that covered the recycled aggregates.

   In addition, recycled aggregate is rougher, which gives a better aggregate-mortar bond strength. However, the specific weight of the recycled aggregate covered by mortar is less, and is more porous and weaker as compared with natural aggregate. Therefore, the strength at late age of CRA is less than that of CNA. That is the reason why that some compressive strength of CRA is less than that of CNA and is more pronounced when w/c is lower.

3) Compressive strength of CRA with 30% of replacement rate of fly ash is generally lower than that of CNA at the same mix proportion with increased w/c. This agrees well with previous research results, i.e., the higher the replacement rate of FA, the less the strength gained.
4) The effect of S/A is shown in Fig.10. It is found that for CRA, the strength from S/A = 0.55 specimens is higher than the S/A=0.50 companion specimens. That is, R55F30SP13(S55) > R55F30SP13, and R60F30SP13(S55) > R60F30SP13.
5) The investigation on the effect of w/c concludes that at the same fly ash replacement rate the smaller the w/c, the higher the 28-day strength. This is true for CRA or CNA.
6) The following regressive equations are obtained for predicting 28-day strength with S/A=0.5:

(1)Amount of fly ash 25%

$0.5 \le w/c \le 0.6$

Normal concrete: $f_c' = 67 \times (w/c)^{-2.8266}$ R^2=0.9496 (kgf/cm^2)

Recycled concrete: $f_c' = 101 \times (w/c)^{-2.36}$ R^2=0.9975 (kgf/cm^2)

(2) Amount of fly ash 30%

$0.5 \le w/c \le 0.6$

Normal concrete: $f_c' = 73.7 \times (w/c)^{-2.5284}$ R^2=0.9795 (kgf/cm^2)

Recycled concrete: $f_c' = 19.1 \times (w/c)^{-4.5785}$ R^2=0.9860 (kgf/cm^2)

It can be observed that the change on the coefficients is smaller for CNA and larger for CRA, which also illustrated the high variability of recycled aggregate.

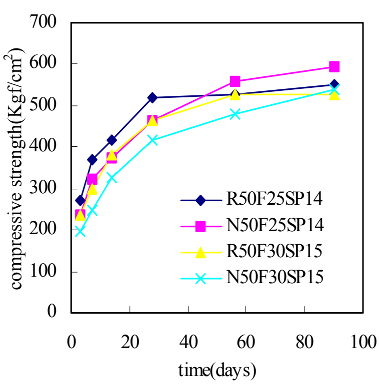

Fig. 7: Development of compressive strength (w/c=0.50)

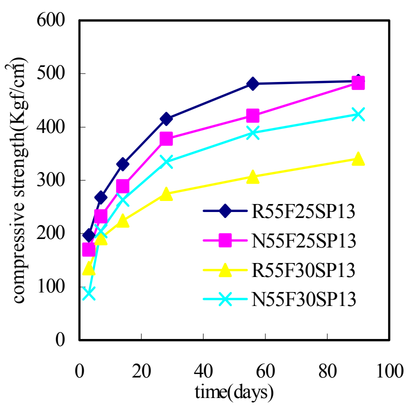

Fig. 8: Development of compressive strength (w/c=0.55)

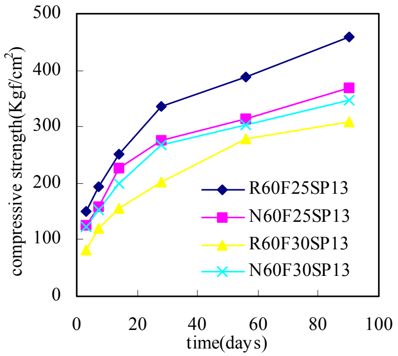

Fig. 9: Development of compressive strength (w/c=0.60)

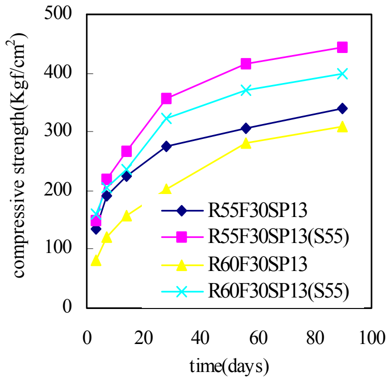

Fig. 10: Development of compressive strength of recycled concrete with different S/A and w/c

3.4. Splitting tensile strength

Test results of splitting tensile strength of high flowing concrete are illustrated in Table 4.

1) From Figs. 11 and 12, it can be observed that at the same FA replacement rate, the lower the w/c, the higher the splitting tensile strength. This is true for both CRA and CNA. At the same w/c, the splitting tensile strength of 25% replacement rate of fly ash is higher than that of 30%. This finding is similar to compressive strength, and shows that splitting tensile strength depends mainly on compressive strength.
2) The ratio of splitting tensile strength (f_{ct}) to compressive strength (f_c') of CRA is 7.44%-12.72%, and the ratio of splitting tensile strength to compressive strength of CNA is 8.25%-11.13%. This shows that the differences arises from different type of aggregate is not obvious.
3) From the last column of Table 4 and Fig..13, it can be observed that the splitting tensile strength, after being normalized by $(f_c')^{0.5}$, the $f_{ct}/(f_c')^{0.5}$ generally agree well with ACI suggested values, from $1.6(f_c')^{0.5}$ to $2.0(f_c')^{0.5}$ (for kgf/cm^2 units, and from 6 $(f_c')^{0.5}$ to $7.4(f_c')^{0.5}$ by U.S. customary units).

   A regression analysis suggests the following:

   Natural-aggregate high flowing concrete:

   $$f_{ct} = 1.715(f_c')^{0.5} \qquad R^2=0.77 \quad (\text{kgf/cm}^2)$$

   Recycled-aggregate high flowing concrete:

   $$f_{ct} = 1.75(f_c')^{0.5} \qquad R^2=0.66 \quad (\text{kgf/cm}^2)$$

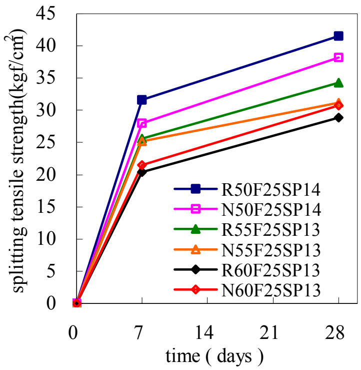

Fig. 11: Development of splitting tensile strength (25% replacement rate of fly ash)

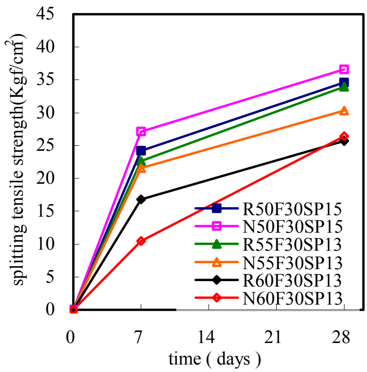

Fig. 12: Development of splitting tensile strength (30% replacement rate of fly ash)

Table 4: Strength development curve model of compressive strength and splitting tensile strength

No.	Mix proportioning no.	Compressive strength (kgf/cm^2)						28-day splitting tensile strength (f_{ct} , kgf/cm^2)	$\frac{f_{ct}}{f_c'}\times 100$	$\frac{f_{ct}}{\sqrt{f_c'}}$
		3d	7d	14d	28d	56d	90d			
1	R50F25SP14	272	368	415	518	527	551	42	8.02 %	1.83
2	N50F25SP14	236	323	372	463	560	592	38	8.25 %	1.77
3	R50F30SP15	234	299	381	465	528	528	35	7.44 %	1.60
4	N50F30SP15	197	247	327	417	480	537	37	8.76 %	1.79
5	R55F25SP13	197	268	330	415	481	486	34	8.27 %	1.68
6	N55F25SP13	170	232	289	378	421	483	31	8.25 %	1.60
7	R55F30SP13	135	192	225	275	307	341	34	12.35 %	2.05
8	N55F30SP13	88	205	264	335	389	424	30	9.05 %	1.66
11	R55F30SP13(S55)	149	220	268	357	415	445	–	–	–
12	R60F25SP13	149	194	251	337	388	458	29	8.56 %	1.57
13	N60F25SP13	125	158	226	276	313	370	31	11.13 %	1.85
14	R60F30SP13	81	120	157	202	280	308	26	12.72 %	1.81
15	N60F30SP13	124	153	200	268	304	348	26	9.87 %	1.62
18	R60F30SP13(S55)	160	204	235	322	370	399	–	–	–

3.5. Bond strength

The results of bond tests are shown in Table 5.

Table 5: Relationship of bond strength and compressive strength

No.	Mix proportioning no.	Position	Bond force (kgf)	Bond strength (kgf/cm^2) (a)	$\sqrt{f_c'}$ (b)	$\frac{a}{b}$
3	R50F30SP15	V	11425	127	21.57	5.9
		H-D	8864	99		4.6
		H-U	5556	62		2.9
4	N50F30SP15	V	17589	195	20.43	9.5
		H-D	11327	126		6.2
		H-U	10848	121		5.9
5	R55F25SP13	V	13371	149	20.37	7.3
		H-D	12553	140		6.9
		H-U	11312	126		6.2
6	N55F25SP13	V	13918	155	19.43	8.0
		H-D	10370	115		5.9
		H-U	10300	114		5.9
7	R55F30SP13	V	9262	103	16.58	6.2
		H-D	8943	99		6.0
		H-U	7589	84		5.1
8	N55F30SP13	V	15117	168	18.30	9.2
		H-D	12496	139		7.6
		H-U	10340	115		6.3
14	R60F30SP13	V	10489	117	14.22	8.2
		H-D	9012	100		7.0
		H-U	6764	76		5.3
15	N60F30SP13	V	9606	107	16.36	6.5
		H-D	7704	86		5.3
		H-U	5818	65		4.0

1) The variability of bond strength of CRA is higher. As shown in Fig. 13, most results of bond strength of CRA are slightly less than that of CNA. (Except when w/c is 0.6, the bond strength of these two materials is similar.)
2) For w/c = 0.5 CRA, the 25% FA replacement rate concrete, shows a 30% higher bond strength than those of 30% replacement ones, which agrees with compressive and tensile strength test results.
3) According to the experiment, the bond strength from various bar positions are V>H-D>H-U, which agrees with previous research [8]. This is true for both CRA and CNA. The main reason is that air and water tends to be more easily accumulated under horizontally placed reinforcing bars than that of vertically

placed reinforcing bars. The top bar may accumulate more water than the bottom bar due to bleeding.

4) To effect of aggregate is not observed in bond test.

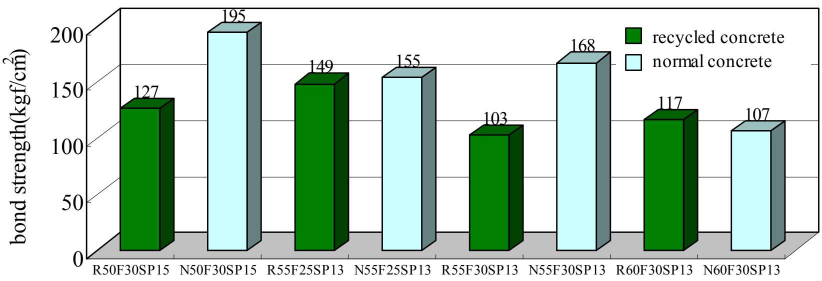

Fig. 13: Bond strength of recycled and natural aggregates (reinforcing bar placed vertically, V)

4. Conclusions

- Recycled-aggregates obtained from crushing deserted concrete have more edges and corners. The surface is highly porous and rough. Therefore, it has a lower specific weight and a higher AR than that of natural-aggregates. Although its shape and other qualities are not as good as natural ones, it still meets the requirement for concrete aggregates.
- It is feasible to produce high flowing concrete by using recycled-aggregates; however, the compressive strength of deserted concrete should be at least 210 kgf/cm^2. Besides, the mix design and production of CRA are the same with those of CNA.
- The loss of slump and slump flow of CRA is relatively 2.04%-8.7% higher right after mixing, and 0.7%-10.0% higher than that of CNA with same proportion after 45 minutes.
- It is helpful for workability to use fly ash (25%, 30%). But FA has a negative influence on the strength of concrete.
- The 28-day compressive strengths of CRA with 25% replacement rate of fly ash are generally higher than those of CNA. However, the strength development for FA added concrete is slowing down at late age (90 days). This is more pronounced for higher w/c specimens.
- Larger amount of replacement of fly ash causes a lower compressive strength of CRA.
- Splitting tensile strength increases with the increase of compressive strength and agree well with ACI suggestions. The normalized splitting strengths (by $(f_c')^{0.5}$) are in the range of $1.6(f_c')^{0.5}$ to $2.0(f_c')^{0.5}$ (in kgf/cm^2).

- The variation of bond strength of CRA is larger than CNA. In addition, the bond strength of CRA is slightly less than that of CNA.
- The bond strength from the specimens as to the relative position is V>H-D>H-U. This is observed for both CRA and CNA and is in consistent with other researches.

5. Conversion Factors

1 kgf/cm^2 = 14.22 psi
= 0.098 MPa

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