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Performance improvement of recycled aggregate concrete using fly ash and Portland blast-furnace slag cement

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ABSTRACT

Several countermeasures are implemented in the manufacture of construction materials to avoid negative impacts on the environment. Using concrete debris in construction demolition waste as a recycled aggregate to make recycled aggregate concrete (RAC) is one of the countermeasures. Further, the use of recycled construction waste and industrial by-products, such as fly ash and ground granulated blast-furnace slag, in concrete not only promotes resource circulation and reduces CO_2 emissions in the cement manufacturing process but also improves concrete performance. In this study, low-quality recycled aggregate was mixed with normal aggregate at various replacement ratios to produce RAC. Additionally, ground granulated blast-furnace slag in Portland blast-furnace slag cement and fly ash were introduced in concrete to improve concrete performance. Applying the relative quality index method for performance evaluation, it was possible to design a mix proportion of RAC that achieved the requisite performance through the application of Portland blast-furnace slag cement and fly ash as a cement substitute or as a fine aggregate substitute.

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1 Introduction

At the beginning of the 21st century, the concrete sector consumed a huge amount of resources. In 2010, the total cement production in the world reached 3.3 billion tonnes [1], which increased to 4.4 billion tonnes in 2021 [2]. The rapid rise in cement production negatively impacts the environment as massive amounts of CO_2 are emitted during the manufacturing process. Therefore, to build a sustainable society, using various industrial by-products, recycling resources throughout their life cycles and reducing CO_2 emissions are crucial. To reduce the environmental impact by recycling resources throughout their life cycles and reducing CO_2 emissions during the cement manufacturing process and concrete manufacturing process, the use of low-quality recycled aggregate with low CO_2 emissions [3] and industrial by-products as cement substitutes, such

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as fly ash type II (FAII) and ground granulated blast-furnace slag in Portland blast-furnace slag cement type B (BB), which is regulated by Japanese Industrial Standards (JIS), is effective. Further, FAII and BB are expected to prevent an alkali-silica reaction [4] and improve the long-term compressive strength. Compared to the other studies, the combination of BB as a cement with FAII as a fine aggregate substitute and the combination of FAII as a cement substitute and/or as a fine aggregate substitute in recycled aggregate concrete (RAC) herein are effective ways to examine the effect of BB and FAII. Accordingly, the performance improvement by the use of FAII and BB in RAC using low-quality recycled aggregate was examined and showed a satisfactory result.

Table 1 – Quality of cement and mineral admixture.

Item	N	FAII*	BB
Density (g/cm^3)	3.16	2.35	3.04
Specific surface area (cm^2/g)	3,300–3,330	3,570–3,620	3,770
Loss on ignition (%)	2.28–2.33	1.4–1.8	1.86
MgO (%)	1.50–1.55	1.69–1.70	3.52
SO_3 (%)	2.02–2.11	-	2.15
Cl^- (%)	0.010–0.014	-	0.013
Total alkali content (%)	0.50–0.55	-	-

* Other chemical contents of FAII (%): SiO_2 (54.65–60.13), Al_2O_3 (22.37–27.13), Fe_2O_3 (6.07–6.51) and CaO (4.18–4.33).

Table 2 – Quality of aggregate*1.

Item	Test method	NS*2	NG*3	RLS	RLG_1	RLG_2	RLG_3
Density in oven-dry condition (g/cm^3)	JIS A 1109	2.56–2.58	2.61–2.65	2.09	2.29	2.28	2.25
Water absorption (%)	JIS A 1110	1.47–1.92	0.65–1.31	9.71	5.34	5.94	6.21
Fineness modulus (F.M.)	JIS A 1102	2.42–2.62	6.62–6.67	3.31	6.49	6.70	6.73
Materials finer than 75-µm sieve (%)	JIS A 1103	2.2–4.6	0.8–1.8	5.2	1.0	1.3	1.2
Solid content in aggregate (%)	JIS A 1104	65.3–67.2	60.8–62.8	63.9	60.9	61.4	62.2
Solid content of particle shape (%)	JIS A 5005	-	59.8–62.3	56.3	60	61.4	60.8
Chloride content (%)	JIS A 1154	-	-	0.02	0.02	0.02	0.00
Aggregate crushing value (%)	BS 812-110	-	14.4–14.5	-	-	24.5	27.0
Ten percent fine value (kN)	BS 812-111	-	294–311	-	-	148	134
F.M. frost damage index	JIS A 5022	-	-	-	-	0.05	0.05
Alkali-silica reaction	JIS A 5021	-	-	-	-	Harmless	Harmless
Amount of contained impurities (mass%)	JIS A 5023	-	-	0.22	0.20	0.16	0.18

*1 Those shown in range were taken in multiple lots. *2 Ibi river sand. *3 Shinshiro crushed stone.

Further, at the present, there is no study on mix proportion design method (MPDM) for RAC using FAII and BB in different combinations as in this study. Based on the experimental results of performance evaluation by the relative quality index method, this study proposes an MPDM for RAC using FAII and BB, which can be used in manufacturing an environmentally friendly concrete that satisfies the required performance.

2 Outline of experiment

2.1 Materials

2.1.1 Cement and mineral admixture

Ordinary Portland cement (N) and BB were used as the cement, while FAII was used as a mineral admixture; their qualities are listed in Table 1.

2.1.2 Aggregate

In Table 2, river sand (NS) was used as normal fine aggregate and crushed stone 2005 (NG) was used as normal coarse aggregate which were taken in multiple lots from the same quarry. Recycled coarse aggregate class L 2005 (RLG_1, RLG_2, RLG_3) and recycled fine aggregate class L (RLS) were used in accordance with JIS A 5023. These originated from the demolition of buildings (raw aggregate: unknown) (RLG_1) and a reinforced-concrete structural frame (raw aggregate: mountain gravel, crushed stone) (RLG_2, RLG_3, RLS).

2.2 Experiment and test method

The experiments and test methods are shown in Table 3.

Table 3 – Experiment and test method.

Type	Experiment	Test method	Remark
Fresh concrete	Slump	JIS A1101	-
	Air content	JIS A 1128	-
	Density	JIS A 1116	-
	Temperature	JIS A 1156	-
	Chloride content	JIS A 5308; JASS 5 T-502	Electrode current method and Mohr method
Hardened concrete	Compressive strength	JIS A 1108	Standard curing method4 weeks,13 weeks
	Static modulus of elasticity	JIS A 1149	
	Drying shrinkage	JIS A 1129-3	At 26 weeks
	Accelerated carbonation depth	JIS A 1153	-

2.3 Mix proportion

In Table 4, recycled aggregate class L was used to make RAC-Class M according to the JIS A 5022. A total of 24 concrete specimens were prepared with three water–binder ratios (W/B) (45%, 55% and 65%), three RLG replacement ratios (0%, 50% and 100%) and two RLS replacement ratios (0% and 30%) in volume. There were four cases of combining binder: only N; FAII with a 20% replacement ratio for a total amount of N + FAII as a fine aggregate substitute (FS) [5]; FAII with a 30% replacement ratio as a cement substitute together with FS (FAFS) and BB together with FS (BBFS). The unit water content was determined by trial mixing (176–183 kg/m^3) for W/B = 45%, 173–180 kg/m^3 for W/B = 55% and 170–177 kg/m^3 for W/B = 65%. Owing to high flowability [6] in the cases of BBFS and FAFS, the unit water content was reduced as compared to N.

Table 4 – Mix proportion.

Specimen[*1]	Mix proportion condition							Unit weight (kg/m^3)		Total alkali content (kg/m^3)	Chloride content (kg/m^3)	*Qdt* (g/cm^3)
	Binder	Replacement ratio (%)				W/B (%)	s/a (%)					
		FA	FS[*2]	RLG	RLS			W	C			
N-NGNS-45	N	-	-	-	-	45	41.9	183	407	2.2	0.06	2.60
N-FS20NGNS-45		-	-	-	-		41.4	183	407	2.2	0.06	2.57
FA30-FS20NGNS-45	N, FAII	30	20	-	-		41.4	178	276	1.5	0.04	2.57
BB-FS20NGNS-45	BB	-	20	-	-		42.5	176	390	0.0	0.05	2.58
N-NGNS-55	N	-	-	-	-	55	44.3	180	327	1.8	0.05	2.60
N-$RLG_2$50NS-55		-	-	50	-		44.0	180	327	2.2	0.09	2.50
N-$RLG_2$50RLS30-55		-	-	50	30		44.0	180	327	2.7	0.11	2.43
N-$RLG_2$100NS-55		-	-	100	-		44.3	180	327	2.8	0.17	2.41
N-FS20NGNS-55		-	20	-	-		43.8	180	327	1.8	0.05	2.58
N-FS20$RLG_1$50NS-55		-	20	50	-		43.4	175	318	2.0	0.10	2.51
N-FS20$RLG_3$50RLS30-55		-	20	50	30		44.3	180	327	2.7	0.07	2.44
N-FS20$RLG_1$100NS-55		-	20	100	-		43.4	175	318	2.3	0.15	2.41
FA30-FS20NGNS-55	N, FAII	30	20	-	-		44.0	175	222	1.2	0.03	2.58
FA30-FS20$RLG_3$50NS-55		30	20	50	-		44.6	175	223	1.6	0.03	2.51
FA30-FS20$RLG_3$50RLS30-55		30	20	50	30		44.3	175	229	2.2	0.10	2.40
FA30-FS20$RLG_3$100NS-55		30	20	100	-		44.6	175	223	2.1	0.03	2.40
BB-FS20NGNS-55	BB	-	20	-	-		44.9	173	314	0.0	0.04	2.58
BB-FS20$RLG_3$50NS-55		-	20	50	-		45.7	173	315	0.4	0.04	2.51
BB-FS20$RLG_3$50RLS30-55		-	20	50	30		45.7	173	315	1.0	0.07	2.45
BB-FS20$RLG_3$100NS-55		-	20	100	-		45.7	173	315	0.8	0.04	2.40
N-NGNS-65	N	-	-	-	-	65	46.0	177	272	1.5	0.04	2.60
N-FS20NGNS-65		-	20	-	-		46.0	177	272	1.5	0.04	2.58
FA30-FS20NGNS-65	N, FAII	30	20	-	-		45.7	172	185	1.0	0.03	2.58
BB-FS20NGNS-65	BB	-	20	-	-		46.5	170	261	0.0	0.03	2.58

*1 Specimens were named by the type of binder - aggregate and replacement ratio - W/B. *2 20% replacement ratio of the total amount of N+FAII as a fine aggregate substitute.

The target slump was set at 18 ± 2.5 cm, and the target air content was 4.5 ± 1.5%. The chemical admixtures included air-entraining and water-reducing admixture (high-performance type) at 1.0–1.5%, air-entraining and high-range water-reducing admixture at 0.5%, air-entraining for fly ash at 0.1–0.8%, air-entraining at 0.005–0.04% and defoaming at 0.0005% of the cement weight. The chloride content calculated from the mix proportion was ≤0.30 kg/m^3 that is specified in JIS A 5308. The total alkali content increased when the recycled aggregate replacement ratio increased, but all specimens had an alkali content that was less than 3.0 kg/m^3, which is specified in JIS A 5022.

Table 5 – Experiment results of fresh concrete.

Specimen	Slump (cm)	Air content*1 (%)	Density (kg/m^3)	Temperature (°C)	Chloride content*2 (kg/m^3)
N-NGNS-45	20.5	3.8	2341	25.5	0.03
N-FS20NGNS-45	19.0	3.1	2343	26.4	0.03
FA30-FS20NGNS-45	17.5	4.2	2313	26.2	0.02
BB-FS20NGNS-45	19.0	3.5	2319	27.6	0.03
N-NGNS-55	19.0	4.1	2249	26.2	0.04
N-RLG$_2$50NS-55	17.5	5.6(0.4)	2191	17.1	0.11
N-RLG$_2$50RLS30-55	20.0	4.9(0.4)	2141	16.8	0.13
N-RLG$_2$100NS-55	19.5	4.8(0.7)	2217	27.0	0.11
N-FS20NGNS-55	18.5	4.7	2283	24.7	0.03
N-FS20RLG$_1$50NS-55	17.0	5.7(0.3)	2227	20.0	0.22
N-FS20RLG$_3$50RLS30-55	18.0	5.0(0.3)	2160	18.9	0.10
N-FS20RLG$_1$100NS-55	20.0	5.5(0.4)	2183	26.7	0.27
FA30-FS20NGNS-55	17.5	5.5	2190	24.5	0.02
FA30-FS20RLG$_3$50NS-55	20.0	5.3(0.3)	2144	14.3	0.09
FA30-FS20RLG$_3$50RLS30-55	20.5	5.5(0.5)	2120	19.2	0.09
FA30-FS20RLG$_3$100NS-55	20.5	4.9(0.3)	2079	14.5	0.10
BB-FS20NGNS-55	19.0	4.6	2320	27.1	0.03
BB-FS20RLG$_3$50NS-55	19.5	4.2(0.3)	2279	12.9	0.06
BB-FS20RLG$_3$50RLS30-55	20.0	5.8(0.3)	2160	15.2	0.07
BB-FS20RLG$_3$100NS-55	20.5	5.4(0.4)	2077	12.7	0.14
N-NGNS-65	20.0	4.3	2250	26.2	0.03
N-FS20NGNS-65	19.5	5.5	2169	25.8	0.03
FA30-FS20NGNS-65	20.0	5.4	2137	26.4	0.02
BB-FS20NGNS-65	19.5	4.9	2126	26.4	0.03

*1 In the round brackets ( ) is the aggregate correction factor. *2 For RAC calculation, refer to JIS A 5023.

The relative density (*Qdt*) [7], which was calculated by Eq. (1), was used to evaluate concrete performance.

$$Qdt = \frac{QvdG\times a + QvdN\times b + QrdG\times c + QrdN\times d + QFA\times e}{a + b + c + d + e} \tag{1}$$

where, *Qdt*: relative density (g/cm^3);

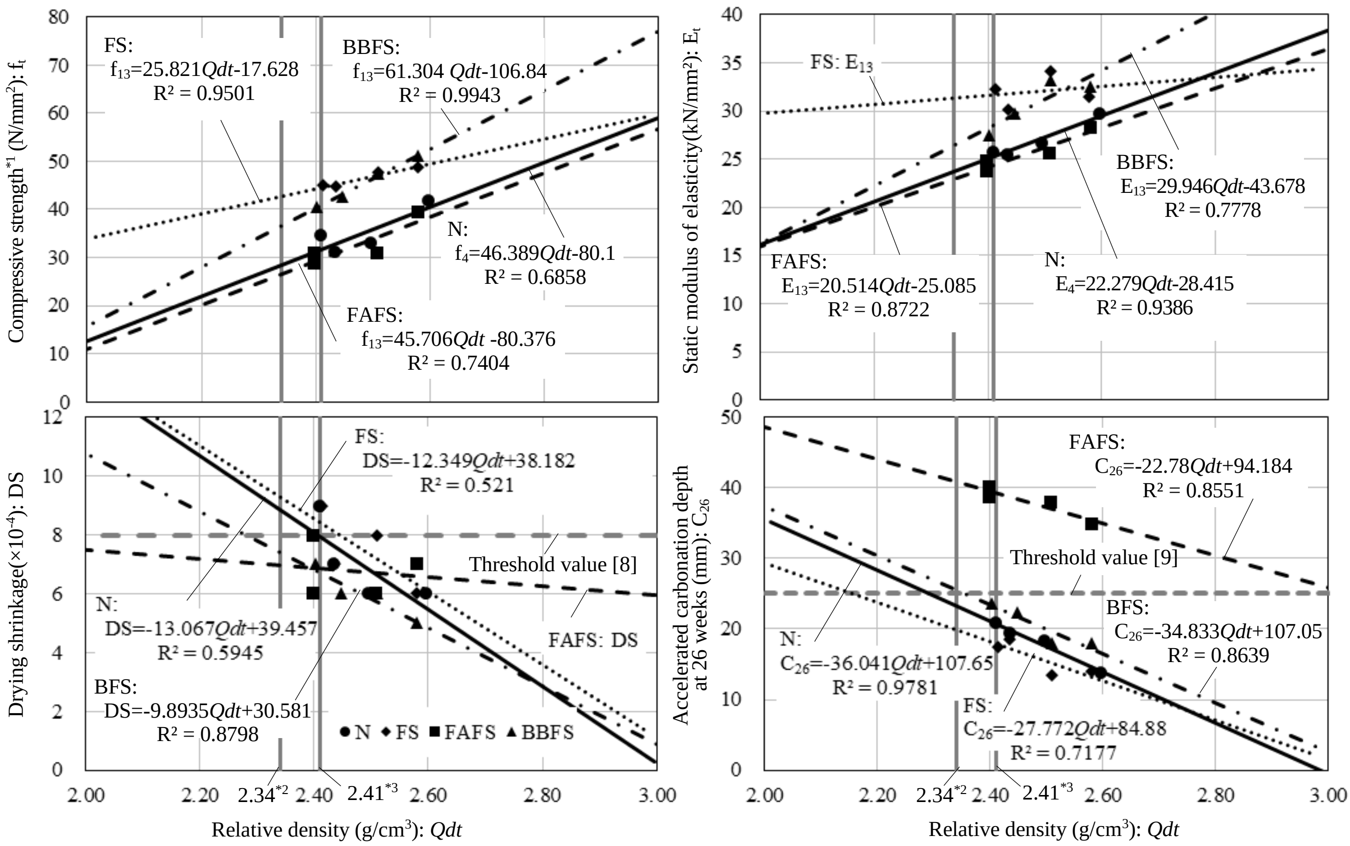
QvdG: density in the oven-dry condition of normal coarse aggregate (g/cm^3);
QvdN: density in the oven-dry condition of normal fine aggregate (g/cm^3);
QrdG: density in the oven-dry condition of recycled coarse aggregate (g/cm^3);
QrdN: density in the oven-dry condition of recycled fine aggregate (g/cm^3);
QFA: density of FAII (g/cm^3);
a, b, c and *d*: absolute volume of aggregate used (L/m^3);
e: absolute volume of FAII (L/m^3).

3 Experiment result

3.1 Fresh concrete

3.1.1 Slump and air content

In Table 5, by the proper use of chemical admixtures, all of the concrete specimens satisfied the target slump of 18 ± 2.5 cm and the target air content of 4.5 ± 1.5%. The aggregate correction factor (ACF) increased when the replacement ratios of RLG and RLS increased. When only RLG was used, the ACF was 0.3–0.7%. When RLG and RLS were used, the ACF was 0.3–0.5%.



*1 Compressive strength of N at 4 weeks and FS, FAFS and BBFS at 13 weeks. *2 RAC-Class M1 using 50% RLG based on JIS A 5022. *3 RAC-Class M2 using 50% RLG and 30% RLS based on JIS A 5022.

Fig. 1 – Relationship between the relative density and concrete performance.

3.1.2 Chloride content

In Table 5, the chloride content increased when the replacement ratios of RLG and RLS increased, but all the specimens satisfied the required value of ≤0.30 kg/m³ in JIS A 5308. The chloride content was higher than the calculated values in Table 4. This was due to the influence of the calculation method in JIS A 5023.

3.2 Hardened concrete

The N, FS, FAFS and BBFS groups were examined by evaluating the relationship between *Qdt* and concrete performance as the relative quality index method. To clarify the effect of FAII and BB, the relationship was examined for each case of performance and binder type.

The threshold values of *Qdt* were calculated using the lower limit of density in the oven-dry condition of NG and NS, as specified in JIS A 5005 and JIS A 5308, respectively, and of FAII, as specified in JIS A 6201. In the cases of RLG and RLS, because JIS A 5023 does not specify the lower limits, they were taken as 2.19 g/cm³ and 1.91 g/cm³ [7], respectively. Also, the replacement ratios of RLG and RLS followed the upper limits for RAC-Class M1 and M2, in accordance with JIS A 5022. In Fig. 1, the threshold value of *Qdt* is 2.41 g/cm³ for the case in which 50% RLG was used in RAC-Class M1 and 2.34 g/cm³ for the cases in which 50% RLG and 30% RLS were used in RAC-Class M2.

In all specimens, concrete performance tended to increase when *Qdt* increased. The results show some variations, but in general, a relationship was obtained.

As shown in Fig. 1, the compressive strength and static modulus of elasticity were evaluated at 4 weeks for N and at 13 weeks for FS, FAFS and BBFS. Accordingly, when *Qdt* increased, these performances tended to increase.

Also, when *Qdt* increased, drying shrinkage tended to decrease. When *Qdt* was higher than 2.41 g/cm³, all specimens satisfied the target quality of 8×10^{-4} [8]. When BB was used, drying shrinkage was lower compared with N. In the case of FAFS, no relationship was observed. For the accelerated carbonation depth, when *Qdt* increased, it tended to decrease. In the case of N, FS and BBFS, even when *Qdt* ≤ 2.41g/cm³, all specimens satisfied the target quality of 25 mm [9]. In the case of FAFS, the target quality was not satisfied.

4 Mix proportion design

In this study, the compressive strength was compared with that of concrete with a 0% replacement ratio of recycled aggregate class L (comparative concrete). This was done in order to reveal the effect of the compressive strength reduction caused by the use of recycled aggregate class L and the quality improvement effect of the mineral admixtures.

4.1 Mix proportion design flow

First, types and qualities of materials were confirmed. Then, the strength equation was examined on the basis of the cement–water ratio. After examining the mix proportion strength, the alkali and chloride contents were confirmed in the material design step. Next, an assumed mix proportion was decided. RAC was made and evaluated using the relative quality index method. Finally, the strength equation for RAC was proposed and the mix proportion was decided.

4.2 Mix proportion strength

According to JASS 5(2018) [8], the mix proportion strength (F) was calculated based on the standard design strength (F_q). The calculation results are shown in Table 6.

4.3 Material design

The calculation results of the chloride and total alkali content of the RACs are shown in Table 4. Compressive strength was determined in the cases of N, FS, FAFS and BBFS. RLG and RLS were replaced up to 50% and 30% in volume, respectively, to make RAC-Class M. RLG was replaced up to 100% in volume to make RAC-Class L.

Table 6 - Calculation result of mix proportion strength.

F_q (N/mm^2) *1	Range of θ (°C)*2	$_{28}S_{91}$ (N/mm^2)*3	$F_m = F_q + {}_{28}S_{91}$ (N/mm^2)*4	σ (N/mm^2)*5	F (N/mm^2)		
					$F \geq F_m + 1.73\sigma$	$F \geq 0.85F_m + 3\sigma$	Set up value
21.0	8 ≤ θ	3	24.0	2.5	28.3	27.9	28.3
	0 ≤ θ < 8	6	27.0	2.7	31.7	31.1	31.7

*1 F_q: quality standard strength of concrete. *2 θ: range of the average temperature. *3 $_{28}S_{91}$: strength correction factor. This factor is derived from the difference between the compressive strength of standard-cured specimens at m days and that of structural concrete at n days (N/mm^2) with m= 28 and n= 91. *4F_m: proportioning control strength of concrete. *5 σ: standard deviation of the compressive strength which is the greater value between 2.5 N/mm^2 and 0.1F_m.

4.4 Strength equation of RAC using FAII and BB

Eq. (2) shows the relationship between *F* and *Qdt* for comparative concrete and RAC, where the concrete using N is at 4 weeks, and FS, FAFS and BBFS are at 13 weeks.

$$F = l + m \times Qdt \tag{2}$$

where, *F*: mix proportion strength of concrete (N/mm^2);

l and *m*: experimental constants (intercept and slope of the relationship equation between compressive strength and *Qdt* in Fig. 1).

With the results of *F* for specimens of W/B = 55%, the strength reduction rate (*R*) of *F* for RACs and comparative concretes can be calculated by Eq. (3).

$$R = F_{tR}/F_{tN} \tag{3}$$

where, *R*: strength reduction rate;

F_{tR}: mix proportion strength of RAC at *t* weeks (N/mm^2);

F_{tN}: mix proportion strength of the comparative concrete at *t* weeks (N/mm^2).

As shown in Eq. (4), the constants *a* and *b* in the strength equation for the comparative concrete are multiplied by *R* to obtain the strength equation for RAC using N, FAII and BB from Table 7. Using the F_{tR} equation, RAC that uses FAII and BB can be manufactured in accordance with the JIS.

$$F_{tR} = R \times (a \times B/W + b) \tag{4}$$

where, *B/W*: binder–water ratio;

a and *b*: constants of the strength equation for the comparative concrete.

Table 7 - Calculation result of strength equation's constant for RAC using FAII and BB.

Binder	F_q*	W/B (%)	NGNS			RLG50NS				RLG50RLS30				RLG100NS			
			F_{tN}*	Constant		F_{tR}*	R	Constant		F_{tR}*	R	Constant		F_{tR}*	R	Constant	
				a	b			a×R	b×R			a×R	b×R			a×R	b×R
N	21.0	55	40.4	31.10	-16.99	35.7	0.88	27.37	-14.95	32.8	0.81	25.19	-13.76	31.7	0.78	24.26	-13.25
FS			49.0	51.51	-43.47	47.2	0.96	49.45	-41.73	45.3	0.92	47.39	-39.99	44.7	0.91	46.87	-39.56
FAFS			37.5	47.40	-48.06	34.3	0.91	43.13	-43.73	29.2	0.78	36.97	-37.49	29.2	0.78	36.97	-37.49
BBFS			51.3	56.46	-55.09	47.1	0.92	51.94	-50.68	43.2	0.84	47.43	-46.28	40.4	0.79	44.60	-43.52

* Unit: N/mm^2.

5 Conclusion

For the fresh condition of concrete that used FAII, BB, and low-quality recycled aggregate, the slump and air content satisfied the target values. This was accomplished by adjusting the amount of chemical admixture even when the replacement ratio of the recycled aggregate was high. Further, the chloride content in all specimens satisfied the required value of ≤0.30 kg/m^3 in JIS A 5308.

For the performance evaluation using the relative quality index method, a relatively clear overall relationship was obtained between *Qdt* and the main performance of concrete. Through the proper use of FAII and BB in concrete that uses low-quality recycled aggregate mixed with normal aggregate and based on the results of the performance evaluation and the strength equations for mix proportion design, RAC can be manufactured with improved performance and the required performance can be assured.

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