

Simplified Approach to Improving the Performance of Recycled Aggregate Concrete

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Abstract

Recycled aggregate concrete (RAC) is an effective use of concrete waste, but its performance is often inferior to that of normal concrete, which limits its applicability. The performance of RAC can be improved through supplementary cementitious materials (SCMs); however, introducing SCMs complicates the concrete manufacturing process at plants that lack adequate storage resources. Therefore, this study investigated the feasibility of improving the performance of RAC by utilizing established cements that already contain SCMs, such as fly ash and ground granulated blast-furnace slag. RAC samples were produced using different classes of recycled coarse aggregate (Class M and Class L) and four types of cement (ordinary portland cement, portland fly ash cement Type B, portland blast-furnace slag cement Type B, and ecocement) to evaluate the combinations and recycled aggregate replacement ratios that resulted in improved performance. The aim of this study was to develop a simplified manufacturing method that promotes the use of recycled aggregates and environmentally friendly cements to realize a high-performance and low-carbon concrete with both excellent resource recyclability and economic efficiency.

Keywords : recycled aggregate concrete; recycled coarse aggregate; supplementary cementitious materials; mix proportion; concrete performance

1. Introduction

In October 2020, the Japanese government announced its objective of achieving carbon neutrality by 2050 and reducing greenhouse gas emissions to zero [1]. The manufacturing industry accounts for 35% of CO₂ emissions in Japan of which ceramics and mineral products comprise 17.4%, and the cement industry has the largest share. CO₂ emissions are inevitably generated during the cement manufacturing process, which involves the calcination of limestone (CaCO₃) via decarboxylation (CaCO₃ → CaO + CO₂). To reach the high temperatures of 1450°C required for the calcination process, fossil fuels such as coal are widely used, which further contribute to CO₂ emissions [2].

Table 1 presents the CO₂ emission intensities of various types of cement along with life cycle inventory (LCI) data [3] published annually by the Japan Cement Association. The production of 1 ton of ordinary portland cement (N) produces more than 700 kg of CO₂. The amount of CO₂ emissions can be reduced by blending cement with supplementary cementitious materials (SCMs) such as fly ash (FA) or ground granulated blast-furnace slag (GGBFS) that also possess cementitious properties. The most versatile blended cements are portland fly ash cement Type B (FB), which contains >10 and ≤20 mass% FA, and portland blast-furnace slag cement Type B (BB), which contains >30 and ≤60 mass% GGBFS. Meanwhile, ecocement (E) mainly comprises ash from the incineration of municipal solid waste and sewage sludge and was first produced in Ichihara City, Chiba Prefecture in 2001 after which it was standardized by the Japanese Industrial Standards (JIS) in July 2002. Although the applications of E are limited owing to its relatively high chloride ion content, each ton of E produced recycles ≥500 kg of waste resources (reference: N = 480 kg, actual results for FY2023 [4]) [5].

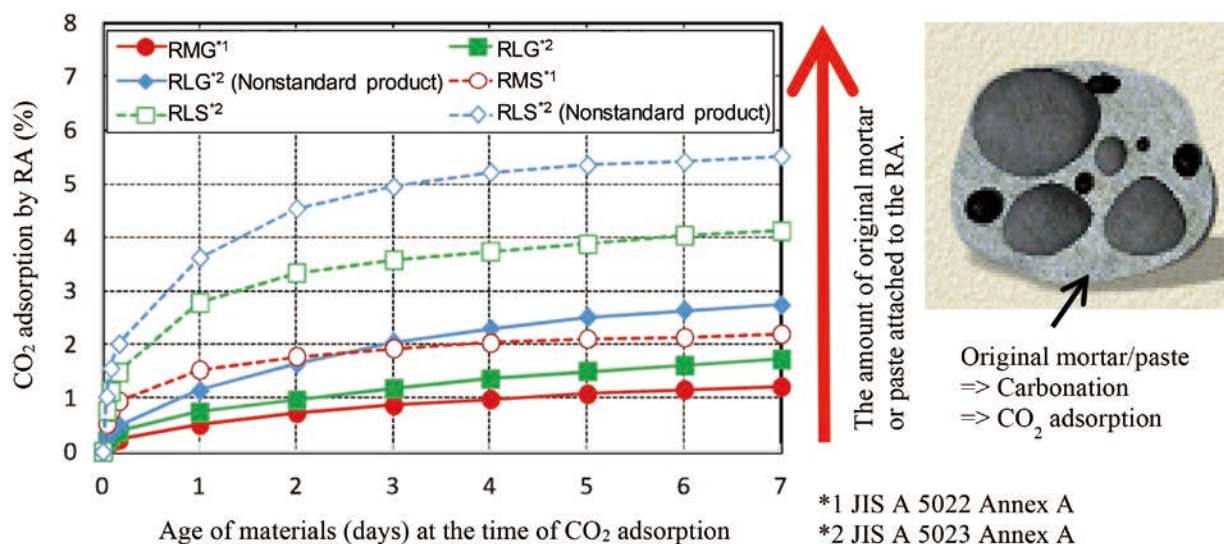
Table 1 CO₂ emission intensities and energy input of various types of cement

Cement type	CO ₂ emission intensity (kg-CO ₂ /t)	Energy input (GJ/t)
N (JIS R 5210)	741.3 [3]	3.40 [5]
FB (JIS R 5213)	612.9 [3]	3.02 [5]
BB (JIS R 5211)	423.3 [3]	2.28 [5]
E (JIS R 5214)	803.0 [5]	6.40 [5]

Cement is primarily used in concrete, so an effective approach to reduce CO₂ emissions is to implement measures targeting both concrete and cement as a single entity. Concrete is the second-most consumed material after water and is fundamental to modern urban environments. About 4 billion tons of cement was produced globally in 2024 [6] compared with about 131 million tons in 1950 [7].

Concrete is extremely durable and can last for hundreds of years. As old concrete structures are demolished, large volumes of waste are generated that can also last for centuries. Billions of tons of waste concrete enter the construction and demolition waste stream each year on a global scale, and the amount is still rapidly increasing because of continuous urbanization and redevelopment activities in many countries. Even though available data exhibit substantial geographical variation, it is estimated that 50%–90% of waste concrete is recycled as aggregates [8]. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism conducted a survey in fiscal year 2018 and reported that 74.4 million tons of construction waste are produced annually, most of which is recycled in compliance with related laws and ordinances. Concrete accounts for 36.9 million tons of the total construction waste. Although 99.3% of the concrete waste is recycled, the most common use is as roadbed material or backfill [9]. However, the demand for roadbed material is not expected to increase owing to the declining construction of new roads [9]. Thus, new uses for concrete waste are needed. Meanwhile, concrete waste also contains harmful trace elements originating from cement such as hexavalent chromium and lead that may leach into the environment when fine powder (diameter ≤ 5 mm) is subjected to wetting [10]. Therefore, decreasing the amount of fine powder during the recycling of concrete waste may help reduce the environmental risks of soil contamination.

The most promising alternative use of concrete waste is in recycled aggregate concrete (RAC) where the concrete waste is recycled as aggregate for new concrete. In particular, recycled aggregate (RA) Class L can be manufactured using a simplified method and offers excellent cost-effectiveness [11]. As shown in Figure 1, RA can also be used to adsorb CO₂ in an aggregate yard via a forced carbonation method [12]. The effectiveness of the CO₂ adsorption increases with the amount of original mortar and paste attached to the RA. The adsorbed CO₂ is then capsulated and fixed in RAC through standard


Fig. 1 CO₂ adsorption by RA (modified from [12])

concrete manufacturing methods. The potential wider adoption of RAC led to the establishment of the ISO 18985:2025 standard to regulate its use [13]. However, while the presence of the original mortar and cement paste in the RA is necessary for CO₂ adsorption, it can also degrade the performance of the resulting RAC.

The authors previously demonstrated that FA and GGBFS can effectively improve the performance of RAC [14]. However, increasing the number of SCMs can make it difficult for concrete plants without available storage silos to respond in a timely and stable manner to various orders [15]. Therefore, rather than use SCMs directly, this study investigated whether the performance of RAC could be improved by employing established cements that already contain these SCMs. Concrete samples were produced using various types of RA and four different types of cement to determine how different combinations and RA replacement ratios affect the performance.

The aim of this study was to develop a simplified manufacturing method that promotes the use of RA and environmentally friendly cement to realize a high-performance and low-carbon concrete with excellent resource recyclability and economic efficiency.

2. Current status of RAC in Japan

Table 2 presents the history of standards for RAC in Japan. JIS A 5021, JIS A 5022, and JIS A 5023 were established in 2005–2007 to regulate the performance of RAC [16]. In 2018, the Ministry of Land, Infrastructure, Transport and Tourism investigated the usage and performance of RAC [9]. They found that RAC recycled 119000 tons of waste concrete, which was approximately twice the amount recorded in 2012 (55000 tons) but remained small relative to the total amount of concrete waste. The total amount of recycled concrete comprised 64000 tons of RAC Class H (to be used in structural and nonstructural members [17]), 50000 tons of RAC Class M standard type (to be used in structural and nonstructural members unaffected by drying shrinkage [17]) and frost-resistant type (to be used in structural and nonstructural members unaffected by drying shrinkage and frost damage [17]), and 5000 tons of RAC Class L (for use in nonstructural members without reinforcement [17]). The use of RAC Class M increased by 48000 tons compared with 2012. In 2018, JIS A 5022 was revised based on recommendations from the Architectural Institute of Japan (AIJ) [18] to stipulate that RA class L can be mixed with normal aggregate to produce RAC Class M [18]. In 2022, JASS 5 [19] was revised to include environmental considerations (resource recycling, low carbon performance, and environmental safety) as performance requirements for reinforced concrete, including the use of byproducts such as RA.

Table 2 History of standards for RAC in Japan

Year	Main trends
2005	Establishment of JIS A 5021 (Recycled aggregate for concrete-class H)
2006	Establishment of JIS A 5023 (Recycled concrete using recycled aggregate class L)
2007	Establishment of JIS A 5022 (Recycled concrete using recycled aggregate class M)
2009	Revision of “Japanese Architectural Standard Specification JASS 5 Reinforced concrete work” (JASS 5) [16]. New provisions in Section 28 of JASS 5 “Recycled aggregate concrete.”
2011	Revision of JIS A 5021
2012	Revision of JIS A 5022 and JIS A 5023
2014	Publication of “Recommendation for mix design, production and construction practice of concrete with recycled concrete aggregate” [17] by the Architectural Institute of Japan (AIJ).
2018	Revision of JIS A 5021, JIS A 5022 (Recycled aggregate concrete-Class M) and JIS A 5023 (Recycled aggregate concrete-Class L). Revision of JASS 5 in Section 28 “Recycled aggregate concrete” [18].
2022	Revision of JASS 5 [19].
2024	Revision of JIS A 5021, JIS A 5022 and JIS A 5023

Table 3 lists the RAC classes and types based on different combinations of coarse and fine aggregates [19]. The RAC classes are based on the quality of the coarse aggregate. Each RAC Class can be further divided into two types based on whether the fine aggregate is normal (Type 1) or either partially or fully RA (Type 2). This study focused on RAC Class M Type 1, in which the coarse aggregate is either fully recycled coarse aggregate (RG) Class M (RMG) or normal coarse aggregate mixed with <50% RG Class L (RLG), and the fine aggregate is normal fine aggregate.

Figure 2 shows the actual shipments of RAC by class [20]. The total volume of RAC peaked at approximately 110000 m³ in 2006 but fell to 34000–52000 m³/year in 2019–2021, which is approximately 30%–50% of the total volume in 2006. Of the cumulative total of 945636 m³, 39410 m³ (4%) was RAC Class H, 478934 m³ (51%) was RAC Class M, and 427493 m³ (45%) was RAC Class L. Even at its 2006 peak, RAC accounted for only 0.2% of the total amount of ready-mixed concrete shipped in 2024 (65963396 m³) [21]. Thus, the impact of the standard revisions listed in Table 2 on RAC shipment volumes remains unclear present.

Table 3 RAC types and combinations of coarse and fine aggregates [19]

RAC	Coarse aggregate	Fine aggregate
RAC Class H Type 1	All or part of the coarse aggregate is RG-Class H (RHG)	Normal fine aggregate
RAC Class H Type 2	All or part of the coarse aggregate is RHG Normal coarse aggregate	All or part of the fine aggregate is recycled fine aggregate Class-H
RAC Class M Type 1 ^{*1}	All or part of the coarse aggregate is RG class M (RMG) Part of the coarse aggregate is RG class L (RLG) (replacement ratio of ≤ 50%) ^{*2}	Normal fine aggregate
RAC Class M Type 2	All or part of the coarse aggregate is RMG	All or part of the fine aggregate is recycled fine aggregate class M (RMS)
		Part of the fine aggregate is recycled fine aggregate class L (RLS) (replacement ratio of ≤ 30%) ^{*2}
	Part of the coarse aggregate is RLG (replacement ratio of ≤ 50%) ^{*2}	All or part of the fine aggregate is RMS
		Part of the fine aggregate is RLS (replacement ratio of ≤ 30%) ^{*2}
	Normal coarse aggregate	All or part of the fine aggregate is RMS
		Part of the fine aggregate is RLS (replacement ratio of ≤ 50%) ^{*2}

*1 Standard products and freeze-resistant products are available.

*2 Satisfies the specifications of RA class L and impurity content of RA class M.

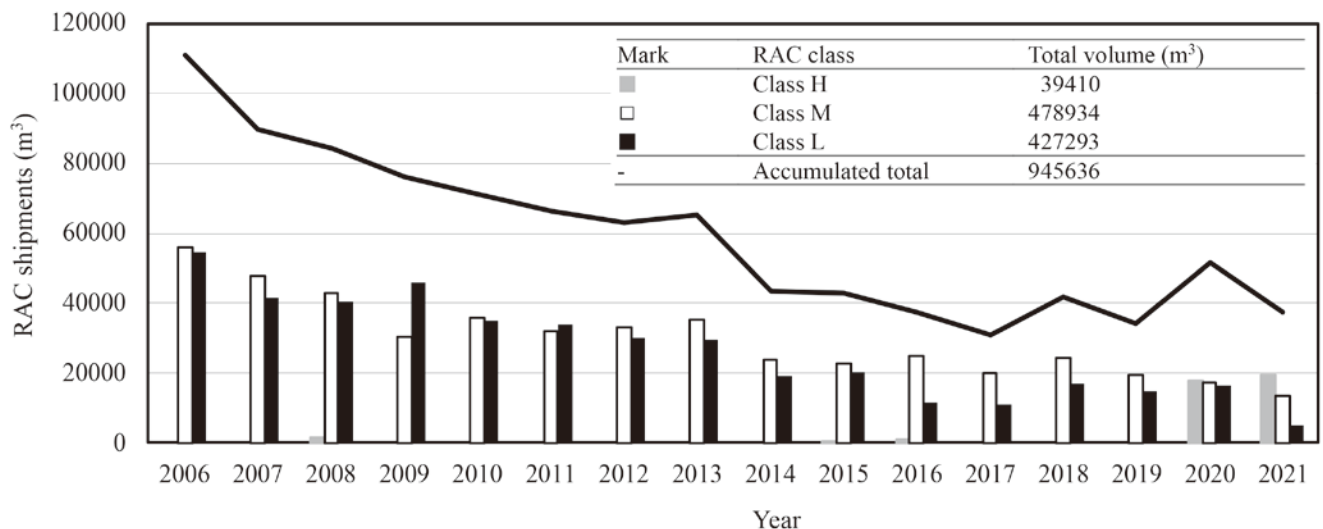


Fig. 2 RAC shipments by type in Japan [20]

3. Materials and methods

3.1 Materials

Four types of cement were used: N, FB, BB, and E. Table 4 lists the main characteristics of these cements. For normal fine aggregates, river sand (NS) was used. For normal coarse aggregates, hard sandstone (NG) and limestone (LG) were used. Air-entraining and water-reducing admixture (high-performance type), and air-entraining admixture were used as chemical admixtures.

Table 4 Main characteristics of cements

Item		N ^{*1}		FB ^{*1}		BB ^{*1}		E ^{*1}
Density (g/cm ³)		3.16	3.16	2.97	2.97	3.04	3.04	3.15
Blaine fineness (cm ² /g)		3270	3320	3670	3670	3620	3770	4100
Set	Water amount (%)	27.7	27.7	27.7	28.1	29.4	29.1	27.3
	Start (hour-min)	2-15	2-11	2-13	2-35	2-45	2-50	2-38
	Finish (hour-min)	3-32	3-31	3-41	3-50	4-11	4-42	4-00
Stability	Compaction method	Good	Good	Good	Good	Good	Good	Good
	3 days	30.9	32.9	27.3	27.7	22.1	22.8	29.8
Compressive strength (N/mm ²)	7 days	47.5	48.1	37.5	38.5	36.3	37.6	42.9
	28 days	64.1	62.4	58.1	58.1	64.2	64.8	58.1
	7 days	339	330	-	-	-	-	-
Heat of hydration (J/g)	28 days	389	388	-	-	-	-	-
	MgO	1.46	1.41	1.04	1.04	3.41	3.53	1.55
Chemical composition (%)	SO ₃	2.18	2.23	1.86	1.92	2.10	2.08	3.31
	Ignition loss	2.23	2.27	1.20	1.18	1.88	1.88	2.50
	Total alkali	0.49	0.54	-	-	-	-	0.57
	Cl ⁻	0.011	0.015	0.015	0.014	0.007	0.012	0.044
Chloride ion residual rate: α		-	-	-	-	-	-	0.24 ^{*2}
Admixture content (mass%)		-	-	15-17	15-17	40-45	40-45	-

*1 Average value *2 Maximum value

For recycled coarse aggregates, RLG₁, RLG₂, and RMG were produced with sizes of 20-5 mm. Table 5 presents an overview of the RGs produced at three plants (A, B, and C). RLG₁ was produced using original concrete for which the application and original aggregate type were unknown at Plant A. The original concrete was used to produce recycled crushed stone with sizes of 40-0 mm, which was then crushed using a fixed-type jaw crusher and divided using a fixed-type screen into RLG₁ and recycled fine aggregate. RLG₂ was produced using original concrete with unknown application and aggregate type at Plant B. After the original concrete was pre-crushed to approximately the size of a human head, it was further crushed using a fixed-type jaw crusher and divided using a fixed-type screen into RLG₂ and recycled fine aggregate. RMG was produced at Plant C using original concrete from a hospital building, although the original aggregate type was unknown. RMG was manufactured using the gravity concentration method [22].

Table 5 Overview of RGs

Original concrete				
Application	Original aggregate	Type of recycled aggregate	Plant	Production method
Building	Unknown	RLG ₁	A	Recycled crushed stone: crushing and classifying
Unknown	Unknown	RLG ₂	B	Crush to head-size of concrete waste: crushing and classifying
Hospital building	Unknown	RMG	C	Gravity concentration method [22]

Table 6 presents the main characteristics of the aggregates. RLG₁ and RLG₂ exhibited water absorption values of 6.42%–6.48%, fines content of 1.35%, and impurity content of 0.31 mass%, satisfying the requirements of JIS A 5023 Annex A. RMG had an oven-dry density of 2.40 g/cm³, water absorption of 3.63%, fines content of 1.76%, and impurity content of 0.13 mass%, satisfying the requirements of JIS A 5022 Annex A. The alkali–silica reactivity classifications were B (not tested) for RLG₁ and RLG₂ and A (harmless) for RMG, as determined according to JIS A 1145 and JIS A 5021.

Table 6 Main characteristics of aggregates

Item	Test method	NS ^{*1}	NG ^{*2}	LG ^{*3}	RLG ₁	RLG ₂	RMG
Density in oven-dry condition (g/cm ³)	JIS A 1109	2.55–2.59	2.54–2.68	2.69	2.30	2.21	2.40
Water absorption (%)	JIS A 1110	1.57–1.72	0.43–1.48	0.41	6.42	6.48	3.63
Fineness modulus (FM)	JIS A 1102	2.50–2.57	6.65–6.87	6.77	6.77	6.54	6.92
Content of materials finer than 75- μ m sieve (%)	JIS A 1103	3.2–3.5	1.3	0.3	1.4	1.6	1.8
Solid content in aggregate (%)	JIS A 1104	63.7–64.8	58.7–64.2	61.5	60.1	60.2	63.6
Solid content of particle shape classification (%)	JIS A 5005	-	56.1–58.4	61.2	59.8	-	61.8
Chloride content (%)	JIS A 5002	-	-	-	0.030	-	0.002
	JIS A 5023	-	-	-	-	0.020	-
Alkali–silica reactivity ^{*4}	JIS A 1145	-	-	-	-	-	A ^{*5}
	JIS A 5021	-	-	-	B ^{*6}	B ^{*6}	-
Amount of contained impurities (mass%)	A				0.16	1.17	0.03
	B				0.09	0.08	0.05
	C				0.02	0.05	0
	D	JIS A 5022	-	-	0	0	0
	E	JIS A 5023	-	-	0	0	0.02
	F				0.04	0.02	0
	G				0	0.01	0.03
Total					0.31	1.33	0.13

*1: Sand from Ibi river. *2: Crushed hard sandstone from Kasugai. *3: Crushed limestone from Fujiwara. *4: Classification according to alkali–silica reactivity, as specified in JIS A 5308 Annex A. *5: Classified as “A” because it was determined to be harmless based on the alkali–silica reactivity test (JIS A 1145). *6: Classified as “B” because the samples were not subjected to the alkali–silica reactivity test.

3.2 Mix proportions

Table 7 lists the mix proportions of the 41 concrete samples prepared using the different types of cement, normal coarse aggregate, and recycled coarse aggregate. In addition, three water–binder ratios (W/B) were considered (i.e., 45%, 55%, and 65%) along with three replacement ratios for the recycled coarse aggregate (i.e., 0%, 50%, and 100%). These replacement ratios were selected based on JASS 5, which specifies an upper limit of 50% for RLG when used in structural members [19], whereas a replacement ratio of 100% is assumed for RMG in structural applications. However, concrete using LG was tested with recycled aggregate replacement ratios of 0% and 50%, and W/B of 45%, 55%, and 65% to evaluate the influence of different kinds of normal coarse aggregates with RAC. Concrete using BB cement was tested with RG replacement ratios of 0%, 50%, and 100% and only W/B of 55% to assess the effects of the cement and replacement ratio. Because E exhibits properties similar to N, concrete using E had RG replacement ratios of 0% and 50% with W/B of 55% only. The mix proportion for RAC involved replacing only the recycled coarse aggregate in the mix proportion of the normal concrete under the same conditions (i.e., W/B, s/a, quantity of material per unit volume of concrete). This explains the presence of –1 (e.g., NNSNG-55-1) and –2 (e.g., NNSNG-55-2) for some test samples of the normal concrete.

The target slump of the concrete samples was set to 18 ± 2.5 cm, and the target air content was set to $4.5\% \pm 1.5\%$. The chemical admixtures included an air-entraining and water-reducing admixture made from modified lignin sulfonate compound and polycarboxylic acid compound complex added at 1.0% of the cement mass and an air-entraining admixture made from a resin-based anionic surfactant added at 0.05%–0.10% of the cement mass. The unit water contents of FB and BB were reduced

Table 7 Mix proportions

Sample	Cement type	Replacement ratio of RG	W/B (%)	s/a (%)	Unit weight (kg/m ³)			NG	LG	RLG ₁	RLG ₂	RMG					
					W	C	NS										
NNSNG-45	N	0	45	43.1	185	411	715	968	-	-	-	-					
NNSNGRLG ₁ 50-45		50						484	-	446	-	-					
NNSNG-55-1		0		45.8				798	968	-	-	-	-				
NNSNG-55-2				44.3				782	1006	-	-	-	-				
NNSNGRLG ₁ 50-55		50	55	45.8	180	327	798	484	-	446	-	-					
NNSNGRLG ₂ 50-55				44.3			782	503	-	-	440	-					
NNSRLG ₁ 100-55		100	45.8	798	-	-	892	-	-								
NNSRLG ₂ 100-55			44.3	782	-	-	-	879	-								
NNSNG-65		0	65	48.3	176	271	868	952	-	-	-	-					
NNSNGRLG ₁ 50-65		50						476	-	439	-	-					
NNSLG-45		N	0	45	41.1	181	402	689	-	1030	-	-	-				
NNSLGRLG ₁ 50-45			50						-	514	467	-	-				
NNSLG-55			0		55				43.3	180	327	754	-	1030	-	-	-
NNSLGRLG ₁ 50-55			50										-	514	467	-	-
NNSLG-65			0	65	45.9	176	271	824	-	1013	-	-	-				
NNSLGRLG ₁ 50-65			50						-	506	459	-	-				
NNSNG-45	FB	0	45	38.8	185	441	642	1010	-	-	-	-					
NNSNGRMG50-45		50						506	-	-	-	486					
NNSNG-55		0						1044	-	-	-	-					
NNSNGRMG50-55		50	55	39.7	180	327	692	522	-	-	-	502					
NNSRMG100-55		100						-	-	-	-	1004					
NNSNG-65		0	65	43.4	176	271	780	1010	-	-	-	-					
NNSNGRMG50-65		50						506	-	-	-	486					
FBNSNG-45	FB	0	45	43.7	176	391	733	968	-	-	-	-					
FBNSNGRLG ₁ 50-45		50						484	-	446	-	-					
FBNSRLG ₁ 100-45		100						-	-	892	-	-					
FBNSNG-55-1		0		46.4				816	-	-	-	-	-				
FBNSNG-55-2				44.9				803	1006	-	-	-	-				
FBNSNGRLG ₁ 50-55		50	55	46.4	171	311	816	484	-	446	-	-					
FBNSNGRLG ₂ 50-55				44.9			803	503	-	-	440	-					
FBNSRLG ₁ 100-55		100	46.4	816	-	-	892	-	-								
FBNSNG-65		0	952	-	-	-	-										
FBNSNGRLG ₁ 50-65		50	65	48.7	169	260	881	476	-	439	-	-					
FBNSRLG ₁ 100-65		100						-	-	877	-	-					
BBNSNG-55-1	BB	0	55	46.3	173	315	813	968	-	-	-	-					
BBNSNG-55-2				44.9			801	1006	-	-	-	-					
BBNSNGRLG ₁ 50-55		50		46.3			484	-	446	-	-						
BBNSNGRLG ₂ 50-55				44.9			801	503	-	440	-						
BBNSRLG ₁ 100-55		100		46.3			813	-	-	892	-	-					
ENSNG-55	E	0	55	45.8	180	327	795	968	-	-	-	-					
ENSNGRLG ₁ 50-55		50						484	-	446	-	-					

by -5% and -4%, respectively, relative to N in accordance with recommendations from the AIJ [5].

3.3 Methods

Table 8 summarizes the properties measured for the concrete samples and the test methods. The slump, air content, density, concrete temperature, and chloride ion content were measured for fresh samples. The chloride ion content was calculated as the equation (1).

Table 8 Test items and methods

Item		Method	Note
Fresh properties	Slump	JIS A 1101	
	Air content	JIS A 1128	
	Density	JIS A 1116	-
	Concrete temperature	JIS A 1156	
	Chloride ion content	Normal concrete JASS 5 T-502	Ion-selective electrode method
		RAC and RAC used E JIS A 5022, JIS A 5023	Calculated using Equation (1)
Hardened properties	Compressive strength	JIS A 1108	At 4 and 13 weeks
	Static modulus of elasticity	JIS A 1149	
	Length change rate (drying shrinkage)	JIS A 1129-3	-
	Accelerated carbonation	JIS A 1153	-
	Freezing and thawing	JIS A 1148	Method A

$$C_0 = \frac{C_1 \times W_1}{100} + \frac{3}{4} \times \frac{C_L \times W_L}{100} + \frac{1}{4} \times \frac{C_H \times W_H}{100} + \frac{3}{4} \times \frac{C_M \times W_M}{100} + \alpha \times \frac{C_2 \times W_2}{100} \quad (1)$$

C_0 is the chloride ion content of RAC Class M or RAC Class L (kg/m^3),

C_1 is the chloride ion content of fresh concrete (%),

W_1 is the unit water content specified in the mix proportion (kg/m^3),

C_L is the chloride ion content of RA Class L (%) $\times 0.607^*$,

W_L is the amount of RA Class L used in the mix proportion (kg/m^3),

C_H is the chloride ion content in RA Class H (%) $\times 0.607^*$,

W_H is the amount of RA Class H used in the mix proportion (kg/m^3),

C_M is the chloride ion content in RA Class M (%) $\times 0.607^*$,

W_M is the amount of RA Class M used in the mix proportion (kg/m^3),

α is the chloride-ion residual rate from JIS R 5214 (0 except for E),

C_2 is the chloride ion content in E (%), and W_2 is the unit cement content specified in the mix proportion (kg/m^3).

*The coefficient of 0.607 was selected to converting NaCl to the Cl equivalent:

$0.607 = \text{Cl molecular weight (35.45)} \div \text{NaCl molecular weight (58.44)}$.

The compressive strength, static modulus of elasticity, length change (drying shrinkage), accelerated carbonation depth, and durability factor were measured for the hardened samples. Concrete samples were prepared by following JIS A 1138, and hardened concrete samples were prepared by following JIS A 1132. Cylindrical samples with a diameter of 100 mm and height of 200 mm were used to test the compressive strength and static modulus of elasticity. After demolding the next day, the samples were cured under standard conditions until the prescribed age was reached. Six samples were tested for each age (28, 91 days), and the average value was recorded. The static modulus of elasticity was measured by using a

compressometer. Three samples with dimensions of 100 mm × 100 mm × 400 mm were used for the drying shrinkage, accelerated carbonation, and freezing and thawing tests. Three samples were used for each test, and the average value was recorded.

For the drying shrinkage test, the samples were kept moist in a room at $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$. After demolding, they were cured under standard conditions for 7 days and were then stored in a humidity chamber at a constant temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and relative humidity of $60\% \pm 5\%$ until the prescribed age was reached for measurement.

For the accelerated carbonation tests, after demolding the samples were placed in water at a temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 4 weeks. They were then kept in a humidity chamber at a constant temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and relative humidity of $60\% \pm 5\%$ for another 4 weeks. The accelerated carbonation test was conducted under the conditions of a temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$, relative humidity of $60\% \pm 5\%$, and CO_2 concentration of $5\% \pm 0.2\%$.

For the freezing and thawing tests, samples were demolded, cured under standard conditions until 4 weeks of age, and then subjected to freezing and thawing cycles until the prescribed age for measurements.

4. Results

4.1 Fresh properties

Table 9 summarizes the fresh properties of the concrete samples.

4.1.1. Slump and air content

FBNSRLG₁100–65 (W/B: 65%, cement: FB, RLG₁ replacement ratio: 100%) had a slump of 10.5 cm, which was substantially below the target value. Thus, the type and volume of chemical admixture needed to be adjusted in this case. For all other samples, the target values for the slump and air content were satisfied. The aggregate modification factor was 0.4%–0.5% at the 50% replacement ratio and 0.6% at the 100% replacement ratio for RLG. The aggregate modification factor was 0.3% at the 50% replacement ratio and 0.5% at the 100% replacement ratio for RMG.

4.1.2. Density

The density of RAC tended to decrease as the RG replacement ratio increased. This is because RG had a lower density than the normal coarse aggregate owing to the adhesion of original mortar or cement paste.

4.1.3. Concrete temperature

Samples were prepared according to JIS A 1138 from mid-July to mid-December of the following year. The concrete temperatures varied because mixing was partially conducted outdoors. However, all samples had temperatures of 8.4°C – 30.1°C and thus stayed below 35°C . The RG replacement ratio had no effect on the concrete temperature.

4.1.4. Chloride ion content

As per JIS A 5022 and JIS A 5023, the chloride ion content was calculated under the assumption that 25% of the total chloride ion content of RMG and RLG in addition to 100% of the chloride ion content of the cement would leach into water. The results demonstrated that the chloride ion content of all samples satisfied the limit of 0.30 kg/m^3 set by JIS A 5308 although it increased with the replacement ratio.

4.2 Hardened properties

4.2.1. Compressive strength

Figure 3 illustrates the compressive strengths of the concrete samples. For samples using RLG₁, the compressive strength tended to decrease as the replacement ratio increased. The type of cement influenced the development of the compressive strength: FB and BB resulted in greater long-term strength than N whereas E had nearly equal strength [19]. With N, the 4-week compressive strength tended to decrease as the replacement ratio increased. With FB, the 13-week compressive

Table 9 Fresh properties of concrete samples^{*1}

Sample	Slump (cm)	Air content ^{*2} (%)	Density (kg/m ³)	Temperature (°C)	Chloride ion content (kg/m ³) ^{*3}
NNSNG-45	20.5	5.6	2263	18.0	0.07
NNSNGRLG ₁ 50-45	19.0	5.0 (0.4)	2230	17.4	0.13 (0.035)
NNSNG-55-1	20.0	5.4	2244	18.6	0.05
NNSNG-55-2	20.5	5.5	2397	25.9	0.02
NNSNGRLG ₁ 50-55	20.5	4.9 (0.5)	2260	18.8	0.12 (0.031)
NNSNGRLG ₂ 50-55	20.5	4.3 (0.7)	2299	22.6	0.09 (0.026)
NNSRLG ₁ 100-55	20.0	4.5 (0.6)	2180	18.2	0.18 (0.033)
NNSRLG ₂ 100-55	19.5	5.3 (0.7)	2173	22.8	0.14 (0.031)
NNSNG-65	20.0	4.4	2261	18.7	0.03
NNSNGRLG ₁ 50-65	17.5	5.2 (0.4)	2180	18.6	0.09 (0.018)
NNSLG-45	20.5	4.0	2214	12.5	0.03
NNSLGRLG ₁ 50-45	20.5	5.1 (0.4)	2199	12.7	0.07 (0.003)
NNSLG-55	20.5	4.4	2343	20.0	0.05
NNSLGRLG ₁ 50-55	20.0	4.9 (0.5)	2261	20.2	0.12 (0.032)
NNSLG-65	20.0	5.3	2306	18.5	0.04
NNSLGRLG ₁ 50-65	20.0	4.9 (0.5)	2273	14.2	0.09 (0.014)
NNSNG-45	20.5	5.6	2286	23.8	0.08
NNSNGRMG50-45	19.5	4.4 (0.3)	2290	24.2	0.07 (0.039)
NNSNG-55	20.5	5.9	2274	26.6	0.03
NNSNGRMG50-55	20.0	5.2, 5.6 (0.3)	2225, 2240	23.0, 23.3	0.05 (0.028)
NNSRMG100-55	19.0, 19.5	4.0, 5.3 (0.5)	2254, 2280	24.4, 24.9	0.05 (0.025)
NNSNG-65	20.0	5.8	2230	23.7	0.04
NNSNGRMG50-65	18.0	5.1, 5.2 (0.3)	2247, 2307	23.5, 23.6	0.06 (0.034)
FBNSNG-45	20.0	3.6	2377	28.2	0.03
FBNSNGRLG ₁ 50-45	20.0	4.5 (0.4)	2274	21.1	0.06 (0.003)
FBNSRLG ₁ 100-45	18.0	3.7 (0.6)	2289	20.5	0.12 (0.013)
FBNSNG-55-1	17.0, 18.0	3.3, 5.8	2300, 2376	24.9	0.03
FBNSNG-55-2	20.5	5.2	2371	25.3	0.01
FBNSNGRLG ₁ 50-55	16.0	3.3 (0.4)	2310	22.1	0.06 (0.004)
FBNSNGRLG ₂ 50-55	20.5	4.6 (0.6)	2310	19.2	0.06 (0.013)
FBNSRLG ₁ 100-55	18.5	3.8 (0.6)	2243	22.3	0.12 (0.007)
FBNSNG-65	18.5	4.0	2351	19.3	0.03
FBNSNGRLG ₁ 50-65	16.5	4.2 (0.4)	2279	20.8	0.06 (0.004)
FBNSRLG ₁ 100-65	10.5	4.4 (0.6)	2223	19.7	0.12 (0.004)
BBNSNG-55-1	18.0, 19.0	5.9, 6.0	2281, 2289	26.1, 26.7	0.04
BBNSNG-55-2	19.5	4.4	2340	25.4	0.02
BBNSNGRLG ₁ 50-55	18.0	4.5 (0.4)	2243	20.4	0.06 (0.016)
BBNSNGRLG ₂ 50-55	19.0	5.2 (0.4)	2350	24.8	0.06 (0.012)
BBNSRLG ₁ 100-55	17.0	5.1 (0.6)	2244	22.3	0.12 (0.020)
ENSNG-55	18.5, 19.5	5.8, 5.9	2200, 2287	27.1	0.10
ENSNGRLG ₁ 50-55	19.5	4.8 (0.4)	2236	14.1	0.14 (0.026)

*1 Including cases where measurements were performed twice simultaneously.

*2 Aggregate correction factor is provided in brackets. Further, it is omitted if the threshold is less than 0.1%.

*3 The value in brackets indicates the value of C_1 in Equation (1).

strength exceeded 50 N/mm² for all samples with a W/B of 45%. However, at W/B of $\geq 55\%$, the effect of the replacement ratio was subtle. With BB, the 13-week compressive strength decreased as the replacement ratio was increased although only at a W/B of 55%. A similar trend was observed with E regarding the 4-week compressive strength.

For samples using LG as the normal coarse aggregate, the effect of the replacement ratio was unclear because the compressive strength was less than 50 N/mm² even at a W/B of 45%. These results may have been influenced by the coarse aggregate strength [23]. The replacement ratio had no effect on the 4- and 13-week compressive strengths of concrete samples using RMG.

4.2.2. Static modulus of elasticity

Figure 3 shows that the replacement ratio affected the static modulus of elasticity for concrete samples using RLG₁, particularly at 13 weeks for samples using FB and BB as the cement and at 4 weeks for samples using E and N as the cement. The replacement ratio barely affected the static modulus of elasticity of concrete samples using RMG. Between the normal coarse aggregates, the static modulus of elasticity tended to be higher with LG than with NG when N was used as the binder, which agrees with previous results [19]. These results indicate that mixing LG with RLG effectively improves the static modulus of elasticity of RAC. The static modulus of elasticity (Young's modulus) can be evaluated by using the following equation (2) from JASS 5 [19]:

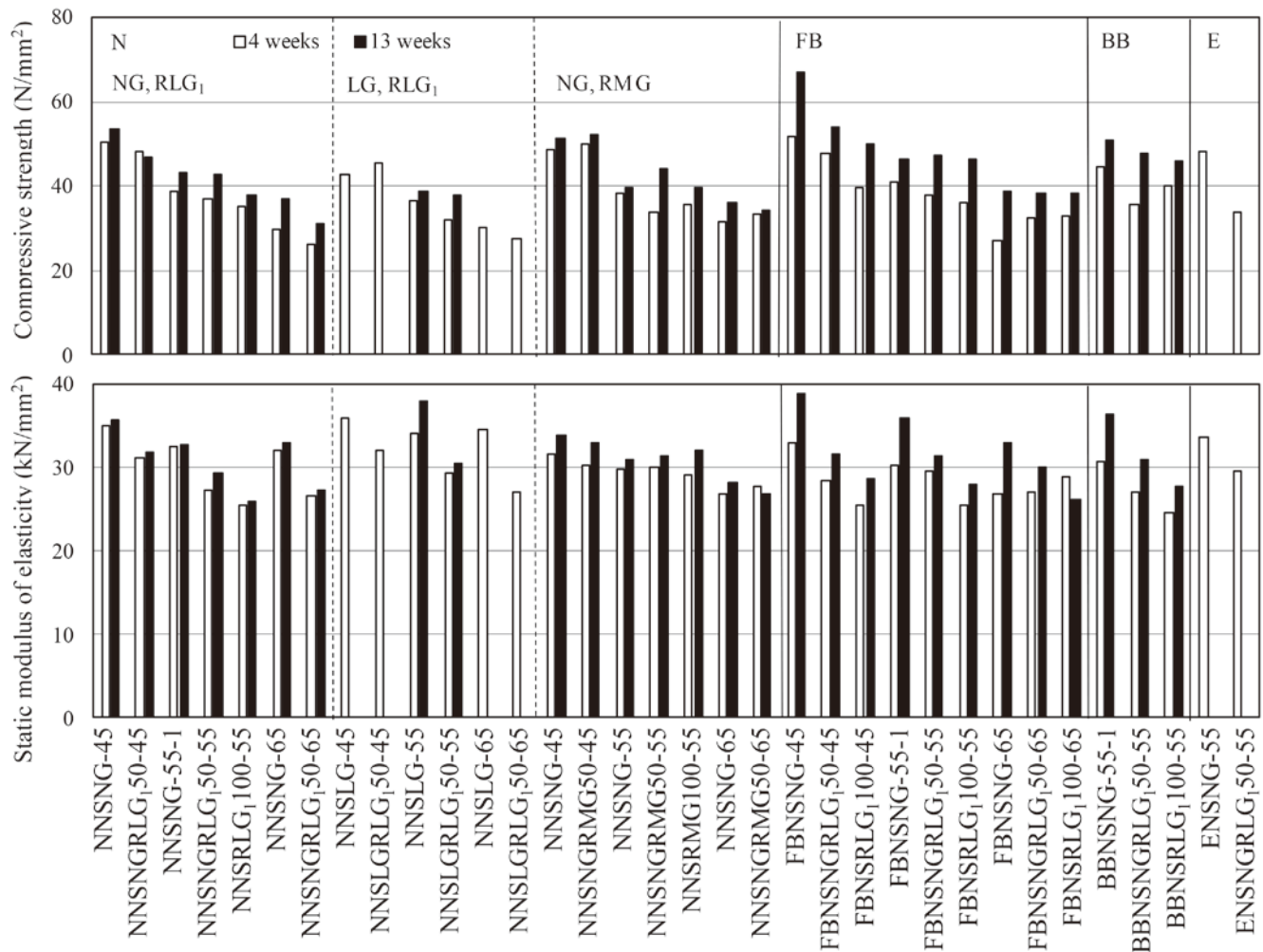


Fig. 3 Compressive strength and static modulus of elasticity of concrete samples

$$E = k_1 \times k_2 \times 3.35 \times 10^4 \times \left(\frac{\gamma}{2.4} \right)^2 \times \left(\frac{\sigma_B}{60} \right)^{1/3} \quad (2)$$

where

E is the Young's modulus (N/mm^2),

k_1 is the modification factor determined by the type of coarse aggregate (1.2 for LG, 1.0 for NG, and 1.0 for no admixture),

k_2 is the modification factor determined by the type of admixture (1.1 for FA (FB), 0.95 for GGBFS (BB), and 1.0 for no admixture (N, E)),

γ is the density of concrete (t/m^3),

σ_B is the compressive strength of concrete (N/mm^2), and B is the concrete age (4 weeks).

The accuracy of this equation is reported to be within $\pm 20\%$ of the actual value. The air-dry density of the concrete was measured from samples used for drying shrinkage after 3 months (i.e., 13 weeks) of storage.

Figure 4 illustrates the relationship between the compressive strength and Young's modulus for the concrete samples according to the coarse aggregate type, cement type, and replacement ratio. The measured static modulus of elasticity was within -10% to $+22\%$ of the value estimated from equation (2) except for NNSNG-65, which was within $+31\%$. Overall, however, the values were generally within $\pm 20\%$, which corresponds with expectations [19].

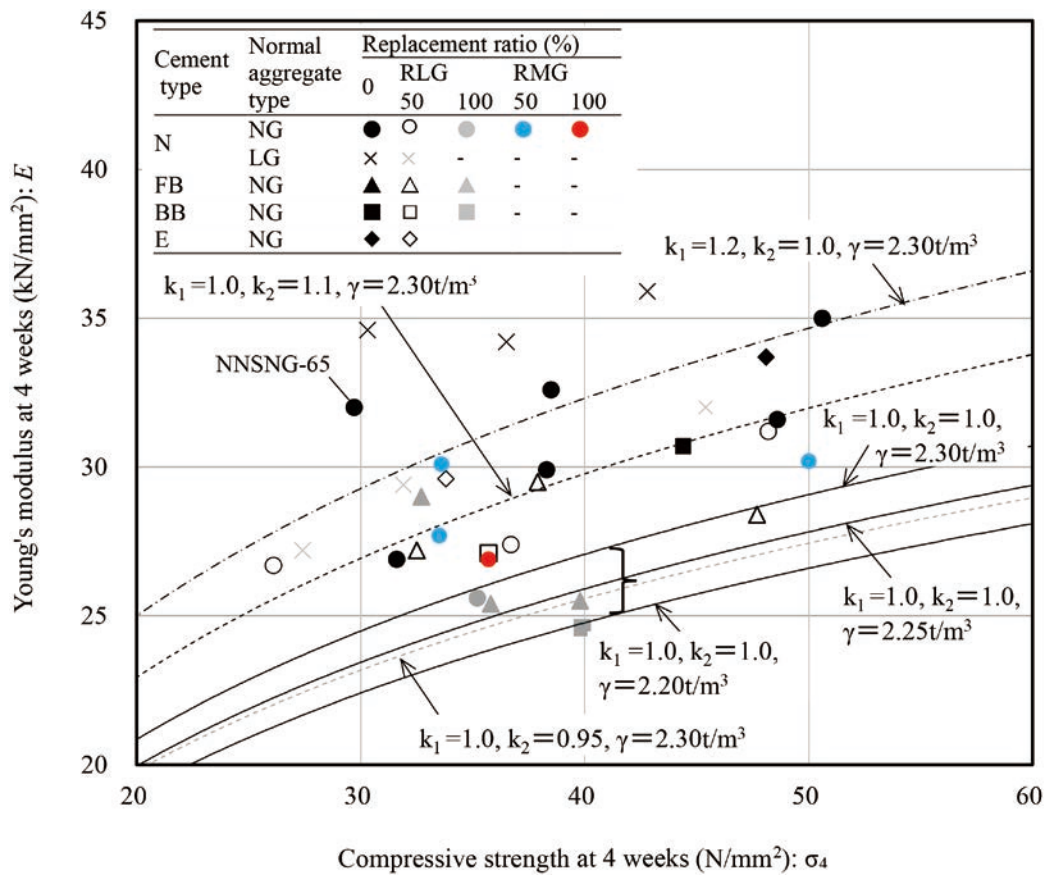


Fig. 4 Relationship between the compressive strength and Young's modulus

4.2.3. Drying shrinkage

Figure 5 shows that the replacement ratio affected the drying shrinkage of concrete samples using RLG₁. BBNSNGRLG₁50-55 and NNSRLG₁100-55 both exceeded the target value of 8×10^{-4} set by JASS 5 [19]. Conversely, the

replacement ratio had little effect on the drying shrinkage of concrete samples using RMG, which remained at $<8 \times 10^{-4}$ even at a 100% replacement ratio. When RLG_1 was mixed with LG, the maximum drying shrinkage was 6×10^{-4} even at a replacement ratio of 50%. This may be because concrete using crushed limestone generally has little drying shrinkage [24]. When comparing $NNSNGRLG_{1,50-45}$ and $NNSLGR LG_{1,50-45}$ with a W/B of 45% and a high-water content per unit volume at N, the study obtained reductions of approximately 2×10^{-4} . Overall, the effect of the cement type was unclear. However, concrete samples using W/B of 55% and 100% replacement ratio for RLG_1 with different types of cement ($NNSRLG_{1,100-55}$, $FBNSRLG_{1,100-55}$, and $BBNSRLG_{1,100-55}$) had drying shrinkages of 10×10^{-4} , 8×10^{-4} , and 8×10^{-4} , respectively. These concrete samples had water contents per unit volumes of 180, 171, and 173 kg/m^3 , respectively, which suggests that the reduced water content per unit volume owing to the use of blended cement influenced the drying shrinkage.

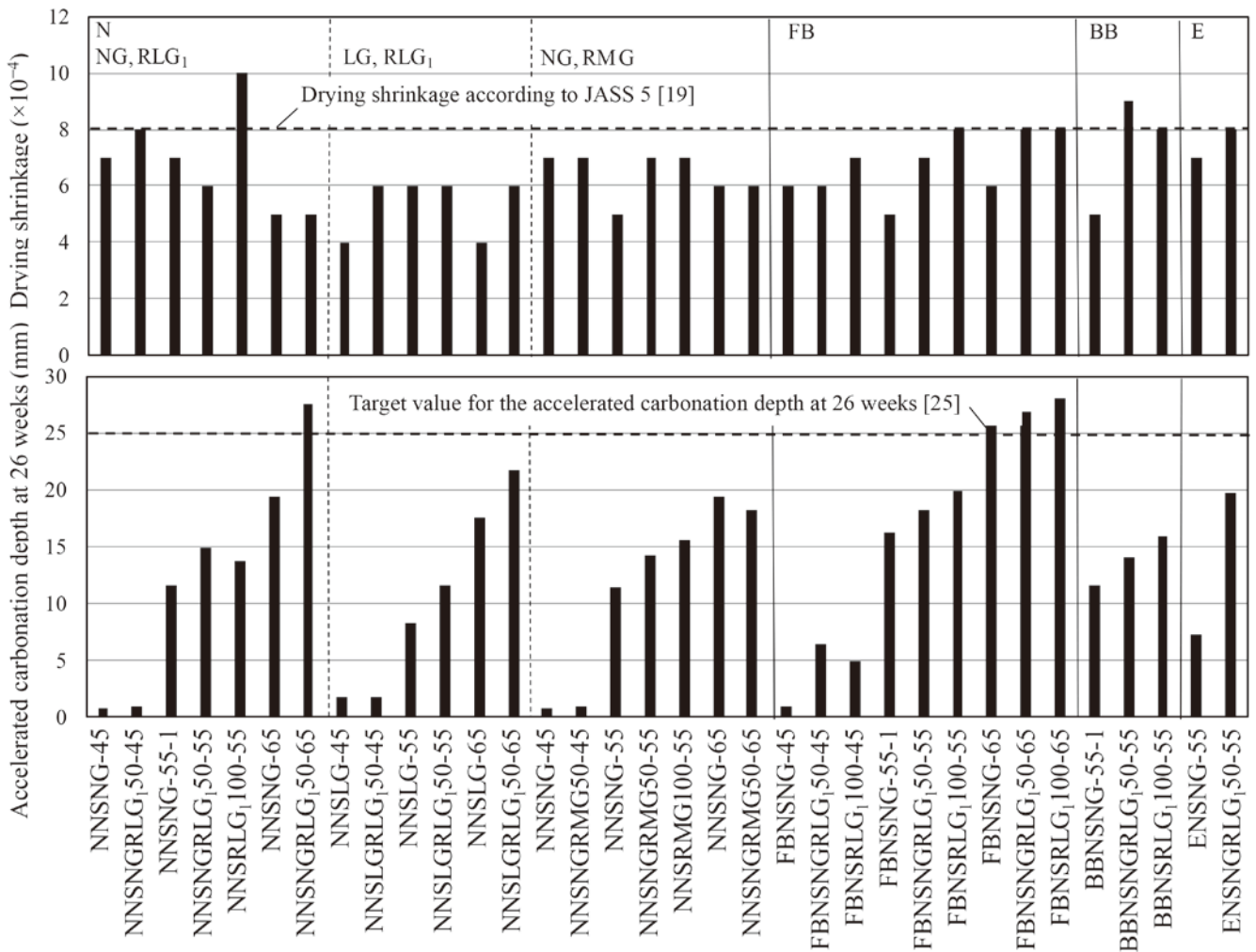


Fig. 5 Drying shrinkage and accelerated carbonation depth of concrete samples

4.2.4. Accelerated carbonation

Figure 5 shows that the accelerated carbonation depth was most affected by the W/B with little progress at W/B of 45%. However, at W/B of 65%, $NNSNGRLG_{1,50-65}$ exceeded the target of <25 mm for highly durable concrete [25]. The replacement ratio clearly affected the accelerated carbonation depth in concrete samples using RLG_1 and with a W/B of $\geq 55\%$. The W/B affected the accelerated carbon depth in concrete samples using RMG, but the effect of the replacement ratio was less evident at W/B of $\geq 55\%$ W/B. Among cement types, the accelerated carbonation depth increased with FB, which agrees with previous results [26].

Figure 6 shows the relationship between the compressive strength of concrete samples and the accelerated carbonation

depth. A strong correlation was observed for all cement types, which indicates that the target quality can be achieved by increasing the compressive strength (i.e., by reducing the W/B). However, BB was used as a reference because of the scarcity of samples.

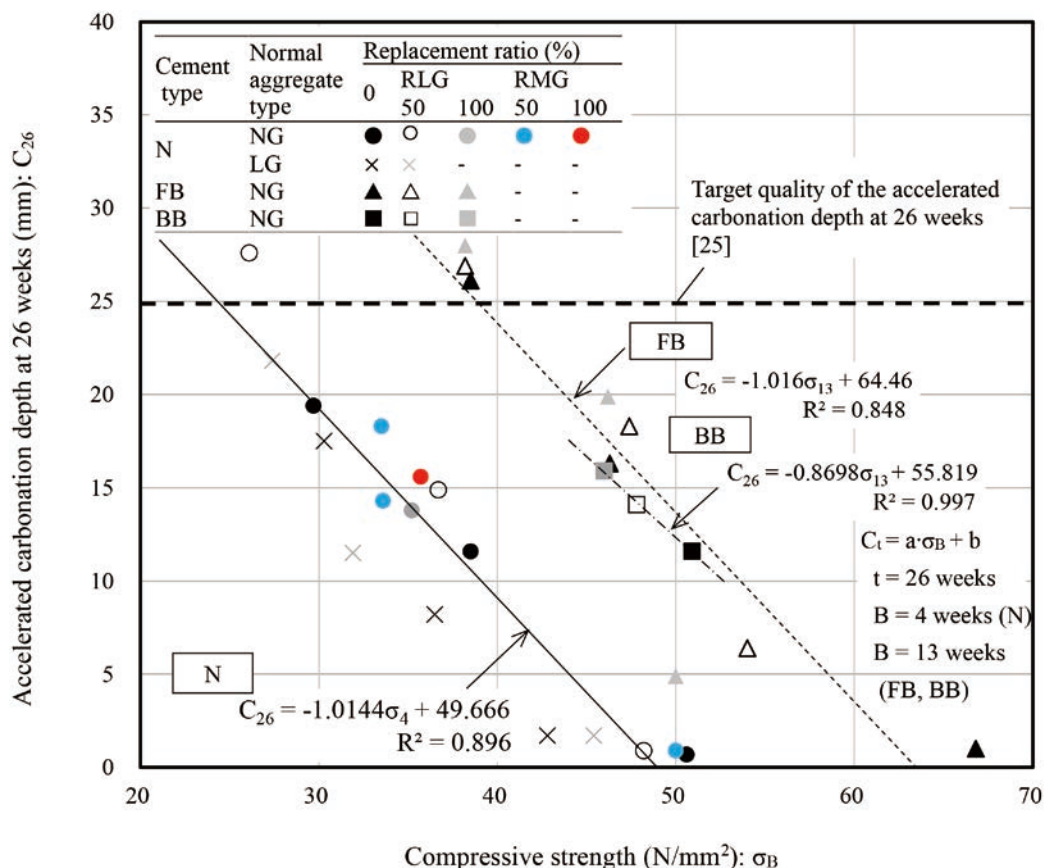


Fig. 6 Relationship between compressive strength and accelerated carbonation depth

4.2.5. Freezing and thawing resistance

Figure 7 shows the relationship between the air content of fresh concrete and its durability factor. The durability factor was >85 regardless of the RA replacement ratio and cement type as long as the air content was within 4.0%–6.0%, which complies with the requirements of JASS 5 [19] for concrete subjected to severe freezing and thawing action. However, the durability factor of RAC is influenced by multiple factors, including the type of original aggregate, air content, W/B manufacturing method of the original concrete, and the crushing method [27]. Further evaluation according to JIS A 5022 Annex D is required to confirm these effects.

4.2.6. Total evaluation

Table 10 presents the relationship between the performance requirements and materials employed according to the mix proportion. The results indicate that the performance of RAC can be elevated by optimizing the replacement ratio of RG and selecting appropriate materials as the cement and normal coarse aggregate while adjusting the mix proportion in terms of the W/B, air content, and water content per unit volume.

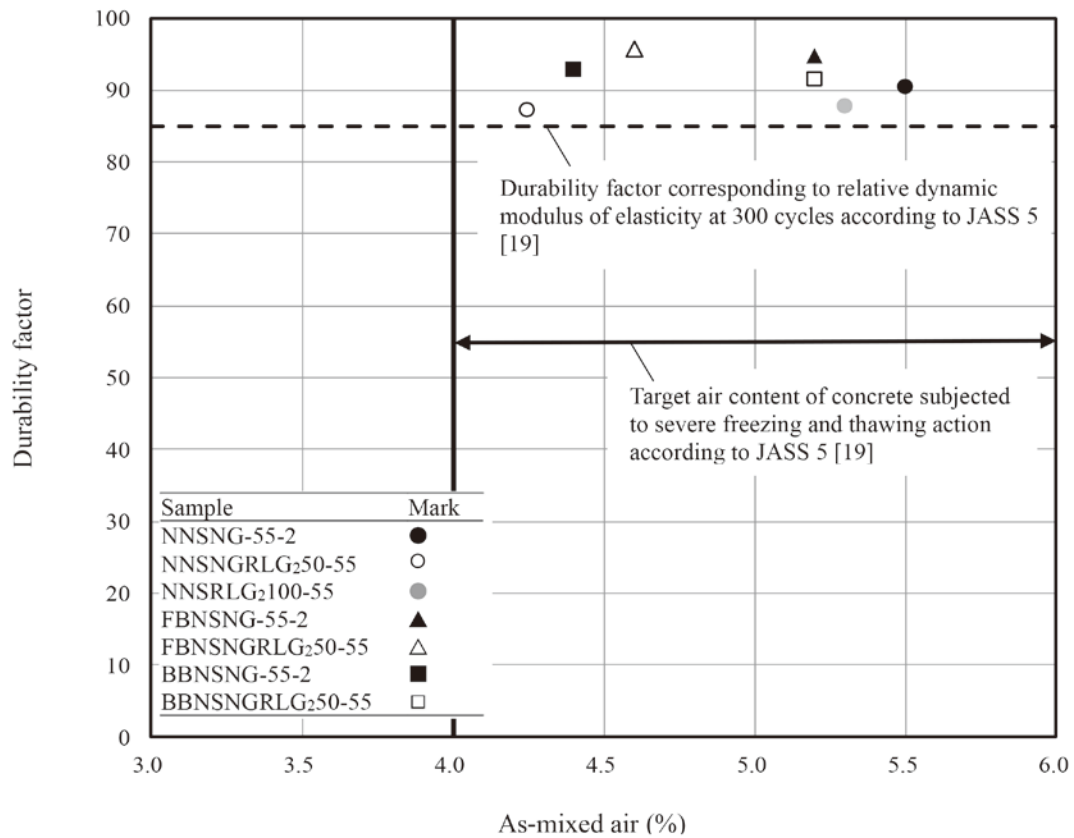


Fig. 7 Relationship between the as-mixed air content and durability factor

Table 10 Relationship between performance requirements and materials used^{*1}

Performance requirement	Cement			Coarse aggregate		Mix Proportion			
	N, E	FB	BB	NG	LG	W/B	Air content	Water ^{*2}	Replacement ratio of RAC
Increase compressive strength	●			●					●
Increase long-term compressive strength		●	●						
Increase static modulus of elasticity					●				●
Suppress drying shrinkage					●			○	●
Suppress carbonation resistance					●	●			●
Improve freezing and thawing resistance							●		

*1 ● : factors contributing to performance improvement. ○ : factors contributing to performance degradation. *2 Water content per unit volume of concrete

4. Conclusions

The aim of this study was to develop a simplified manufacturing method that promotes the use of RG and environmentally friendly cements to produce concrete with excellent resource recyclability and economic efficiency. To simplify the improvement of RAC Class M, general-purpose cements and aggregates were used instead of SCMs. The following conclusions were obtained:

(1) The slump and air content of RAC samples using RLG and RMG mostly satisfied the target values, regardless of the cement type and replacement ratio. The density of RAC tended to decrease with increasing replacement ratio, which can be attributed to the lower density of RG due to the adhesion of original mortar or cement paste. The RG replacement ratio had

no significant effect on the concrete temperature, and the chloride ion contents of the RAC samples satisfied the limit of 0.30 kg/m³.

(2) The replacement ratio influenced the compressive strength of RAC samples using RLG but had no effect on samples using RMG. The cement type influenced the development trend of compressive strength. The static modulus of elasticity decreased with increasing replacement ratio when more RLG was used. These results indicate that mixing crushed limestone with RG is effective for improving the static modulus of elasticity.

(3) The replacement ratio had a greater influence on the drying shrinkage when RLG was used. The drying shrinkage can be reduced by mixing RG with crushed limestone. It can also be reduced by lowering the water content per unit volume, which can be achieved by using blended cement.

(4) The replacement ratio influenced carbonation when RLG was used. Carbonation was also accelerated when FB was used as the cement type. The influence of the W/B was dominant, and the target quality could be achieved by reducing the W/B even at high replacement ratios.

(5) When the air content of the as-mixed fresh concrete was within a suitable range, the durability factor was >85, regardless of the RG replacement ratio and cement type. However, multiple factors influence the durability factor of RAC, including the type of original aggregate, air content, W/B, manufacturing method of the original concrete, and the crushing method. Further evaluation according to JIS A 5022 Annex D is necessary to confirm these effects.

These results indicate that replacement with RMG had almost no effect on the concrete performance, whereas replacement with RLG degraded the concrete performance. However, the performance of RAC using RLG can be enhanced by applying the same approach used to optimize the performance of normal concrete, such as selecting the appropriate cement type and normal coarse aggregate and adjusting the mix proportion to modify the W/B, air content, and water content per unit volume.

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Conflicts of interest

The authors declare no conflict of interest.

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