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Research Paper

Dissemination of technic for concrete using low-quality recycled aggregate to achieve a sustainable environment: examination on design method and validity of recycled aggregate concrete

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ABSTRACT

Many resources are used in the concrete-related sector to construct civil engineering buildings. Therefore, using the various by-products for resource circulation throughout the lifecycle of the concrete-related sector is critical to building a sustainable society. This study focuses on resource recycling, low carbon emissions, and environmental safety as means to building a sustainable environment in order to reinforce concrete works, particularly in civil engineering buildings. It also presents the examination results of the design method and validity for the active use of low-quality recycled aggregate concrete to decrease waste generation, reduce CO₂ emissions, and ensure environmental safety. Consequently, it was confirmed that the water–cement ratio could be set on the basis of safety reasons for the production of recycled aggregate concrete-Class M using the aggregate replacement method at all ready-mixed concrete factories. This was achieved by employing the strength reduction ratio obtained from the difference between the relative water absorption of normal-weight concrete and that of recycled aggregate concrete.

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1 Introduction

Many resources are used in the concrete-related sector to construct civil engineering buildings. Therefore, the use of various by-products for resource circulation throughout the lifecycle of the concrete-related sector is critical for building a sustainable society.

Demolition concrete wastes are used as roadbed and backfill materials, as well as recycled aggregate in some cases. This not only conserves natural resources but also reduces the total amount of waste disposal. However, there are concerns about the appropriate reuse of demolition concrete waste and the more effective use of by-products discharged from other

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industries. Further efforts are required to address these issues and build a resource recycling system.

Based on the verification of the reduction effect of greenhouse gas emissions during the first commitment period of the Kyoto Protocol, new countermeasures are required to be promoted globally at this stage with regard to lower carbon dioxide (CO₂) emissions. The Paris Agreement, adopted in 2015, sets a goal to limit the increasing global average temperature to less than 2°C; all countries that have ratified the agreement are obligated to create and submit CO₂ emission reduction targets and take measures to achieve them.

For environmental safety, buildings must be free of hazardous amounts of heavy metals and other toxic chemicals during their planned service life. As part of the efforts to achieve a sustainable environment aimed at reinforced concrete or concrete works in civil engineering buildings, this study reduces waste generation and CO₂ emissions, as well as ensures environmental safety. It also presents the examination results on the design method and validity for the active use of concrete using low-quality recycled aggregate (recycled aggregate class L).

2 The use of recycled aggregate concrete

Currently, concrete waste is used almost entirely as roadbed gravel, such as RC-40 (recycled crusher run 0 to 40 mm); however, the demand for roadbed gravel is not expected to increase due to a decline in the construction of new roads [1]. To offset the expected increase in the generation of this waste with newer construction projects, alternative uses of concrete waste should be identified. Due to the presence of cement in concrete waste, they contain harmful trace elements, such as hexavalent chromium and lead. These trace elements may leach into the environment when fine mortar grits (diameter ≤ 5 mm), such as recycled fine aggregates and powders, are subjected to wetting [2]. Therefore, reducing the amount of fine powder may help reduce the environmental risks of soil contamination associated with concrete waste recycling.

Recycled aggregate concrete (RAC) prepared using the aggregate replacement method is the most promising alternative material. RAC is manufactured by mixing a certain amount of recycled aggregate class L with normal aggregate, which is affected by the original adhesive mortar or cement paste that contains toxic elements like hexavalent chromium. A survey conducted by the Ministry of Land, Infrastructure, and Transport in 2018 revealed that 74.4 million tonnes of construction waste are produced annually in Japan, most of which are recycled in compliance with the related laws and ordinances. Concrete waste accounts for 36.9 million tonnes of total waste. Although the concrete recycling rate has reached 99.3%, most of the waste is used as roadbed gravel or backfill materials [1]. Therefore, there is a need to develop a high-value recycling method for concrete waste that would improve resource diversion and environmental preservation.

In 2018, the amount of RAC used in Japan was 119,000 tonnes, equivalent to 0.3% of the concrete recycling rate, while the remaining amount was used as roadbed gravel or backfill materials. This amount was approximate twice the 55,000 tonnes recorded in 2012; nevertheless, it is still a small amount. RAC-class H, M and L amounts were 64,000, 50,000 and 5,000 tonnes, respectively. Among them, the amount of RAC-Class M increased by 48,000 tonnes.

In the revision of the Japanese Industrial Standard JIS A 5022 (recycled aggregate concrete-Class M), RAC-Class M (M1 and M2) can be manufactured by mixing a certain amount of recycled aggregate class L, which is smaller than the regulated upper limit of the replacement ratio, with normal aggregates [3]. Accordingly, the negative environmental impact can be decreased by increasing the use of the recycled aggregate class L [4]. Therefore, it is important to promote the use of RAC-Class M.

3 Examination of validation for RAC in manufacturing factory

Based on the evaluation of the impact of recycled aggregate on concrete performance, a normal aggregate could be replaced with recycled aggregate class L while still satisfying the required performance for RAC-Class M. This can be achieved using recycled aggregate class L through the aggregate replacement method. In the mix proportion design for RAC-Class M, the water-cement ratio (W/C) that satisfied the mix proportioning strength was obtained using the W/C equation based on the relationship between cement-water ratio and compressive strength [5] of RAC-Class M. The strength reduction ratio (R) was multiplied with the W/C equation of each manufacturing factory in case recycled aggregate was used. R is calculated using Eq. (1) [6].

$$R = \frac{F_{Re=x}}{F_{Re=0}} = \frac{l + m \times Qat_{Re=x}}{l + m \times Qat_{Re=0}} \quad (1)$$

where, $F_{Re=x}$: compressive strength in case of recycled aggregate replacement ratio is x% (N/mm²);

$F_{Re=0}$: compressive strength in case of recycled aggregate replacement ratio is 0% (normal-weight concrete) (N/mm²);

$Qat_{Re=x}$ and $Qat_{Re=0}$: relative water absorption when the replacement ratio is x% and 0%, respectively (according to Eq. (2)) (%);

l and m : intercept and slope in the relation equation of relative water absorption and compressive strength.

$$Qat = \frac{QvaG \times a + QvaN \times b + QraG \times c + QraN \times d}{a + b + c + d} \quad (2)$$

where, Qat : relative water absorption (%);

$QvaG$: water absorption of normal coarse aggregate (%);

$QvaN$: water absorption of normal fine aggregate (%);

$QraG$: water absorption of recycled coarse aggregate (%);

$QraN$: water absorption of recycled fine aggregate (%);

a, b, c and d : absolute volume of aggregate used (L/m³).

In this study, validation for RAC in manufacturing factories was examined using the relative quality index method with the actual data of RAC-Class H, M and L from 16 ready-mixed concrete factories (16 factories). The recycled aggregate replacement ratio, W/C and quality of the recycled aggregate (water absorption, etc.) were not comparable across the 16 factories examined. Therefore, R was considered below because it was difficult to evaluate R for each W/C, as shown in Eq. (1).

Similar to Eq. (1), R is defined as the ratio of the compressive strength of RAC to normal-weight concrete. Additionally, the compressive strength of normal-weight concrete in this study was assumed to be used for material design; it was a calculated value obtained from the strength equation of normal-weight concrete based on cement-water ratio theory, which was owned by the factories. In the R calculation equation, for each W/C set as an experiment, the compressive strength of normal-weight concrete and RAC were used to calculate R and for evaluation. However, the evaluation method described below was used because the actual data of RAC from the 16 factories were insufficient for the relationship equation between relative water absorption and compressive strength.

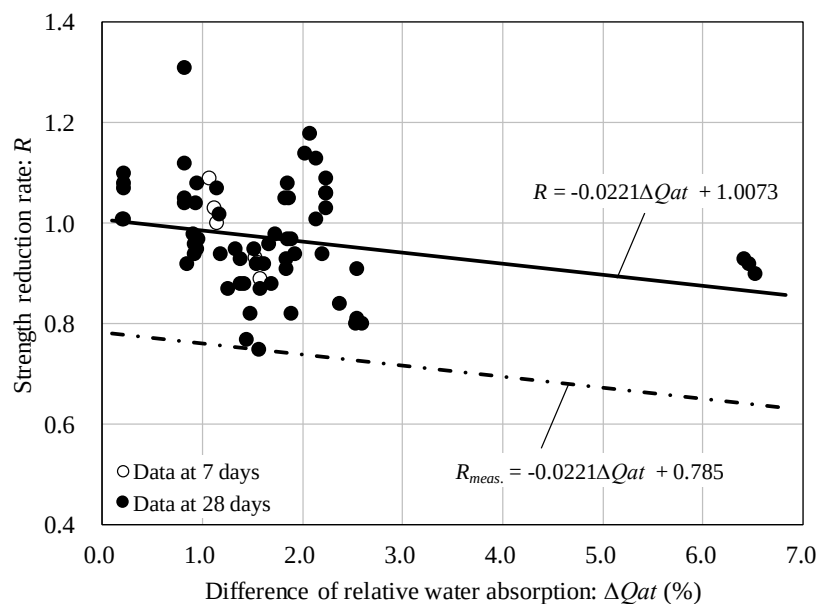


Fig. 1 – Relationship between the difference in relative water absorption ΔQat and the strength reduction rate R .

When the compressive strength of concrete was compared with the same W/C, the strength of RAC was lower than that of normal-weight concrete. This was due to the difference in relative water absorption according to the results of the

aggregate replacement method. Therefore, Eq. (3) was used to calculate the difference between the relative water absorption of RAC and that of normal-weight concrete.

$$\Delta Qat = Qat_{Re=x} - Qat_{Re=0} \quad (3)$$

where, ΔQat : difference in relative water absorption (%);

$Qat_{Re=x}$: relative water absorption when the replacement ratio is x% (%);

$Qat_{Re=0}$: relative water absorption when the replacement ratio is 0% (relative water absorption of normal-weight concrete) (%).

R was also calculated using Eq. (4) for safety reasons ($R_{meas.}$).

$$R_{meas.} = p + q \times \Delta Qat = \frac{F_{Re=x}}{F_{Re=0}} \quad (4)$$

where, $R_{meas.}$: strength reduction ratio;

ΔQat : difference in relative water absorption (%);

p and q : constants that were set appropriately;

$F_{Re=x}$: actual compressive strength in case of recycled aggregate replacement ratio is x% (N/mm²);

$F_{Re=0}$: calculated compressive strength in case of recycled aggregate replacement ratio is 0% (normal-weight concrete) (N/mm²).

Tables 1 and 2 depict the data of actual mixed concrete and the calculated compressive strength at 28 days of RAC. Additionally, the O and P factories in Table 2 are added compressive strength data at 7 days. Further, as in a study by author [6], the factories L, O and P in this study were marked as A, B and C in that previous study, respectively.

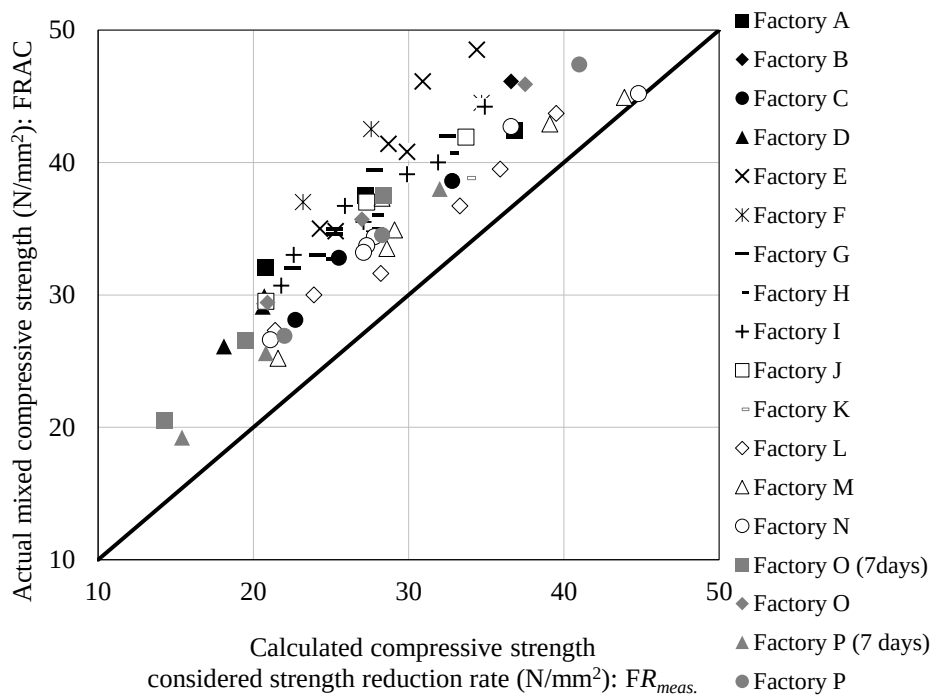


Fig. 2 – Relationship between calculated compressive strength considering the strength reduction rate and compressive strength of actual mixed concrete.

The compressive strength at a replacement rate of 0% was obtained from the W/C equation of normal-weight concrete at each factory. Fig.1 shows the relationship between the difference in relative water absorption (ΔQat) and R . Accordingly, constants p and q were chosen as follows for the safety evaluation of all data.

$$p = 0.785$$

$$q = -0.0221$$

ΔQat was based on the data of actual mixed concrete from each factory, which was employed in Eq. (4) to calculate the $R_{meas.}$ used in this examination. The compressive strength of concrete was then calculated by multiplying $R_{meas.}$ by 0% of the replacement ratio (W/C equation of normal-weight concrete in each factory) to calculate the compressive strength. Fig. 2 shows the relationship between the calculated compressive strength using the aggregate replacement method and the compressive strength of actual mixed concrete. The compressive strength of the actual mixed concrete was all within the safe zone (above the line). Therefore, it was confirmed that it is possible to set a W/C that is within the safe zone for the manufacturing of RAC-Class M. This was achieved using the aggregate replacement method in all ready-mixed concrete factories by employing $R_{meas.}$ obtained from Eq. (4) using the constants p and q .

Table 1 – Data of actual mixed concrete and calculated results of compressive strength of RAC in A to N factory.

Factory	Data of actual mixed concrete				FNC* ³ (N/mm ²)	R	QatNC* ⁴ (%)	ΔQat (%)	$R_{meas.}$	FR $R_{meas.}$ * ⁵ (N/mm ²)
	W/C (%)	RLG* ¹ (%)	Qat (%)	FRAC* ² (N/mm ²)						
A	58.0	100	2.69	32.1	28.2	1.14	0.66	2.02	0.74	20.8
	48.0	100	2.80	37.5	37.0	1.01		2.13	0.74	27.2
	38.0	100	3.03	42.4	50.5	0.84		2.37	0.73	36.8
B	45.0	100	2.32	46.1	48.6	0.95	1.00	1.33	0.75	36.6
C	58.5	100	3.17	28.1	30.4	0.92	1.54	1.62	0.75	22.7
	53.0	100	3.20	32.8	34.2	0.96		1.66	0.75	25.5
	42.5	100	3.24	38.6	44.0	0.88		1.69	0.74	32.8
D	55.0	100	7.68	29.9	32.3	0.93	1.27	6.41	0.64	20.7
	60.0	100	7.74	26.1	28.3	0.92		6.46	0.64	18.1
	55.0	100	7.79	29.1	32.3	0.90		6.52	0.64	20.6
E	40.0	100	1.96	52.5	46.9	1.12	1.15	0.82	0.76	35.8
	46.0	100	1.96	40.8	39.1	1.04		0.82	0.76	29.9
	52.0	100	1.96	34.8	33.2	1.05		0.82	0.76	25.3
	44.5	100	1.96	53.6	40.9	1.31	1.13	0.82	0.76	31.2
	40.0	100	1.96	48.5	46.9	1.03		2.23	0.73	34.4
	46.0	100	3.35	41.4	39.1	1.06		2.23	0.73	28.7
	52.0	100	3.35	35.0	33.2	1.06		2.23	0.73	24.3
	43.5	100	3.35	46.1	42.1	1.09		2.23	0.73	30.9
F	58.0	100	3.15	37.0	31.5	1.18	1.08	2.07	0.74	23.2
	50.0	100	3.22	42.5	37.6	1.13		2.14	0.73	27.6
	41.0	100	3.28	44.5	47.3	0.94		2.20	0.73	34.7

*1 Replacement ratio of recycled coarse aggregate. *2 Compressive strength of RAC. *3 Compressive strength at 28 days based on W/C equation of normal-weight concrete (recycled aggregate replacement ratio 0%) in factory. *4 Qat of normal-weight concrete (recycled aggregate replacement ratio 0%). *5 Compressive strength based on $R_{meas.}$.

4 Conclusion

Based on the examination results of the design method and validity for the active use of low-quality recycled aggregate concrete (RAC), our aim was the reduction of waste generation, reduction of CO₂ emissions, and the assurance of environmental safety. This study contributes to a sustainable environment for reinforcing concrete works, particularly in civil engineering buildings. Using the strength reduction rate obtained from the difference between the relative water

absorption of normal-weight concrete and that of RAC, this study established that in all ready-mixed concrete factories, it is possible to set a W/C in the safe zone for manufacturing RAC-Class M using the aggregate replacement method.

Table 1 – Data of actual mixed concrete and calculated results of compressive strength of RAC in A to N factories. (cont.)

Factory	Data of actual mixed concrete				FNC* ³ (N/mm ²)	R	QatNC* ⁴ (%)	ΔQat (%)	$R_{meas.}$	$FR_{meas.}$ * ⁵ (N/mm ²)
	W/C (%)	RLG* ¹ (%)	Qat (%)	FRAC* ² (N/mm ²)						
G	53.9	100	2.33	33.0	31.7	1.04	1.39	0.93	0.76	24.1
	49.0	100	2.32	35.0	36.6	0.96		0.92	0.76	27.9
	44.0	100	2.30	42.0	42.6	0.98		0.91	0.76	32.5
	49.0	100	2.34	39.4	36.6	1.08		0.95	0.76	27.8
	49.0	100	2.34	34.9	36.6	0.95		0.95	0.76	27.8
	57.1	40	1.66	32.0	29.0	1.10	1.45	0.21	0.78	22.5
	53.1	40	1.65	35.0	32.4	1.08		0.21	0.78	25.2
	49.7	40	1.64	36.0	35.8	1.01		0.20	0.78	27.9
	53.1	40	1.65	34.6	32.4	1.07		0.21	0.78	25.2
	53.1	40	1.65	32.7	32.4	1.01		0.21	0.78	25.2
H	45.0	100	2.36	40.7	43.5	0.93	0.97	1.38	0.75	32.7
I	55.0	100	3.04	33.0	30.5	1.08	1.19	1.85	0.74	22.6
	50.0	100	3.05	36.7	35.0	1.05		1.86	0.74	25.9
	45.0	100	3.08	39.1	40.4	0.97		1.89	0.74	29.9
	40.0	100	3.12	44.2	47.3	0.94		1.93	0.74	34.9
	56.5	100	3.02	30.7	29.4	1.05		1.83	0.74	21.8
	48.5	100	3.04	35.5	36.5	0.97		1.85	0.74	27.1
	43.0	100	3.03	40.0	43.0	0.93		1.84	0.74	31.9
	60.0	30	2.09	29.5	27.5	1.07		1.15	0.76	20.8
J	50.0	30	2.10	37.0	36.1	1.02	0.93	1.17	0.76	27.3
	43.0	30	2.11	41.9	44.5	0.94		1.18	0.76	33.7
K	45.0	100	2.29	38.8	44.8	0.87	1.04	1.25	0.75	33.8
L	60.0	30	1.88	27.3	28.1	0.97	0.92	0.96	0.76	21.4
	55.0	50	2.54	30.0	33.0	0.91		2.54	0.73	23.9
	50.0	50	2.54	31.6	38.8	0.81		2.54	0.73	28.2
	45.0	50	2.60	36.7	45.9	0.80		2.60	0.72	33.3
	45.0	50	2.53	39.5	49.4	0.80		2.53	0.73	35.9
	43.0	30	1.89	43.7	53.4	0.82		1.89	0.74	39.5

*1 Replacement ratio of recycled coarse aggregate. *2 Compressive strength of RAC. *3 Compressive strength at 28 days based on W/C equation of normal-weight concrete (recycled aggregate replacement ratio 0%) in factory. *4 Qat of normal-weight concrete (recycled aggregate replacement ratio 0%). *5 Compressive strength based on $R_{meas.}$.

**Table 1 – Data of actual mixed concrete and calculated results of compressive strength of RAC in A to N factories.
(cont.)**

Factory	Data of actual mixed concrete				FNC ^{*3} (N/mm ²)	R	QatNC ^{*4} (%)	ΔQat (%)	$R_{meas.}$	FR _{meas.} ^{*5} (N/mm ²)
	W/C (%)	RLG ^{*1} (%)	Qat (%)	FRAC ^{*2} (N/mm ²)						
M	50.0	30	2.08	34.9	38.1	0.92	1.23	0.85	0.76	29.1
	60.0	50	2.60	25.2	28.7	0.88		1.38	0.75	21.6
	50.0	50	2.64	33.5	38.1	0.88		1.42	0.75	28.6
	50.0	50	2.96	37.3	38.1	0.98		1.73	0.74	28.3
	40.0	50	2.70	42.9	52.2	0.82		1.48	0.75	39.1
	37.5	50	2.66	44.9	58.6	0.77		1.44	0.75	43.9
N	50.0	30	1.90	34.4	36.5	0.94	0.98	0.92	0.76	27.8
	60.0	50	2.49	26.6	28.1	0.95		1.52	0.75	21.1
	50.0	50	2.52	33.7	36.5	0.92		1.54	0.75	27.3
	50.0	50	2.82	33.2	36.5	0.91		1.84	0.74	27.1
	40.0	50	2.56	42.7	49.1	0.87		1.58	0.75	36.6
	37.5	50	2.55	45.2	60.0	0.75		1.57	0.75	44.8

*1 Replacement ratio of recycled coarse aggregate. *2 Compressive strength of RAC. *3 Compressive strength at 28 days based on W/C equation of normal-weight concrete (recycled aggregate replacement ratio 0%) in factory. *4 Qat of normal-weight concrete (recycled aggregate replacement ratio 0%). *5 Compressive strength based on $R_{meas.}$.

Table 2 – Data of actual mixed concrete and calculated results of compressive strength of RAC in O and P factories.

Factory	Data of actual mixed concrete				FNC ^{*3} (N/mm ²)	R	QatNC ^{*4} (%)	ΔQat (%)	$R_{meas.}$	FR _{meas.} ^{*5} (N/mm ²)
	W/C (%)	RLG ^{*1} (%)	Qat (%)	FRAC ^{*2} (N/mm ²)						
O ^{*6}	60	50	1.97	(20.5) 29.4	(18.8) 27.5	(1.09) 1.07	0.89	1.08	0.76	(14.3) 20.9
	50	50	2.01	(26.5) 35.7	(25.6) 35.6	(1.03) 1.00		1.12	0.76	(19.5) 27.0
	40	50	2.04	(37.5) 45.9	(37.3) 49.4	(1.00) 0.93		1.15	0.76	(28.4) 37.5
P ^{*6}	60	50	2.51	(19.2) 26.9	(20.5) 29.3	(0.93) 0.92	0.98	1.53	0.75	(15.4) 22.0
	50	50	2.54	(25.6) 34.5	(27.7) 37.7	(0.92) 0.92		1.56	0.75	(20.8) 28.3
	40	50	2.56	(38.0) 47.4	(42.7) 54.7	(0.89) 0.87		1.58	0.75	(32.0) 41.0

*1 Replacement ratio of recycled coarse aggregate. *2 Compressive strength of RAC. *3 Compressive strength at 28 days based on W/C equation of normal-weight concrete (recycled aggregate replacement ratio 0%) in factory. *4 Qat of normal-weight concrete (recycled aggregate replacement ratio 0%). *5 Compressive strength based on $R_{meas.}$. *6 In the round brackets () is the data at 7 days.

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