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Structure Strength Correction Value for Concrete's Mix Proportion Strength Using Low-Quality Recycled Aggregate

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Abstract: To develop a design method for concrete using low-quality recycled aggregates, an experimental study was conducted on applicability to examine the structural strength correction value (S value) and calculation of mix proportion strength of recycled aggregate concrete-Class M, which used recycled aggregate class L mixing with the normal aggregate. Cement used in the experiment was ordinary Portland cement (in this case, fly ash type II was used as a fine aggregate substitute), Portland blast-furnace slag cement type B, and low-heat Portland cement. As a result, the mix proportion strength of recycled aggregate concrete-Class M could be determined using the S value according to JASS 5 (2018) as normal-weight concrete.

Keywords: recycled aggregate concrete; low-quality recycled aggregate; mix proportion strength; structural strength correction value; simple adiabatic curing

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1. Introduction

As regulated in the revision of JIS A 5022 (recycled aggregate concrete-Class M), recycled aggregate concrete-Class M (types 1 and 2) [1] can be manufactured using recycled aggregate class L mixing with the normal aggregate. In the future, it will be effective to expand the use of recycled aggregate class L due to its minute environmental impact. Therefore, it is necessary to discriminate between the applications of recycled aggregate concrete-Class M and -Class L.

A recycled aggregate comprises coarse aggregate (original aggregate) in the original concrete, mortar (adhered mortar), and cement paste (adhered paste) attached to the aggregate [2]. Because many adhered mortars and pastes are mixed in recycled aggregate class L, there is a large variation in quality. Therefore, data accumulation is necessary. In addition, for countermeasures against the alkali–silica reaction (ASR) of recycled aggregates [3] and improving long-term compressive strength, fly ash (FA) [4] and ground granulated blast-furnace slag (BFS) [5] are considered effective. It is necessary to consider the applications of these materials to ensure the required quality of structural concrete, especially the effect on reducing a decrease in compressive strength and an increase in drying shrinkage rate in concrete using recycled aggregate concrete-Class L [6].

In this study, we developed a design method for concrete using low-quality recycled aggregates. In concrete manufactured by mixing a low-quality recycled aggregate with the normal aggregate, using major cement and mineral admixture, the structural strength correction value (S value) was experimentally examined; consequently, the results of mix proportion strength calculations were shown.

2. S Value and Mix Proportion Strength

According to JASS 5 (2018) [1], for recycled aggregate concrete-Class M, which used recycled aggregate class L mixing with normal aggregate in a certain amount, the nominal and mix proportion strengths can be considered the same as those of normal concrete. However, there is no experimental study on the S value of concrete using recycled aggregate class L. In addition, the effect of FA and BFS on improving the quality of recycled aggregate concrete and the use of low-heat Portland cement (L) in mass concrete need to be examined.

The selection of cement types according to the required performance is shown in Table 1 [7]. The three types of cement are ordinary Portland cement (N), Portland BFS cement type B (BB), which is limited to underground structure, and L, which is used for preventing temperature cracking due to hydration heat in mass concrete. For N, FA type II (FAII) was used as a fine aggregate substitute with a mass of 20% of the total mass of N and FA, at least 80 kg/m^3 to suppress the ASR [4]. Table 2 shows the results of examining the S value when the three types of cement were used. In this study, the evaluation was performed mainly during the hot season, considering the application to mass concrete, such as the main building foundation (turbine construction) of a thermal power plant and the machine base foundation of a boiler.

Table 1. Selection of cement type according to required performance [2].

Required Performance \ Type of Cement	N	L	BB	N + FA [1]
Measure against temperature cracks due to heat of hydration	-	○	-	-
Durability performance due to carbonation	○	○	-	-
Measure for suppressing ASR	-	-	○	○

[1] FA is used as a fine aggregate substitute.

Table 2. Structural strength correction value ${}_{28}S_{91}$.

Type of Cement	Outline [1]		
N [2]	Hot season	$8 \leq \theta$	$0 \leq \theta < 8$
BB	Hot season	$13 \leq \theta$	$0 \leq \theta < 13$
L	Hot season	$14 \leq \theta$	$0 \leq \theta < 14$
Structural strength correction value ${}_{28}S_{91}$ (N/mm^2)	6	3	6

[1] θ: temperature (°C) [2] Including the case of (N + FA) in which FAII is used as a fine aggregate substitute.

2.1. Outline of Experiment

The main qualities of cement and mineral admixture are summarized in Table 3, an outline of recycled aggregates is presented in Table 4, and the qualities of aggregates are listed in Table 5.

2.1.1. Cement and Mineral Admixture

In this study, N was used as cement, which is in accordance with JIS R 5210 [8]. Mineral admixtures are FAII in accordance with JIS A 6201 [9] and BFS 4000 in accordance with JIS A 6206 [10].

2.1.2. Aggregates

For normal coarse aggregates, crushed limestone size 2005 (G_1) and crushed hard sandstone size 2005 (G_2) were used at Plant A, and crushed limestone size 2005 (G_3) was used at Plant B (where Plants A and B are two ready mixed concrete plants). For normal fine aggregate, a mixture of land sand and crushed sand in a mass ratio of 7:3 was used at Plant A (S_1), mountain sand (S_2) and crushed sand (S_3) were used at Plant B.

Two types of recycled coarse aggregates (RLG_1 and RLG_2) and one type of recycled fine aggregate (RLS) produced simultaneously with RLG_1 were manufactured from different original concrete and used in the experiment. For the recycled coarse aggregates, RLG_1 had a 6.60% absorption and content of materials finer than 75-µm sieve of 0.7%, whereas RLG_2 had a 6.22% absorption and content of materials finer than 75-µm sieve of 2.1%. Both of them are equivalent to recycled aggregate concrete-Class L in JIS A 5023 Annex A. The total amount of contained impurities was 1.03 and 0.03 mass% for RLG_1 and RLG_2, respectively.

Moreover, RLS had a 15.0% absorption due to the effect of the adhesive mortar and cement paste. It did not satisfy the requirement of recycled aggregate concrete-Class L (≤13%); therefore, it was used as an equivalent product as recycled fine aggregate L (Appendix A). The total amount of contained impurities was 0.60 mass%. All aggregates were tested for alkali–silica reactivity and confirmed to be harmless.

Table 3. Main qualities of cement and mineral admixtures.

Item		N	L	FAII [1]	BB
Density (g/cm^3)		3.15	3.24	2.24	3.04
Blaine fineness (cm^2/g)		-	-	3400	-
Specific surface area (cm^2/g)		3300	3300	-	3990
Moisture content (%)		-	-	0.5	-
MgO (%)		1.58	0.63	-	3.52
SO_3 (%)		1.90	2.19	-	1.79
Cl^- (%)		0.011	0.005	-	0.009
SiO_2 (%)		-	-	≥45.0	-
Ignition loss (%)		2.06	0.70	1.40	1.60
Mortar flow ratio (%)		-	-	≥95	100
Activity index (%)	28 days	-	-	≥80	-
	91 days	-	-	≥90	-

[1] Manufactured in Hekinan.

Table 4. Outline of recycled aggregate.

Type	Original Concrete	Manufacture Method
Recycled coarse aggregate class L: RLG_1	Office building, reinforced concrete (RC) structure, about 45 years	Crushing and classifying original concrete at a demolition site
Recycled fine aggregate class L: RLS		
Recycled coarse aggregate class L: RLG_2	Steel chimney foundation and machine base foundation of a thermal power plant, RC structure, about 40 years	

2.1.3. Mix Proportion

Table 6 lists the mix proportions used in this study. The concrete in the experiment used N, BB, and L. Further, six types of recycled aggregate concrete L and two types of normal-weight concrete were produced at Plants A and B.

(1) N

For concrete using N, FAII was used as a fine aggregate substitute with 20% of the total mass of N and FAII to suppress ASR [2]. The water–cement ratio (W/C) was set to two levels of 40% and 60%, and the replacement rate of recycled aggregates was 50% for the recycled coarse aggregates. Two types of recycled aggregate concrete-Class M were manufactured at Plant A. The chemical admixture was air-entraining and water-reducing (high-performance type). The target slump at the placement location was 18 ± 2.5 cm; therefore, 20 ± 2.5 cm was considered for slump loss. The target air content was 4.5 ± 1.5%.

Table 5. Qualities of aggregates.

Item		Test Method	Normal Coarse Aggregate: 2005			Normal Fine Aggregate			Recycled Coarse Aggregate Class L: 2005		RFA [7]
			Plant A		Plant B	Plant A	Plant B				
			G_1 [1]	G_2 [2]	G_3 [3]	S_1 [4]	S_2 [5]	S_3 [6]	RLG_1	RLG_2	RLS
Density in oven-dry condition (g/cm^3)		JIS A 1109 [11]	2.67	2.70	2.69	2.54	2.52	2.64	2.26	2.30	1.90
Absorption (%)		JIS A 1110 [12]	0.63	0.39	0.34	2.73	1.85	1.35	6.60	6.22	15.0
Fineness modulus (F.M.)		JIS A 1102 [13]	6.60 [8]	6.60 [8]	6.61 [8]	2.70 ± 0.2	2.10	2.64	6.56	6.52	3.63
Content of materials finer than 75-µm sieve (%)		JIS A 1103 [14]	≤3.0	≤3.0	0.6	≤3.0	1.6	3.4	0.7	2.1	3.0
Solid content in aggregate (%)		JIS A 1104 [15]	-	-	61.2	-	-	-	-	-	-
Solid content of particle shape (%)		JIS A 5005 [16]	≥56	≥56	59.6	-	-	60.1	59.1	60.5	57.8
Abrasion loss (%)		JIS A 1121 [17]	≤40	≤40	≤40	-	-	-	29.3	28.9	-
Soundness (%)		JIS A 1122 [18]	≤12	≤12	≤12	≤10	-	-	19.8	36.0	8.5
Chloride ion content (%)		JIS A 5002 [19]	-	-	-	-	0.001	-	0	0.001	0.004
ASR [9]		JIS A 1146 [20]	-	-	H	-	H	H	H	H	H
		JIS A 1804 [21]	-	-	-	-	-	-	H	H	H
		ZKT-206 [22]	-	-	-	-	-	-	-	H	-
Amount of contained impurities (mass%) [10]	A	JIS A 5023 [23]	-	-	-	-	-	-	0.660	0.007	0.401
	B								0.010	0.000	0.001
	C								0.000	0.003	0.008
	D								0.000	0.004	0.000
	E								0.145	0.005	0.119
	F								0.017	0.004	0.025
	Other								0.196	0.007	0.041
	Total								1.03	0.03	0.60

[1] G_1: Crushed limestone size 2005 from Akiyoshi, Yamaguchi Prefecture [2] G_2: Crushed hard sandstone size 2005 from Ome, Tokyo. [3] G_3: Crushed limestone size 2005 from Torigata, Kochi Prefecture [4] S_1: Land sand from Kimitsu, Chiba Prefecture mixed with crushed sand from Kamiiso, Hokkaido with a ratio of 7:3 [5] S_2: Mountain sand from Ichihara City, Chiba Prefecture [6] S_3: Crushed sand from Torigata mountain in Kochi Prefecture [7] RFA: Recycled fine aggregate class L equivalent [8] For normal coarse aggregate Gmax = 20 mm [9] H: Harmless [10] Classification of A–F based on JIS A 5023.

(2) BB

For concrete using BB, two levels of W/C were 35% and 55%, and the replacement ratio of recycled aggregate was 30% and 30% for the recycled coarse and fine aggregates, respectively. At Plant A, two types of recycled aggregate concrete-Class M were manufactured. An air-entraining and water-reducing admixture (high-performance type) was used as the chemical admixture. The target slump at the placement location was 18 ± 2.5 cm; therefore, 20 ± 2.5 cm was considered for slump loss. The target air content was 4.5 ± 1.5%.

(3) L

For the concrete using L, two types of normal-weight concrete were manufactured at Plant B with two levels of W/C of 40% and 50% for the standard period. In addition, two types of recycled aggregate concrete-Class M were manufactured at Plant B, the W/C was 40% and 60%, and the replacement ratio of recycled aggregate was 50% for the recycled coarse aggregate. An air-entraining and water-reducing admixture (high-performance type) was used as the chemical admixture for these concretes. The target slump at the placing location was 15 ± 2.5 cm for all concretes; therefore, 17 ± 2.5 cm was considered for slump loss. The target air content was 4.5 ± 1.5%.

Table 6. Mix proportion.

Specimen [2]	Mix Proportion [1]										Unit Weight (kg/m^3)											
	Plant	CT [3]	MA [4]	RA [5] (%)		TS [6] (cm)	W/C (%)	s/a [7] (%)	W	C	Coarse Aggregate					Fine Aggregate					Ad [8]	SP [9]
				RLG	RLS						G_1	G_2	G_3	RLG_1	RLG_2	S_1	S_2	S_3	RLS	FA		
NFARLG$_1$50-40	A	N	FAII	50	0	20.0 ± 2.5	40	38.0	175	438	344	149	-	442	-	587	-	-	-	110	-	3.50
NFARLG$_1$50-60				50	0		60	45.6	175	292	336	144	-	427	-	778	-	-	-	73	-	1.90
BBRLG$_1$30RLS30-35		BB	-	30	30		35	35.0	198	566	490	211	-	266	-	365	-	-	131	-	14.15	-
BBRLG$_1$30RLS30-55				30	30		55	47.4	175	318	468	201	-	257	-	585	-	-	209	-	6.36	-
LG-40	B	L		0	0	17.0 ± 2.5	40	42.2	167	418	-	-	1029	-	-	-	429	297	-	-	4.18	-
LG-50				0	0		50	46.2	155	310	-	-	1023	-	-	-	501	348	-	-	3.10	-
LRLG$_2$50-40				50	0		40	40.7	176	440	-	-	516	-	464	-	403	281	-	-	4.40	-
LRLG$_2$50-60				50	0		60	47.3	158	263	-	-	510	-	459	-	522	364	-	-	2.63	-

[1] The target air volume in each specimen is 4.5 ± 1.5% [2] In specimen name, types of cement, types of RLG, replacement ratio of RLG, RLS, and water-binder ratio are shown [3] CT: cement type [4] MA: mineral admixture [5] RA: replacement ratio of recycled aggregate [6] TS: Target slump, slump loss is considered as + 2.0 cm [7] s/a: Fine aggregate ratio [8] Plant A: Hydro complex/lignin derivative, AE water-reducing admixture, Plant B: Lignin sulfonate air-entraining and water-reducing admixture [9] Plant A: Poly-carboxylic acid copolymer high-performance air-entraining and water-reducing admixture.

2.2. S Value in the Standard Period

In subsection 3.4 of JASS 5 (2003) [24], mix proportion strength at a controlled age of 28 days (F) was the larger of values calculated using Equations (1) and (2). Further, the value of L in this study was not specified.

$$F = F_q + T + 1.73\sigma \quad (1)$$

$$F = 0.85(F_q + T) + 3\sigma \quad (2)$$

F: Mix proportion strength of concrete (N/mm^2)
F_q: Quality standard strength of concrete (N/mm^2)
T: Correction value of compressive strength due to the estimated average temperature from mixing to 28 days of structural concrete on 28th days (N/mm^2)
σ: Standard deviation of compressive strength of concrete (N/mm^2)

F_q was calculated using Equation (3), the difference between the compressive strengths of structural concrete and standard cured specimen (ΔF), ΔF = 3 N/mm^2 was employed for this study (Appendix B).

$$F_q = F_c + \Delta F \quad (3)$$

F_c: Design standard strength of concrete (N/mm^2)

As shown in Table 2, one of the purposes of using L for recycled aggregate concrete-Class M is to reduce the thermal stress when mass concrete is used for a structure. Further, ΔF is employed for components that do not have a temperature record, and in case the temperature record is available, ΔF needs to be examined.

When applied to mass concrete, the temperature record of structural concrete is determined. Therefore, for the concrete using L, the validity of 3 N/mm^2 as the value of ΔF was confirmed based on experimental investigation.

Table 7 shows the fresh condition properties for two types of concrete using L, and the compressive strength of cores obtained from the standard cured and block specimens (dimensions: 1.0 × 1.0 × 1.0 m^3) (JIS A 1107 [25]). Further, Figure 1 shows the temperature records at the block specimen's center.

Table 7. Calculation results of S value in the standard period in the case of L.

Specimen	Slump (cm)	Air Content (%)	Bulk Density (kg/m^3)	Chloride Ion Content (kg/m^3)	Placing Temperature (°C)	Highest Temperature (°C)	f_m (N/mm^2)		f_{nc} (N/mm^2)		${}_mS_n$ (N/mm^2)	
	JIS A 1101 [26]	JIS A 1128 [27]	JIS A 1116 [28]	JIS A 5308 [29]			28 Days	91 Days	28 Days	91 Days	m = 28 n = 28	m = 28 n = 91
LG-40	17.5	5.2	2334	0.020	21.4	43.9	43.1	68.1	45.9	53.7	−2.8	−10.6
LG-50	17.5	5.3	2327	-	24.1	35.6	32.6	47.9	33.2	43.1	−0.6	−10.5

S value is calculated using the compressive strength of standard curing and core specimens in a certain age using Equation (4).

$${}_mS_n = f_m - f_{nc} \quad (4)$$

f_m: Compressive strength of standard curing specimen on mth day (N/mm^2)
f_{nc}: Compressive strength of core specimen on nth day (N/mm^2)

The concept of the S value is that when ${}_mS_n < 0$, then ${}_mS_n$ is considered 0. Therefore, according to Table 7, when the control age of the standard curing specimen strength in the case of L was 28 days and the control age of structural concrete was 91 days, ${}_{28}S_{91}$ was negative. Thus, ${}_{28}S_{91}$ = 0 N/mm^2 (ΔF = 0 N/mm^2). Meanwhile, when the control age of structural concrete was 28 days, the maximum value of ${}_mS_n$ was −0.6 N/mm^2. In this study, for safety evaluation, ${}_{28}S_{28}$ in the case of L was considered to be 3 N/mm^2

($\Delta F = 3$ N/mm^2), as indicated in JASS 5 (2003). Because $_{28}S_{91}$ in the standard period of JASS 5 (2018) was 3 N/mm^2, this value can be used in safety evaluation.

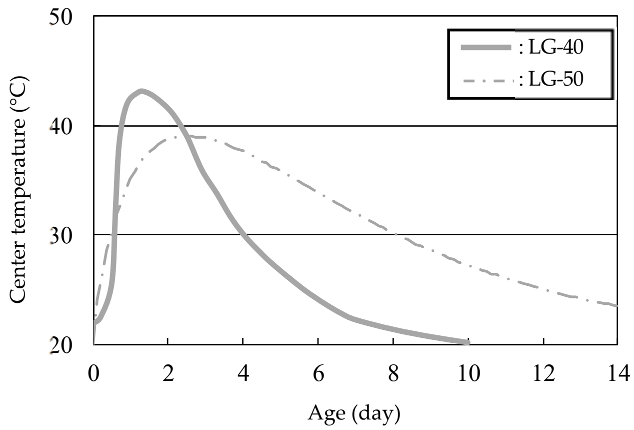

Figure 1. Temperature records in the center of block specimen.

The S value in the case of N (FAII is used as a fine aggregate substitute) and BB in the standard period was set based on the relationship between the average temperature up to the age of 28 days and the structural strength correction value $_{28}S_{91}$ in Explanatory figure 5.3 of JASS 5 (2018) [1]. Alternatively, for the difference in the measured strength of standard cured specimen at 28 days and the structural concrete at 91 days, the concrete using N, FA cement type B (FB), and BB had the upper limit of 3 N/mm^2. Therefore, in all cases, the value of 3 N/mm^2 was adopted for $_{28}S_{91}$.

2.3. S Value in Hot Season

The simple adiabatic curing method shown in Figure 2 was performed as the temperature-controlled curing for structure during a hot period. S value was calculated from the difference in compressive strength between the standard and simple adiabatic cured specimens. Table 8 shows the properties of fresh conditions for the various types of concrete in the experiment, and Table 9 shows the results of the simple adiabatic curing method. Further, Figure 3 shows the temperature records of specimens by cement type. The target temperature at the time after mixing was 35 °C [1], which was regulated for concrete in a hot period, and the experiment was implemented at room temperature of 25 °C.

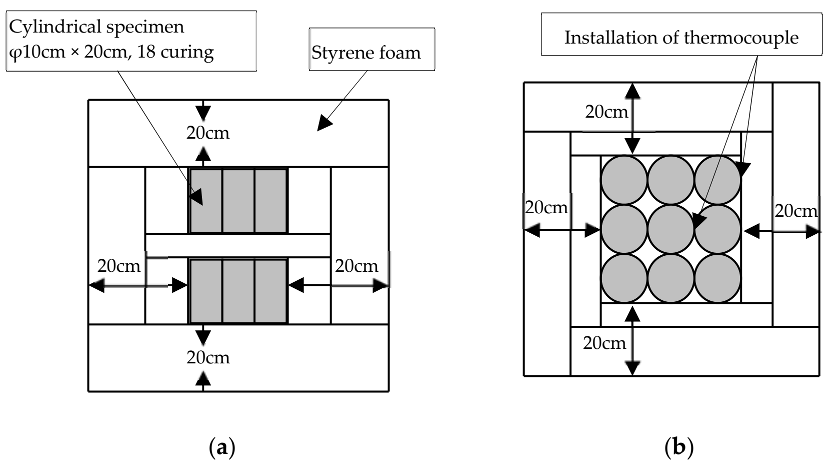

Figure 2. Simple adiabatic curing method: (**a**) side view and (**b**) plain view.

Table 8. Qualities of fresh concrete.

Specimen	Slump (cm)	Air Content (%)	Bulk Density (kg/m^3)	Chloride Ion Content (kg/m^3)
	JIS A 1101	**JIS A 1128**	**JIS A 1116**	**JIS A 5308**
NFARLG$_1$50-40	21.5	4.2	2264	-
NFARLG$_1$50-60	22.5	5.6	2219	-
BBRLG$_1$30RLS30-35	18.0	3.4	2271	-
BBRLG$_1$30RLS30-55	20.5	5.6	2193	-
LRLG$_2$50-40	17.5	4.2	2290	0.025
LRLG$_2$50-60	18.0	4.8	2266	-

Table 9. Results of simple adiabatic curing method.

Specimen	Placing Temperature (°C)	Highest Temperature (°C)	f_m (N/mm^2)		f_n (N/mm^2)			${}_m S_n$ (N/mm^2)		
			28 Days	91 Days	28 Days	81 Days	91 Days	m = 28 n = 28	m = 28 n = 81	m = 28 n = 91
NFARLG$_1$50-40	33.3	73.2	44.8	49.7	36.3	39.3	40.5	8.5	5.5	4.3
NFARLG$_1$50-60	33.4	59.5	28.2	34.2	24.5	26.8	27.2	3.7	1.4	1.0
BBRLG$_1$30RLS30-35	32.5	76.5	47.5	57.8	39.5	43.6	44.8	8.0	3.9	2.7
BBRLG$_1$30RLS30-55	32.0	55.9	29.9	37.0	26.2	29.9	29.4	3.7	0	0.5
LRLG$_2$50-40	33.4	54.1	35.3	49.1	32.8	40.9	41.6	2.5	−5.6	−6.3
LRLG$_2$50-60	33.2	45.5	22.1	36.3	22.7	29.4	30.1	−0.6	−7.3	−8.0

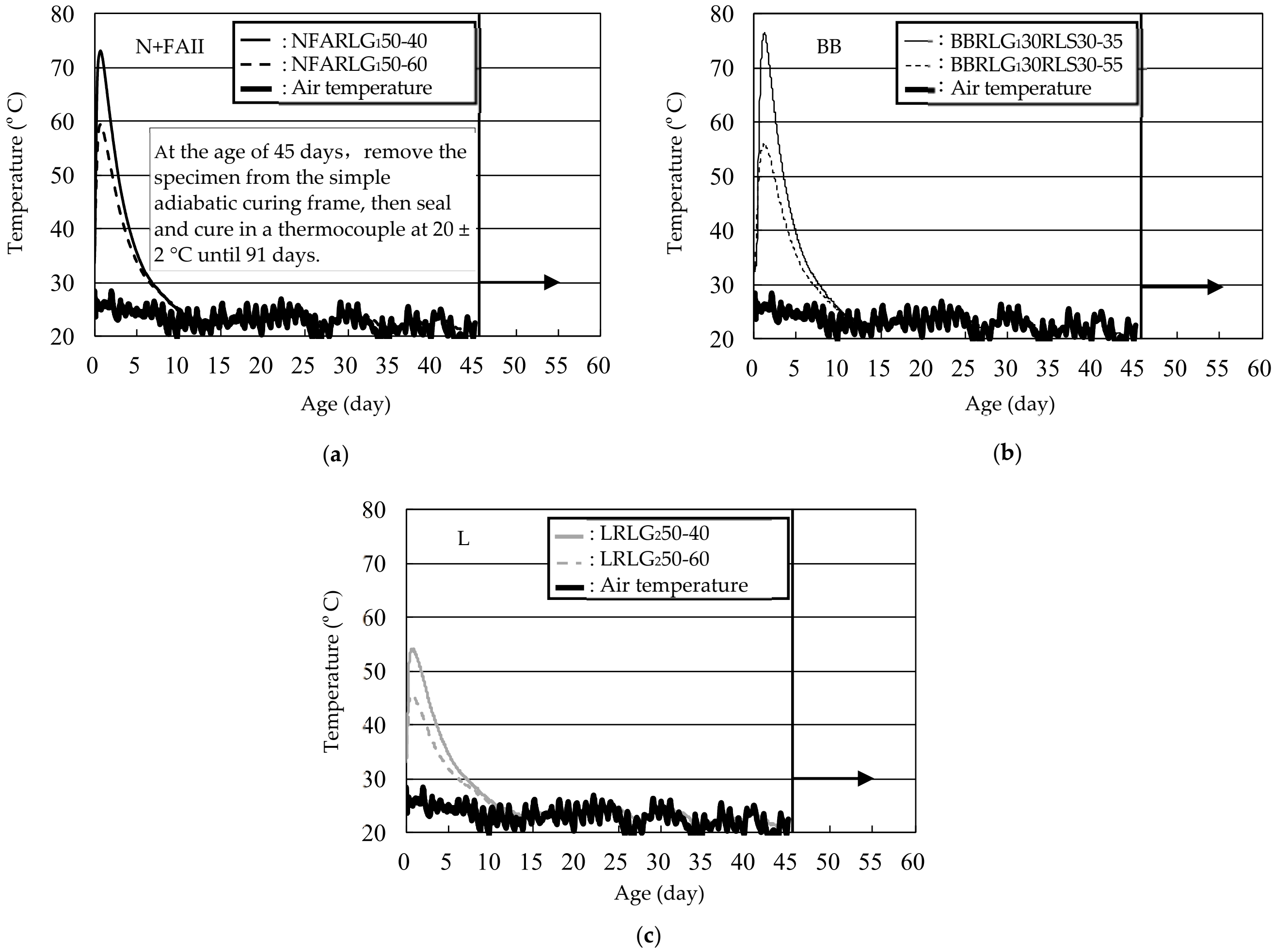

Figure 3. Temperature records of simple adiabatic cured specimens by cement type: (**a**) N + FAII, (**b**) BB, and (**c**) L.

2.3.1. Calculation Method of S Value

The S value was calculated from the compressive strength (JIS A 1108 [30]) of standard and simple adiabatic cured specimens in a specified age based on JASS 5 (2018) as follows [1]:

$$ {}_{m}S_{n} = f_{m} - f_{n} \quad (5) $$

f_n: Compressive strength of simple adiabatic cured specimens on nth days (N/mm^2)

2.3.2. Calculation Results of S Value

(1) N

For the case FAII was used as a fine aggregate substitute in N specimens, the compressive strength of standard cured specimen NFARLG$_1$50-40 with recycled coarse aggregate at a 50% replacement ratio and 40% W/C was 44.8 and 49.7 N/mm^2 at 28 and 91 days, respectively. Meanwhile, for NFARLG$_1$50-60 with a 60% W/C, it was 28.2 and 34.2 N/mm^2 at 28 and 91 days, respectively; the difference was about 5–6 N/mm^2. For the simple adiabatic cured specimens, the placing temperature was 33 °C, the maximum temperature of NFARLG$_1$50-40 was 73.2 °C, and the compressive strength was 36.3 and 40.5 N/mm^2 at 28 and 91 days, respectively; the increase in compressive strength was ~4 N/mm^2. ${}_{28}S_{28}$ = 8.5 N/mm^2, which exceeded 6 N/mm^2, but ${}_{28}S_{81}$ = 5.5 N/mm^2 and ${}_{28}S_{91}$ = 4.3 N/mm^2. Moreover, for NFARLG$_1$50-60, the maximum temperature was 59.5 °C, and the compressive strength of the simple adiabatic cured specimen was 24.5 and 27.2 N/mm^2 on 28th and 91st days, respectively; the increase in strength after 28 days was about 3 N/mm^2. ${}_{28}S_{28}$ = 3.7 N/mm^2, and ${}_{28}S_{91}$ = 1.0 N/mm^2, which are both lower than 6 N/mm^2.

(2) BB

The compressive strength of the standard cured specimen BBRLG$_1$30RS30-35 using BB with a 35% W/C and replacement ratio was 30% of recycled coarse aggregate and 30% of recycled fine aggregate was 47.5 and 57.8 N/mm^2 on 28th and 91st days, respectively. For BBRLG$_1$30RS30-55 with a 55% W/C, the compressive strength was 29.9 and 37.0 N/mm^2 on 28th and 91st days, respectively; the difference in strength was about 7–10 N/mm^2. For the simple adiabatic cured specimen, the placing temperature was about 32 °C, the maximum temperature was 76.5 °C for BBRLG$_1$30RLS30-35, and the compressive strength was 39.5 and 44.8 N/mm^2 on 28th and 91st days, respectively; the increase in compressive strength after 28 days was about 5 N/mm^2. ${}_{28}S_{28}$ = 8.0 N/mm^2, which exceeded 6 N/mm^2, but ${}_{28}S_{81}$ = 3.9 N/mm^2 and ${}_{28}S_{91}$ = 2.7 N/mm^2. Meanwhile, the maximum temperature of BBRLG$_1$30RLS30-55 was 55.9 °C, the compressive strength was 26.2 and 29.4 N/mm^2 on 28th and 91st days, respectively; the increase in strength from 28 days to 91 days compared with the case of 35% W/C was quite similar, about 3 N/mm^2. ${}_{28}S_{28}$ = 3.7 N/mm^2 and ${}_{28}S_{91}$ = 0.5 N/mm^2, which are both lower than 6 N/mm^2.

(3) L

The compressive strength of the standard cured specimen LRLG$_2$50-40 with a 40% W/C was 35.3 and 49.1 N/mm^2 on 28th and 91st days, respectively. For LRLG$_2$50-60 with a 60% W/C, the strength was 22.1 and 36.3 N/mm^2 at 28 and 91 days, respectively; the difference was about 14.0 N/mm^2. For the simple adiabatic cured specimen, the placing temperature was about 33 °C, the maximum temperature was 54.1 °C for LRLG$_2$50-40, and the compressive strength was 32.8 and 41.6 N/mm^2 on 28th and 91st days, respectively; the increase in compressive strength from 28 to 91 days was about 9 N/mm^2. ${}_{28}S_{28}$ = 2.5 N/mm^2 and ${}_{28}S_{91}$ = −6.3 N/mm^2, which were both lower than 6 N/mm^2. Meanwhile, for the LRLG$_2$50-60 specimen, the maximum temperature was 45.5 °C, the compressive strength was 22.7 and 30.1 N/mm^2 on 28th and 91st days, respectively; the strength increase from 28 to 91 days was about 7 N/mm^2. ${}_{28}S_{28}$ = −0.6 N/mm^2 and ${}_{28}S_{91}$ = −8.0 N/mm^2, which were both lower than 6 N/mm^2.

Based on these results, the S value for all concrete specimens with m = 28 and *n* = 91 was within 6 N/mm^2 during the hot season, as mentioned in JASS 5 (2018) [1]. Therefore, the value of 6 N/mm^2 can be used for ${}_{28}S_{91}$ in the hot season. In the cold season, the value of 6 N/mm^2 was also employed for ${}_{28}S_{91}$.

2.4. Mix Proportion Strength

The mix proportion strength should satisfy Equations (6) and (7) based on JASS 5 (2018) [1]. The calculation of F_q is based on Equation (9) (Appendix B). Further, the concrete using L was applied to actual structures [2]; an outline of the applied structure is shown in Table 10, and examples of mix proportion strength are shown in Table 11.

$$F \geq F_m + 1.73\sigma \tag{6}$$

$$F \geq 0.85F_m + 3\sigma \tag{7}$$

F: Mix proportion strength of concrete (N/mm^2)
F_m: Mix proportion control strength of concrete (N/mm^2)
σ: Standard deviation of compressive strength of concrete (N/mm^2)

Table 10. Outline of the applied structure.

Item		Outline	
Certificated by MLIT [1]		MCON-2090	
Applied structure		Foundation of the main building of thermal power plant (Turbine building)	Machine base foundation in thermal power plant [2]
Structure type		RC structure (upper frame: steel structure)	RC structure
Location		Coastal area in Kanagawa Prefecture	
Design standard strength: F_c		21 N/mm^2	
Recycled aggregate concrete-Class M1	Amount	About 8000 m^3	About 3000 m^3
	Use for	Mass concrete	
	Cement	L	
	Replacement ratio	Recycled coarse aggregate: 50%	

[1] Minister of Land, Infrastructure, Transport and Tourism [2] Foundation of HRSG (Heat recovery steam generator for gas turbine), transformer, and air intake chamber.

Table 11. Example of mix proportion strength calculation.

Cement Type	Range of θ (°C)	F_c (N/mm^2)	${}_{28}S_{91}$ (N/mm^2)	$F_m = F_c + {}_{28}S_{91}$ (N/mm^2)	σ (N/mm^2)				F (N/mm^2)		
					Plant 1	Plant 2	Plant 3	Set Value	28 Days	81 Days	91 Days
N + FA	$14 \leq \theta$ [2]	21	3	24	2.0	2.5	2.0	3.0	F ≥ 29.2	F ≥ 29.4	29.4
BB	$13 \leq \theta$										
L [1]	$14 \leq \theta$										
N + FA	$0 \leq \theta < 8$ [2]		6	27	2.2	3.0	2.5		F ≥ 32.2	F ≥ 32.0	32.2
BB	$0 \leq \theta < 14$										
L [1]	$0 \leq \theta < 14$										

[1] Mixing date of structure $14 \leq \theta$: March 30–May 18, $0 \leq \theta < 14$: December 24–March 27 [2] FA is used as a fine aggregate substitute.

$$F_m = F_q + {}_mS_n \tag{8}$$

F_q: Quality standard strength of concrete (N/mm^2)
$_mS_n$: Structural strength correction value to be derived from the difference between the compressive strength of standard cured specimen on mth day and the compressive strength of structural concrete on nth day (N/mm^2), m = 28, n = 91

$$F_q = F_c \quad (9)$$

F_c: Design standard strength of concrete (N/mm^2)

3. Conclusions

For developing a design method for concrete using low-quality recycled aggregates, the structural strength correction value and calculation of mix proportion strength of concrete using recycled aggregate class L were examined within a certain range of recycled aggregate replacement ratio. As a result, the following conclusions have been drawn.

(1) From the difference in compressive strength between a structural concrete and standard cured specimen, for the concrete using L with 40% and 50% W/C, $_{28}S_{28}$ can be considered as 3 N/mm^2 (ΔF = 3 N/mm^2), which was indicated in JASS 5 (2003) [24]. Further, because $_{28}S_{91}$ in the standard period of JASS 5 (2018) is 3 N/mm^2, this value can be employed for safety evaluation. In addition, the value can be applied for the concrete using N (with FAII used as a fine aggregate substitute) and BB.
(2) The S value of the recycled aggregate concrete-Class M using N (with FAII used as a fine aggregate substitute), BB, and L with W/C in the range of 35–60%, m = 28, n = 91 during the hot season can be employed as 6 N/mm^2. Further, in the cold season, $_{28}S_{91}$ can also be employed as 6 N/mm^2.
(3) The structural strength correction value shown in JASS 5 (2018), which are $_{28}S_{91}$ = 3 N/mm^2 and $_{28}S_{91}$ = 6 N/mm^2 can be applied to concrete using low-quality recycled aggregate based on the condition of temperature and cement types. Further, L can be employed in a structure for actual mass concrete.

From the above conclusions, within the scope of this study, the mix proportion strength of recycled aggregate concrete-Class M can be determined based on the structural strength correction value indicated in JASS 5 (2018) [1].

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Appendix A

According to JIS A 5023 Annex A, the absorption of RLS does not satisfy the regulation. Although it cannot be classified as recycled fine aggregate class L in accordance with JIS A 5023, in Table 10, regarding MCON-2090 approved by MLIT for an applicable structure, MCON-2090 regulates the absorption of RLS, which is ≤15.5% (Table A1). Therefore, in this study, RLS was considered equivalent to recycled fine aggregate concrete-Class L.

Table A1. Quality standard of recycled aggregate (MCON-2090).

Inspection Item	Test Method	Inspection Frequency	Control Value		
			Recycled Coarse Aggregate		Recycled Fine Aggregate
Density in oven-dry condition	JIS A1109 [11] JIS A 1110 [12]	At the time producing; 1 time/1000 tons of produced volume during production and at the time of changing production area or aggregate type At the time of receiving (per construction); 1 time/500 tons received and at the time of change of origin or aggregate type	≥2.2 g/cm^2		≥1.9 g/cm^2
Absorption	JIS A 1109 [11] JIS A 1110 [12]		≤8.0%		≤15.5%
Fineness modulus	JIS A 1102 [13]		Gmax = 20 mm	F.M.:6.60 ± 0.50	1.95–3.68
			Gmax = 25 mm	F.M.:6.90 ± 0.50	
Content of materials finer than 75-μm sieve	JIS A 1103 [14]		≤3.0%		≤15.0%
Amount of contained impurities	JIS A 5021 [31]		Total amount: ≤1.0% Paper and wood chips: ≤0.1%		
Chloride ion content	JIS A 5023 [23]		≤0.04%		
ASR	JIS A 1804 [21]		Harmless [1,2]		
	ZKT-206 [22]	Before the start of construction and at the time of change of origin or aggregate type	Harmless [3]		

[1] At the time of acceptance by checking the test report [2] In the case of "not harmless" by JIS A 1804, conduct an inspection according to JASS 5N T-603 and confirm that the inspection result is "harmless." However, this does not apply when effective measures are taken to control the ASR of concrete, such as using FA as mineral admixture [3] Harmless in case of no reaction (A).

Appendix B

Quality standard strength of concrete (F_q) is selected by the larger value between design standard strength (F_c) and durability design standard strength (F_d) [1,29]. However, in this study, the planned service period was not specified as a design condition; therefore, only F_c was considered in the calculation.

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