- *Technical Paper* -

TENSILE PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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ABSTRACT

This study presents the experimental results on recycled aggregate concrete (RAC). The tests included shrinkage ring tests and uniaxial tensile creep tests. Three moisture contents for the recycled coarse aggregate were tested. No visible cracks were observed on the surface of ring specimen up to 100days, which compares favorably to most normal concrete. This indicates RAC has potential to develop enough tensile strength to resist stress from drying shrinkage. The ratio of creep to free shrinkage of RAC under fully restraint conditions was similar to that of normal concrete up to 7days.

Keywords: Recycled Aggregate Concrete, Ring Test, Uniaxial Test, Tensile Creep

1. INTRODUCTION

Critical shortages of natural aggregate for concrete products is an ongoing issue in many urban areas all over the world. At the same time, quantities of demolished concrete from deteriorated structures are also increasing as a waste material in the same areas. Shortages in both raw materials as well as landfill area will continue to increase.

One of the most effective measures against above issue is use of recycled aggregate concrete (RAC). However, in most cases, crushed concrete will have higher absorption, porous structure [1], and lower strength at equal water cement ratio and slump [2] than concrete made with similar type of virgin aggregate. In addition, drying shrinkage of RAC has been shown to be greater than that of normal concrete [3]. Thus, RAC is commonly believed to have lower resistance to cracking caused by drying stresses. Such perceptions, however, are based on limited work in literature that has not deeply considered processing options to improve performance.

To improve the performance of recycled aggregate, two-stage mixing (TSM) was proposed and developed by Tam et al. [4], [5]. This method divides the mixing process into two parts and proportionally split the required water into two which are added at different times shown in Fig. 1. Improvement of strength has been recorded up to 21.2% for 20% of replacement of recycled aggregate used after 28 days of curing for TSM in that paper. However, some properties relevant to tensile resistance were not investigated yet.

It is noted that, in some case of using TSM, initial moisture content of recycled coarse aggregate was controlled as partial dried (approximately 80% of saturated and surface-dry condition) in order to make the cement paste, which has low water to cement ratio, absorbed into recycled coarse aggregate at first mixing. Therefore, this study focus on the influence of initial moisture content of recycled coarse aggregate on the various components of tensile creep in RAC made with TSM or single mixing (SM).

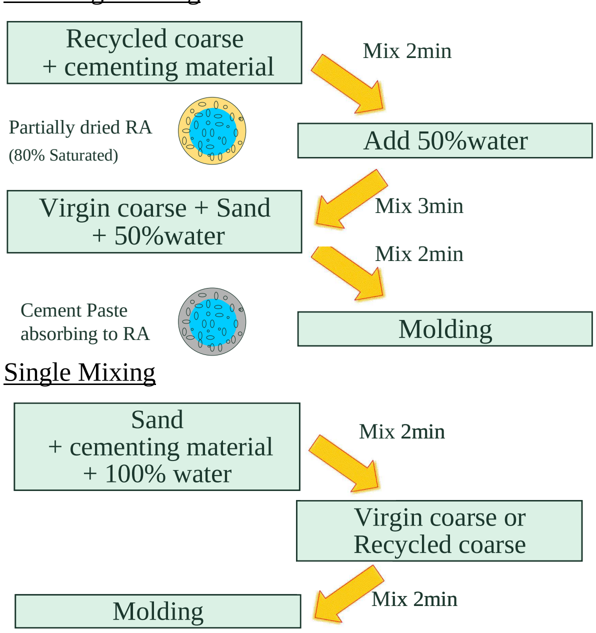

Fig.1 Mixing Procedures of TSM and SM

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Materials used in this study are shown in Table 1 and mixture proportions for one cubic meter of RAC and normal concretes are presented in Table 2, assuming that both fine and coarse aggregates are in a saturated and surface-dry condition. As can be seen in Table 2, 20% of the cement was replaced by fly ash in

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Table 2 Mixture Proportion

	W/C	Real W/C	Slump (cm)	kg/m^3						
				W	C	FlyAsh	NFA	NCA-7	NCA-16	RCA
N42	0.42	0.42	5.0	220	420	105	1460	1450	406	-
RAC100	0.42	0.42	1.5	220	420	105	1460	-	-	1674
RAC74	0.42	0.47	5.0	220	420	105	1460	-	-	1674
RAC0	0.42	0.60	6.5	220	420	105	1460	-	-	1674

Table 1 Property of Aggregate

Type	Density (g/cm^3)	Absorption Capacity (%)
Natural Coarse Aggregate CA-7 (NCA-7)	2.68	2.73
Natural Coarse Aggregate CA-16 (NCA-16)	2.67	1.90
Recycled Coarse Aggregate (RCA)	2.41	5.73
Natural Fine Aggregate (NFA)	2.57	2.43

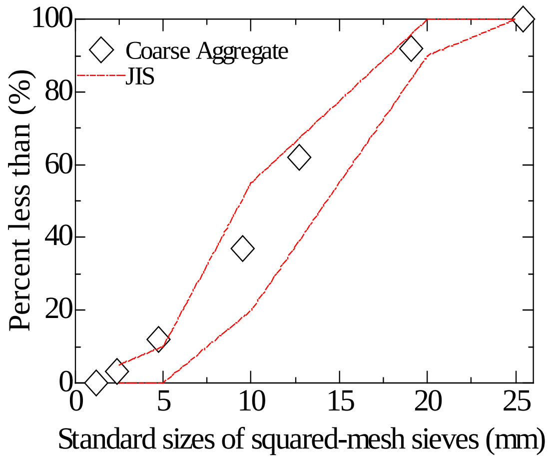

Fig.2 Size Distribution of Coarse Aggregate

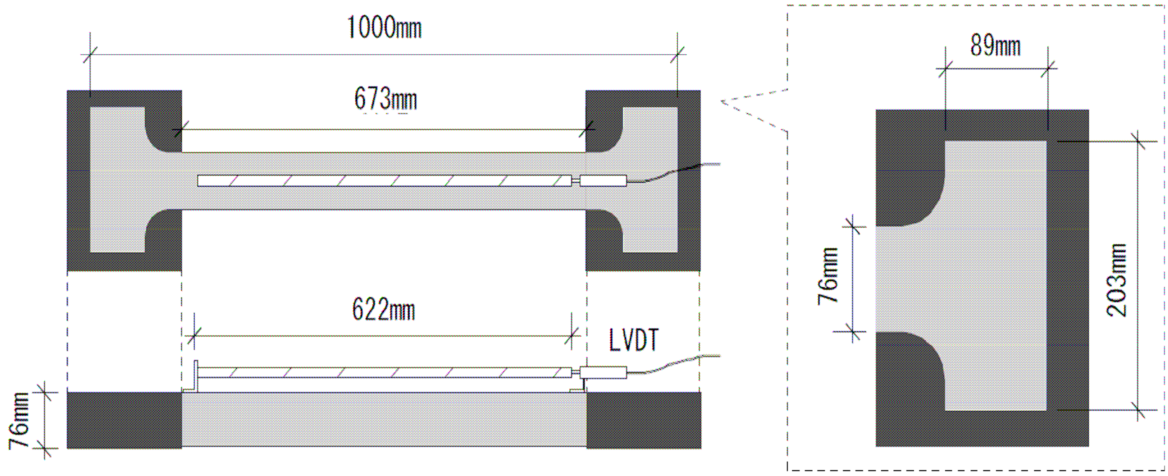

Fig.3 Uniaxial Tensile Loading Device

all mixture proportions.

The recycled coarse aggregate used in this experiment is estimated with some variability on size distribution. The size distribution of recycled coarse aggregate was controlled as same size distribution of virgin coarse aggregate used in normal concrete. Fig. 2 shows controlled size distribution of recycled aggregate.

In this research, initial moisture content of recycled coarse aggregate was qualified as 0% (RAC0), 74% (RAC74) and 100% (SSD:RAC100). In the cases of 0% and 74%, compensation water was added to free water in order to confirm the amount of water to 100%. This compensation water was not expressed in mixture proportion, but must have an impact on water to cement ratio of cement matrix. Real water to cement ratio in each case were also shown in Table 2, where, real water to cement ratio is calculated as (W + compensation water) / (C + Fly Ash).

2.2 Uniaxial Test

A uniaxial tensile loading device was used to measure the creep and shrinkage. The system tests two identica "dog-bone" samples; one specimen is restrained and the load developed by drying shrinkage is measured, and the other specimen is unrestrained and the drying shrinkage is measured.

Each sample is 1000 mm long and 76 x 76 mm in cross-section. The dimensions of the specimen accommodated a maximum aggregate size of 25 mm. The general view of specimen was shown in Fig. 3.

The computer-controlled test checked shrinkage deformation continuously, and when the threshold (0.005mm) was exceeded, an increase in tensile load was applied by the actuator to restore the specimen to its original length. In this way, a restrained condition was achieved. Thus, stresses in the restrained specimen were self-induced by restraining shrinkage, which increased with age and led to fracture.

Comparison of the free shrinkage results with the shrinkage of the restrained specimen enabled discrimination of creep strain from shrinkage strain. The creep strain calculation is based on the hypothesis that free shrinkage can be simply subtracted from the deformation of the restrained specimen as shown in Eq. (1), an approach that is common in the literature [6].

$$\varepsilon_{creep} = \left(\varepsilon_{total} - \sum \varepsilon_{elastic}\right) - \varepsilon_{free} \qquad (1)$$

where, ε_{creep} :total creep strain , ε_{total} :total strain obtained from restricted specimen, $\varepsilon_{elastic}$: elastic deformation obtained from restricted specimen,, ε_{free} : free shrinkage obtained from non-restrgicted specimen

The tests started at the age of 23~24 hours. At the age of that time, the top surface of samples was sealed with self-adhesive aluminum foil after demolding and then exposed under drying conditions of 50 % RH and 23^{o} C for all mixtures.

The applied load was increased throughout the restrained tests as required to maintain the specimen length change at near zero. Computer recorded this loading regime.

2.3 Ring Test

The detail of ring specimen was shown in Fig. 4. Shrinkage at inside of steel ring was measured with strain gage attached to the inner steel surface at mid-height. The size of the concrete ring was determined by the need for the ring to have the same thickness (76mm) and height (76mm) with specimens in Uniaxial test. It should be pointed out that volume/surface area ratio of ring test was different from that of uniaxial test.

The tests were started at the same age as the uniaxial test. The top surface of ring specimen was also sealed with self-adhesive aluminum foil when drying was started.

2.4 Strength Test

Compressive test were carried out at 1, 3, 7, 28 and 56 days. Split tensile test was carried out at 7 days.

There are a lot of investigations dealing with strength issue of RAC cured in water or under 100% RH condition. In this study, all specimens for compressive and split tensile strength tests were cured in sealed condition until 1 day, then exposed under drying conditions of 50 % RH and 23^{o} C for all mixtures after 1 day in order to simulate similar condition to uniaxial and ring test.

3. RESULTS AND DISCUSSION

3.1 Strength Test

Fig. 5 shows results of compressive strength with ages up to 56 days. As can be seen, RAC shows lower strength than normal concrete for all age up to 56 days. There is a big difference between each RAC. This difference was mainly caused by varying of the real water to cement ratio. The RAC0, which has a highest real water to cement ratio, shows lowest compressive strength from early age up to 56 days. While RAC74

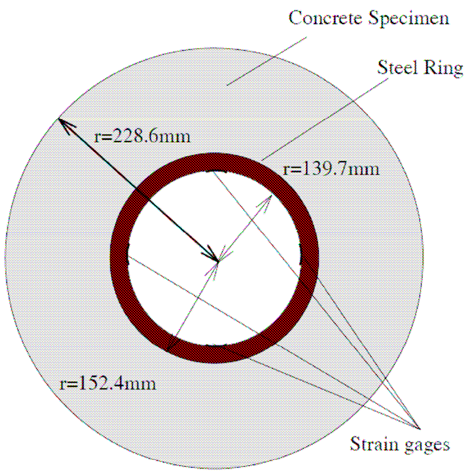

Fig.4 Detail of Ring Specimen

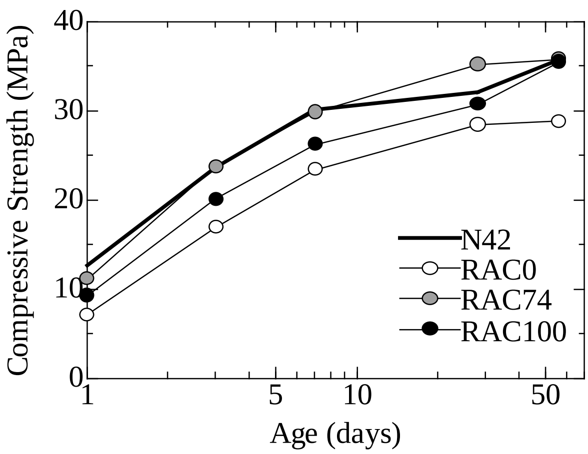

Fig.5 Compressive Strength with Ages

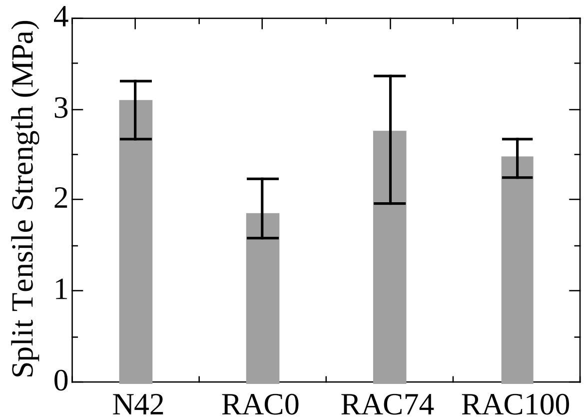

Fig.6 Tensile Strength at 7days

made with TSM shows higher compressive strength than RAC100 as well as normal concrete, even though RAC74 has higher real water to cement ratio than RAC100. This result revalidated that TSM can improve compressive strength as the previous paper mentioned [4].

From standpoint of long term compressive strength, N42, RAC74 and RAC100 show almost the same compressive strength at 56 days. Especially, RAC100 shows biggest developing in 28 days to 56 days. The larger amount of water in the pores of recycled coarse aggregate can facilitate internal curing.

Due to this effect, RAC can be expected to have almost same compressive strength with normal concrete with same water to cement ratio in long term drying condition.

Fig. 6 shows the test result of split tensile strength at 7 days. RAC74 shows the highest split tensile strength in all RAC specimens, as with compressive strength.

3.2 Uniaxial Test

Fig. 7 shows restrained stress caused by drying shrinkage. The tensile stress developed at early age was substantial, and led to fracture of all restrained specimens before 7 days. As shown, the time to fracture varied from RAC100 to other mixture proportions. However, there is no big difference between other RAC and normal concrete.

The tensile stress at fracture of each specimen was 1.94 MPa for normal concrete and 1.71 MPa, 1.61 MPa, 1.51 MPa for RAC100, RAC74 and RAC0 respectively. As described above, the tensile stress at fracture of RAC was slightly lower than that of normal concrete. The relaxation effect is not immediately clear from Fig. 7.

The measurement of free shrinkage and creep strain was shown in Fig. 8 and Fig. 9 respectively. The free shrinkage in this test consisted of autogenous shrinkage and drying shrinkage.

All specimens made of RAC shows the lower initial rate of free shrinkage than that of normal concrete up to 7 days. This indicated larger amounts of water (total of absorbed water in aggregate and free water) suppress shrinkage caused by hydration or drying. From the viewpoint of mixing procedure, RAC74 made with TSM shows higher ratio of free shrinkage than that of other RACs. In the case of applying TSM, water to cement ratio of mortar matrix could be reduced due to half amount of water was added at different timing. Therefore, autogenous shrinkage of RAC74 could be larger than RAC made with SM.

Fig. 9 shows total tensile creep strain obtained in the uniaxial test. In this study, the total tensile creep was considered to the sum of at least two components, an intrinsic drying creep with its own mechanisms and a structural drying creep resulting from micro-cracking effect due to the non-uniformity of the free drying shrinkage in the concrete specimen.

It can be observed that the total tensile creep strain of RAC was lower than that of normal concrete in 7 days and creep behavior of RAC74 was analogous with that of normal concrete. This tendency is similar to strength behavior and free shrinkage behavior in early ages.

M. V. Gomez-Soberon and A. Domingo-Cabo et. al. [7], [8] reported that the compressive creep in RAC showed higher value than that in normal concrete. And Iriya et. al. mentioned that the difference of creep behavior in compression and tension was similar in normal concrete [9]. The obtained data in these experiments disagree with previous knowledge. This result might be caused by difference of method to obtain total creep. In this study, tensile stress of uniaxial

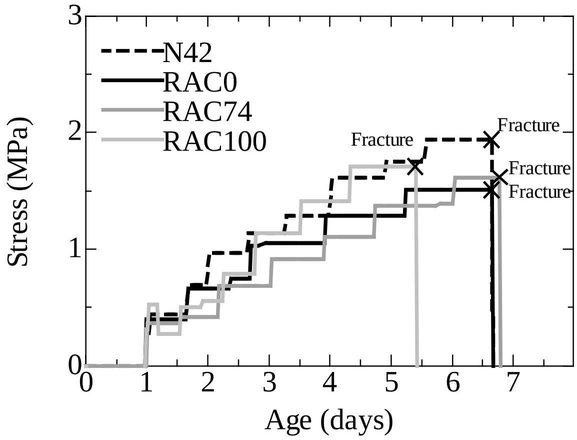

Fig.7 Stress Developing in Uniaxial Specimen

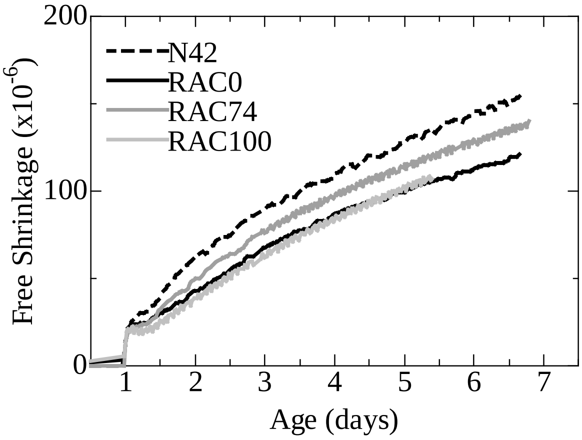

Fig.8 Free Shrinkage with Ages

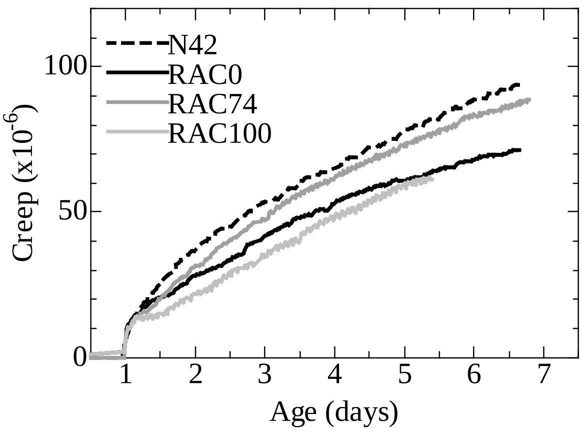

Fig.9 Total Creep Strain with Ages

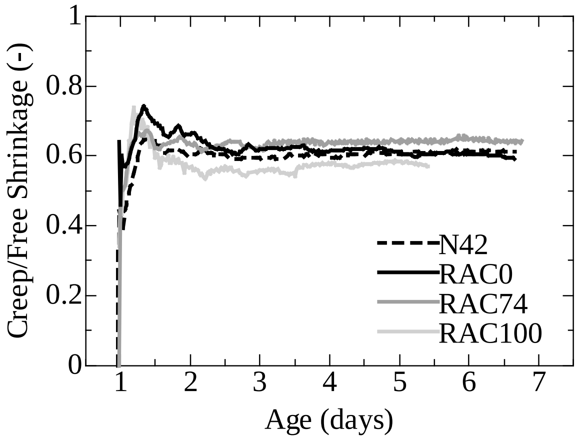

Fig.10 Ratio of Creep to Free Shrinkage

specimen was induced by drying shrinkage. Since total creep develops with increase of free shrinkage. Then the ratio of total tensile creep to free shrinkage was used for evaluation of creep behavior in these cases, as shown in Fig. 10.

Apparently, the initial ratio of creep to shrinkage in RAC was equal to that of normal concrete up to 7 days. This indicates tensile resistance of RAC in early age was determined by tensile strength, Young's modulus and magnitude of free shrinkage as well as normal concrete.

3.3 Ring Test

The steel strain with ages up to 100 days is shown in Fig. 11. At the ring test, steel strain was determined by Young's modulus and free shrinkage of concrete ring, Young's modulus of steel ring and the ratio of the cross-sectional area of the steel ring to concrete ring. Due to the volume/surface area ratio was different in each test, average drying shrinkage of concrete ring was different from that of uniaxial specimen. But general trend, which RAC shows lower free shrinkage in early age, may be not changed. In addition, Young's modulus of RAC is much lower than that of normal concrete [10]. Therefore, steel strain of RAC shows lower shrinkage in early age as shown in Fig. 11. Then, rate of steel strain of RAC developed after 10days. Finally steel strain of RAC100 and of RAC74 reached that of normal concrete at 68 days and 86 days respectively. RAC0 shows lowest value in all ages. Developing of steel strain approximately converged about 100 days. Macro cracking was not observed in this term.

The theoretical distribution of the circumferential stress in the steel and concrete rings is parabolic and may easily be computed according to the theory of elasticity.

$$\sigma_t = \frac{b^2 \cdot p}{\left(b^2 - a^2\right)} \cdot \left(1 + a^2 / r^2\right) \tag{2}$$

where, σ_t :circumferential stress at radius, p :external applied stress, a : inner radius of steel ring, b : outer radius of steel ring, and r : radius of steel ring. The compressive steel stress at the outer face σ_b is then given by Eq. (3)

$$\sigma_b = \frac{\left(a^2 + b^2\right)}{2b^2} \cdot \sigma_a \tag{3}$$

Hence, the average steel stress, assuming linear stress distribution across the steel section is given by Eq. (4)

$$\sigma = \left\{1 + \frac{\left(a^2 + b^2\right)}{2b^2}\right\} \cdot \frac{\sigma_a}{2} \tag{4}$$

The compressive stress at the inner face is known from the measured steel strain and the Young's modulus of steel (E_s =2.05*10^5 MPa was used). And the ratio of the cross-sectional area of the steel ring to concrete ring is also known. Then average restrained stress in concrete was calculated from Eq. (2) ~ (4) as shown in Fig. 12. .

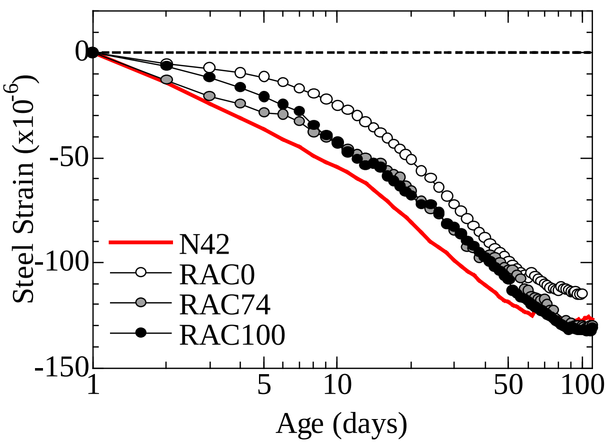

Fig.11 Steel Strain with Ages

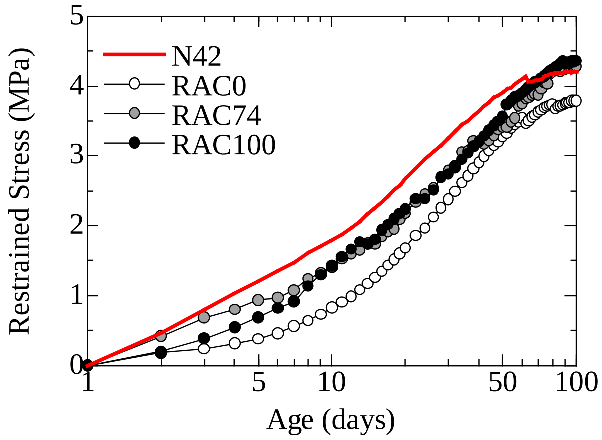

Fig.12 Restrained Stress in Concrete Ring

Table 3 Tensile Stress Condition at 7days

	N42	RAC0	RAC74	RAC100
Fracture Stress in Uniaxial Test (MPa)	1.94	1.51	1.61	1.71
Restrained Stress in Ring Test (MPa)	1.47	0.56	1.08	0.92
Split Tensile Strength (MPa)	3.08	1.83	2.74	2.45
Stress/ Strength ratio in Ring Test	0.48	0.30	0.39	0.38

At early ages, high local stresses occur at both the inner and outer surfaces of the concrete. The drying and residual stress distributions should be considered to depict the stress in the concrete ring. With time, though the stress distribution in the ring becomes more uniform through the cross-section, then the average stress of the specimen is a reasonable approximation. Previous paper indicated that when the average stress in the concrete exceeds 80% of the tensile strength, macro cracking would occur on the outer surface of the concrete ring [11].

Calculated restrained stress in each concrete ring at 7 days was put down with stress at fractured age in uniaxial test, split tensile strength and the ratio of restrained stress to tensile strength in concrete ring in

Table 3.

By comparing these figures, it can be seen that stress/strength ratio at 7 days in ring test was comparatively low. These results correspond to the fact of non-visible crack was observed in ring specimen. On the other hand, fractured stress in uniaxial test is lower than split tensile strength at 7 days. This indicates if the system can provide a greater degree of restraint, the risk of cracking could be larger.

In this research, this relation ship between risk of cracking and degree of restraint was not clear. Therefore, it should be considered essential to know the level of restraint provided by the system and to account for it properly. For example, the thicker steel ring provided a greater degree of restraint and causes a greater residual stress in the concrete.

4. CONCLUSIONS

Ring and uniaxial tests were conducted to characterize the drying shrinkage stress of three types of RAC, which used recycled coarse aggregate with different initial moisture contents. From this investigation, the following conclusions are obtained.

(1) It was revalidated that RAC made with a two-stage mixing had the same compressive strength as normal concrete up to 56 days under drying condition. And tensile split strength was also improved by using TSM.
(2) The ratio of creep to free shrinkage of RAC was similar to that of normal concrete up to 7 days under fully restrained condition.
(3) The risk of cracking in RAC is dependent upon restraint conditions. In the case of high restraint condition as achieved using the uniaxial test, RAC and normal concretes fractured under drying stresses after about 7days. In the case of the ring test, which exerts somewhat less restraint than the uniaxial test, the RAC remained uncracked at 100 days.
(4) RAC can perform similarly to normal concrete of the same w/c ratio when appropriate mixing techniques and pre-saturated aggregate are used.

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