PROCESSING AND PROPERTIES OF RECYCLED AGGREGATE CONCRETE

BY

HYUNGU JEONG

THESIS

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Adviser:

Professor David A. Lange

Abstract

As interest in sustainable materials such as recycled aggregate concrete (RAC) rises, effort, it is important to understand the properties of RAC that relates to its use in construction. To respond to this need, various tests were performed to investigate the properties of RAC. Properties of RAC are highly affected by processing. Processing variables indeed in this study are two-stage mixing approach (TSMA) and control of RAC initial moisture contents. By two-stage mixing approach, the compressive strength of RAC improved with different initial moisture states of recycled coarse aggregates. However, in case of shrinkage, some previous studies showed that RCA can absorb larger amount of water than natural aggregates because RCA has a higher porosity which leads concrete to increase shrinkage. To make a balance strength with shrinkage, our tests were performed by various mixture batches. In addition, ring and dog bone tests were studied when the specimen is restrained and is affected by internal tensile stress. With using 74% initial moisture states of recycled coarse aggregates, the compressive strength was similar to that of normal concrete and the drying shrinkage was less. Furthermore, test with using recycled fine aggregates(RFA) was performed and fly ash was used to reduce shrinkage of RAC. As RFA increases, the shrinkage of the specimen also increased because RFA is composed with mortar which plays an important role in volume of porosity.

Dedication

Firstly, I would like to thank my advisor Dr. Lange who has provided me encouragement in my studies. At the first time in UIUC as a master student, I was afraid of my future but with his support and belief, I could build my future in a better shape as a researcher. I will never forget his integrity as an advisor. Secondly, I would like to thank my past group member, Atsushi Teramoto who helped me in most of my experiments. I cannot imagine my experiments without him. Thirdly, this study was supported by the O'Hare Modernization Program through the Center of Excellence for Airport Technology (CEAT). Fourthly, I should thank my parents, Jong-gun and Young-sun, for encouraging me to get in UIUC. Lastly, I want to say "thank you" to all of the construction material graduate students. I spent a great time with them in here, foreign country.

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1. Introduction

1.1. Purpose

To achieve sustainable issue in construction area, researchers and companies focus on using waste concrete as a new construction material. It is called recycled aggregate which can be produced by concrete crusher. The aggregates are categorized by size as coarse and fine aggregate. If recycled aggregates were practically useful in construction area, two aspects would be expected. One is illustrated at the beginning of introduction, the other one is that we could reduce consumption of natural aggregate resources. Although using recycled aggregates has great opportunity to preserve healthy environment, the properties and characteristics of recycled aggregates has not been fully investigated yet. Since it is hard to standardize the characteristic of recycled aggregates, all the researchers who study recycled aggregate should perform experiment of their concrete, which will be used for recycled aggregate, to gain the characteristics of their specimens. The characteristic of recycled aggregates could be different by its parent concrete because the parent concrete was designed for its purposes such as permeable, durable and high strength concrete. For example, water to cement ratio of parent concrete will give an impact on water absorption capacity of recycled aggregates which is related to characteristics of concrete issue such as durability, permeability, strength and elastic modulus.

1.2. Objective

Although recycled aggregates are complicated to specify their properties, following properties are well-known factors of recycled aggregate concrete(RAC): a lower density, elastic modulus, strength and a higher water absorption capacity. Due to the fact that recycled aggregate has a proportional mortar which attached to aggregate, it gives a higher porosity and a lower strength to RAC than the normal concrete. To improve these weakness of RAC, this experiment was performed by TSMA[1] and different initial moisture contents of recycled coarse aggregate. In addition, since recycled aggregates require a more amount of water than natural aggregate, shrinkage issue could be a problematic to use RAC in practically. Thus, with ring (AASHTO PP34-99) and dog bone [2] tests, restrained shrinkages of RAC was monitored and compared.

2. Literature Review

2.1. Two Stage Mixing Approach (TSMA)

In concrete structure, interfacial zones (ITZ) between coarse aggregate and mortar matrix plays a critical role in improving strength of concrete. Tam et al. [1] assumed that if the aggregates were wet first and then cementitious materials were added, it would produce a denser ITZ. By assuming that, Tam et al. [1] developed TSMA which is different from normal mixing approach (NMA). NMA allows the following steps: First, coarse and fine aggregate are mixed for one minute. Second, water and cementitious materials are added and mixed for three minutes. However, TSMA follows different steps: First, coarse and fine aggregates are mixed for 60 seconds and then half of water for the specimen is added and mixed for another 60 seconds. Second, cementitious material is added and mixed for 30 seconds. Thirdly, the rest of water is added and mixed for 120 seconds. The specific procedure of TSMA induces a thin layer of cement slurry on the surface of RA which is expected to permeate into the porous old mortar and fill the old cracks and voids. According to Tam et al. [1], the result of his test showed that the compressive strength of RAC was enhanced by strengthening ITZ.

2.2. Initial moisture states of recycled aggregates

Normally, air-dried(AD) aggregates are used for mixing concrete and absorption capacity of aggregates are measured for compensating water. Due to the high absorption capacity of recycled aggregates, C.S. Poon et al. [3] suggested an idea that the properties of the fresh and hardened concrete could be influenced by the initial moisture states of the recycled aggregates. They set the initial moisture states as oven-dried(OD), air-dried(AD) and saturated surface-dried(SSD). The slump of the mixes with AD and SSD states of recycled aggregates did not decrease to zero in 165 min after mixing, although the slump of the mix with OD state of recycled aggregate reached zero at 165 min after mixing. In addition, the result from compressive strength test showed that AD state of recycled aggregate concrete had the highest 28 days compressive strength among the other specimens. The assumed reason of that the use of SSD state of recycled aggregate may be attributed to the bleeding of concrete, which was observed during compaction of the concrete cubes on the vibrating table. The water inside the recycled aggregates may move toward the cement matrix. Those phenomena induce high local water to cement ratio in the boundary area of the recycled aggregates particles. Thus, the compressive strength of the mix with SSD state of recycled aggregate showed the lowest compressive strength. However, in the concrete with OD state of recycled aggregate, water from cement matrix is moved to OD state of recycled aggregate particles. This movement of water may accumulate around the boundary of the recycled aggregate particles. A stronger bonding strength between the cement matrix and the recycled aggregate particles could be originated from the movement of water. On the other hand, another researcher, M. Barra de Oliveira et al.[4], showed that by the compressive strength test of the cylindrical specimen, the concrete with OD state of recycled aggregate recorded the lowest compressive strength among the other specimens. They also performed the compressive strength test of cubic specimens and the result was that concrete with OD state of recycled aggregate had a slightly higher strength than the concrete with SSD state of recycled aggregate.

2.3. Replacement of recycled fine aggregates

When obsolete concrete is demolished by crusher to produce recycled aggregates, the particles of the products have variety sizes and the particles can be categorized by its size as coarse and fine aggregates. Recycled fine aggregate is defined as material that will pass a No.4 sieve (4.75mm). Some researchers [5, 6] have interests that it would be economical for not only using recycled coarse aggregate but also using recycled fine aggregate as new construction materials. They have been studied the proper amount of replacement fine aggregate with recycled fine aggregate to minimize weakness of the concrete with recycled fine aggregate. According to J.M. Khatib [6], when 100 percent natural fine aggregate was replaced by recycled fine aggregate, the compressive strength reduced rapidly below 75 percent of the concrete (50Mpa) with no recycled fine aggregate. Both researchers [5, 6] mentioned that replacing 30 percent fine aggregate with recycled fine aggregate would not be attributed to reduction of compressive strength and elastic modulus. However, L. Evangelista et al. [5] found that the abrasion resistance increased with the replacement of fine aggregate with fine recycled aggregate.

2.4. Creep and shrinkage of recycled aggregate concrete

Normal properties of recycled coarse aggregates are a lower density, a lower elastic modulus and a higher absorption than natural coarse aggregates. These properties are due to the fact that the recycled coarse aggregates have partially adhered mortar which has relatively high volume of porosity [7, 8]. It is hard to deny that properties of recycled aggregates are highly dependent on the amount of adhered mortar. The other proper possibilities to develop properties of recycled aggregates are the method of crushing parent concrete and the irregular shape of recycled aggregate. Thus, a few researchers [9, 10] have interests about creep and shrinkage behavior of recycled concrete. A. Domingo-Cabo et al. [9] observed was that shrinkage of recycled concrete had 70 percent higher shrinkage rate than normal concrete after a period of 180 days in the case of using 100% replacement of recycled aggregates and the shrinkage of recycled concrete kept increasing over 252 days. However, K.K. Sagoe-Crentsil et al. [10] found that the shrinkage of recycled aggregates increased with time and stabilized at about 91 days. The basic reason of the disagreement is that both researchers were not using the same batches such as adding mineral admixtures and using fine recycled aggregates. For creep behavior, A. Doming-Cabo et al. [9] found that the substitution percentage of recycled aggregate affected the creep deformations and the creep of recycled concrete was a 51% higher for a period of 180 days than normal concrete. Thus, for the uncertainties of properties of recycled concrete, we concluded that the shrinkage and creep of recycled concretes were needed to be investigated based on the lab experiment by using recycled aggregate from O’Hare airport.

3. Experimental Procedures

3.1. Materials

The tested recycled aggregates which are shown in Figure 1, were from concrete structures of Chicago O’Hare airport. The mixture designs are organized in Table 1. In the table, N stands for normal concrete, RAC stands for recycled aggregates concrete, and 100, 74 and 0 mean the initial moisture contents of recycled coarse aggregate (%). From the mixture designs, we investigated shrinkage effect from using 100 percent of recycled coarse aggregates and various proportions of recycled fine aggregates. The gradations of recycled coarse aggregates are the same with natural coarse aggregates. Once the fresh concretes are being tested, all the testing specimens are exposed at constant 23℃ and 50% RH.

Table 1. Mixture Proportion

	W/C	lb/yd^3							
		W	C	FlyAsh	NFA	NCA-7	NCA-16	RCA	RFA
N42	0.42	372	709	176	2461	2444	684	-	-
RAC42 100	0.42	372	709	176	2461	-	-	2822	-
RAC42 74	0.42	372	709	176	2461	-	-	2822	-
RAC42 0	0.42	372	709	176	2461	-	-	2822	-
RAC42 C1	0.42	217	414	103	671	-	-	1691	550
RAC42 C2	0.42	217	310	207	671	-	-	1691	550
RAC42 C3	0.42	217	207	310	671	-	-	1691	550
RAC42 C4	0.42	217	414	103	934	-	-	1691	330
N42 M	0.42	372	709		2300	-	-	-	-
R42 M	0.42	372	709	176	1150	-	-	-	942

Figure 1. Recycled coarse aggregates

3.2. Different initial moisture states

For saturated-surface-dry (SSD) conditioned aggregates, according to the ASTM C 127-07, recycled aggregates are immersed in water for 24 ± 4h to fill the pores of the recycled aggregates. Then the recycled aggregates are removed from water, superfluous water around the recycled aggregates is cleaned with a towel or a piece of cloth and the mass of recycled aggregates are determined. For oven-dried (OD) conditioned aggregates, the recycled aggregates (SSD) are dried in the oven to constant mass at temperature of 110 ± 5 ℃ for over 24 hr. The water absorption capacity (AC) of the recycled aggregates is calculated by eq (1). Once the AC value is calculated, then the SSD conditioned aggregates are dried in the air for a few hours to satisfy the target moisture content of recycled aggregates. If the recycled aggregates reached around the target moisture, the recycled aggregates are placed in the buckets and covered with caps on the buckets to protect the recycled aggregates from evaporation.

3.3. Two stage mixing approach (TSMA)

Different from TSMA in the literature review, in our experiment, firstly recycled coarse(RCA) and fine aggregates(RFA) are mixed for 60s and cementitious materials are added and mixed for another 60s. Secondly, three quarters of the total water are supplemented and mixed for 120s. Lastly, rest of the total water and natural fine aggregates are added and mixed for 60s. These procedures are presented in Figure 2. Since recycled fine aggregates and mineral admixtures were used for our experiment, we accepted different steps of TSMA from the TSMA in the literature review.

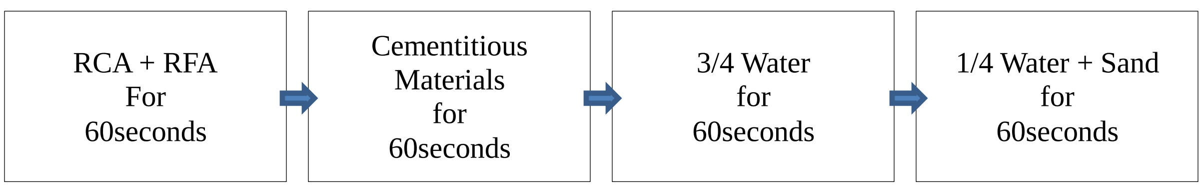

Figure 2. Two Stage Mixing Approach in the experiment

3.4. Prism for drying shrinkage

According to ASTM C157 and ASTM C490, the drying shrinkage was measured. In addition, for the idea using embedded gages, we allowed one different step which is not presented in ASTM C157 and ASTM C490. For keeping the embedded gages in the center of the prism mold, we used fishing guts and scotch tape as presented in Figure 3.

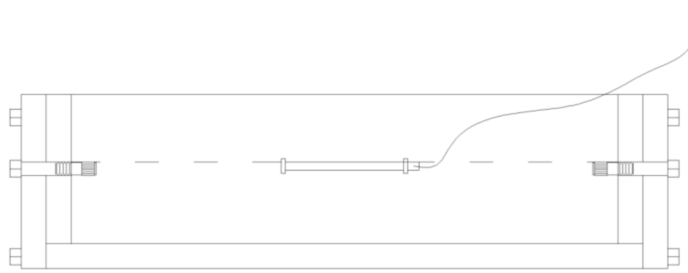

Figure 3. Plane view of mounted embedded gage

3.5. Ring test

According to AASHTO PP34-99, the dimension of ring specimen was selected as shown in Figure 4. For some researchers, the dimension of ring specimen could be variable to reduce testing time. However, our experiment followed AASHTO PP34-99. This test is developed to determine the effects of concrete variations on cracking tendency such as type of aggregates, water content, cement content, cement type and admixtures. As shown in Figure 4, the four strain gages are attached at four equidistant mid-height locations on the interior of the steel ring. For outer mold of ring specimen, we used ϕ18 inches of carbonate board which is non-absorptive material. Once the concrete is cast, the data acquisition system is connected to the specimen as soon as possible. Then we could monitor the strain data of steel ring in every 10 min. With plastic wrap, the top of ring specimen was covered to permit cure and after 24 ± 1h, the outer mold of ring specimen was removed. The plastic wrap was replaced with aluminum tape to induce the drying shrinkage from the outer space of ring specimen.

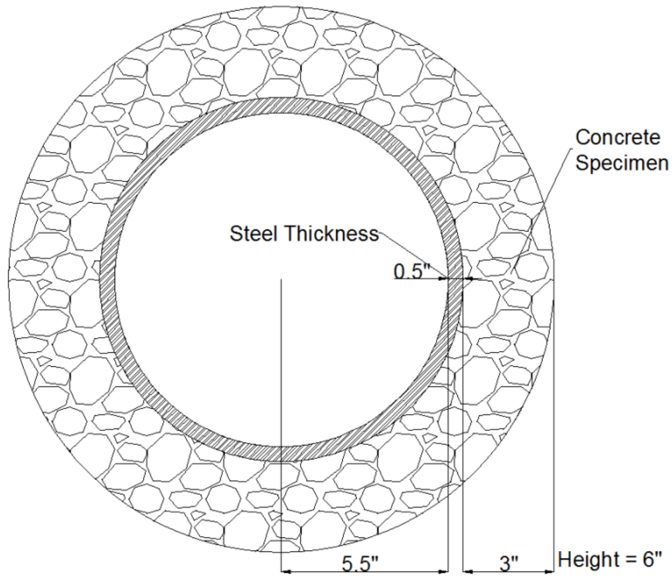

Figure 4. Dimension of ring apparatus

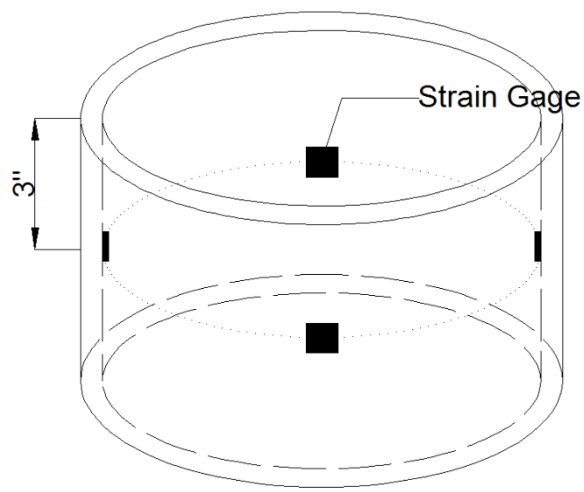

Figure 5. The locations of strain gages

3.6. Dog bone test

By setting two identical dog bone specimens, one specimen is restrained by actuator and the load developed by drying shrinkage is measured. Another specimen is unrestrained and the drying shrinkage is measured. This experiment was stopped at failure of the specimen. From the collected data, we could measure the creep and shrinkage of the specimens. The dimension of this specimen is shown in Figure 6.

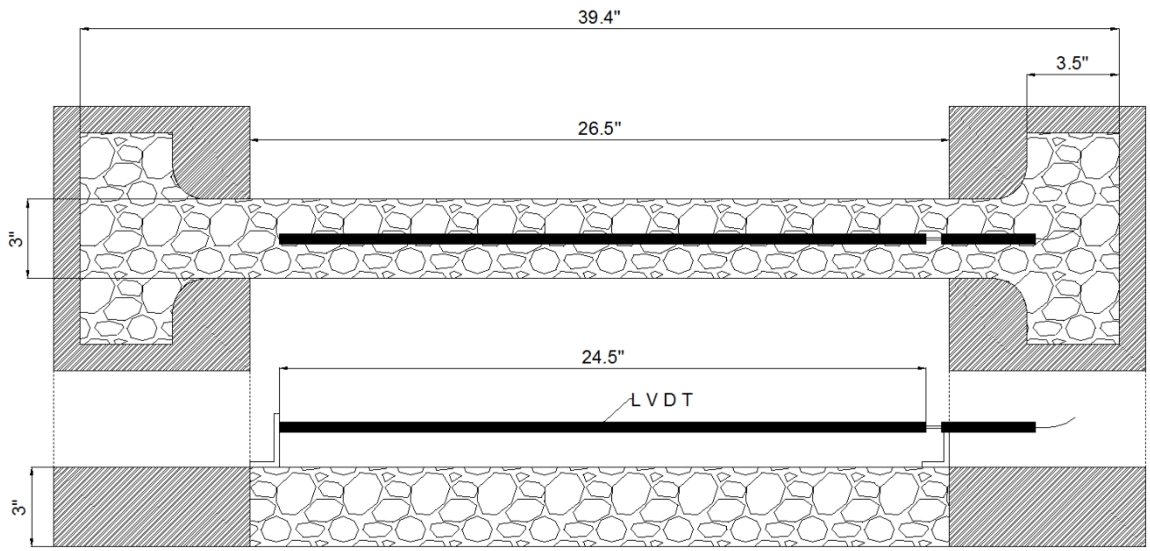

Figure 6. Dimension of dog bone apparatus

4. Analysis

4.1. Initial moisture states of recycled aggregates

Firstly, the absorption capacity of recycled aggregates (AC) is calculated by Eq. (1).

$$\mathrm{AC} = \left(\frac{SSD-OD}{OD}\right) \cdot 10 \quad (1)$$

where SSD is the weight of saturated surface dried recycled aggregates and OD is the weight of oven dried recycled aggregates. Then for the moisture content of the aggregates (MC), we used Eq. (2).

$$\mathrm{TM} = \frac{W_{stock}-W_{OD}}{W_{OD}} \cdot 10 \quad (2)$$

where TM is the quantity total moisture, W_{stock} is the weight of the aggregates in the stock and W_{OD} is the weight of oven-dried aggregates. By Eq. (1) and (2), the moisture content is calculated.

$$\mathrm{MC} = \mathrm{TM} - \mathrm{AC} \quad (3)$$

By Eq. (3), our 0%, 80% and 100% initial moisture contents were calculated and used for the mixing our concrete batches.

4.2. Drying shrinkage of the prisms

According to ASTM C157, the shrinkage of the prisms were calculated by

$$\varepsilon_x = \frac{CRD - initial\ CRD}{G} \qquad (4)$$

where ε_x is the length change of specimen at any age(%), CRD is the difference between the comparator reading of the specimen and the reference bar at any age, and G is the gage length. Normally G value is 10-in because the comparator dial gage specified for use with 10-in. However, in our experiment, the G value was used as the initial lengths of our prism specimens.

4.3. Drying shrinkage of ring specimen

For our ring test, we attached four strain gages which are shown in Figure 5. The gages consist of the Wheatstone bridge system which is a circuit that consists of a power source connected across four components that are resistances. The Wheatstone bridge determines the change in resistance that a gage undergoes when the resistance subjected to a strain. Initially the bridge will balance to produce an output voltage E = 0 and an output voltage develops when resistances R_1, R_2, R_3 and R_4 are varied by amounts $\Delta R_1, \Delta R_2, \Delta R_3$ and ΔR_4 respectively. The response of the bridge can be given by

$$\frac{\Delta E}{V_0} = \frac{r}{(1+r)^2} \cdot \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \qquad (5)$$

where r = $\frac{R_3}{R_4}$ = $\frac{R_2}{R_1}$ and normally it is 1 because in most strain-gage Wheatstone bridge circuits, the nominal value of R_1, R_2, R_3 and R_4 are all the same. Thus Eq. (5) could be expressed as

$$\frac{\Delta E}{V_0} = \frac{1}{4} \cdot \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \tag{6}$$

Theoretically, the strain (ε_a) could be given by

$$\varepsilon_a = \frac{4}{S_g} \cdot \frac{\Delta E}{V_0} \tag{7}$$

where $S_g = S_a(1 - K_t \nu)\varepsilon_a$ is called the gage factor. The value of S_g is 2.0 to 2.1 for the most common type of gage element material. To briefly mention about 1-gage with 3-wire system which used in our experiment, Eq. (7) can be expressed as

$$\varepsilon_a = \frac{4}{S_g} \cdot \left(\frac{V_0 - V_{ref}}{V_s} \right) \cdot \left\{ \frac{1}{1 + 2\left(\frac{V_0 - V_{ref}}{V_s} \right)} \right\} \tag{8}$$

where V_0 is output voltage, V_{ref} is reference voltage and V_s is supply voltage.

4.4. Restrained stress in ring specimen

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

$$\sigma_t = \frac{b^2 \cdot p}{\left(b^2 - a^2\right)} \cdot \left(1 + a^2 / r^2\right) \tag{9}$$

where σ_t is circumferential stress at radius, p is external applied stress, a is inner radius of steel ring, b is outer radius of steel ring, and r is radius of steel ring. The compressive steel stress at the outer face σ_b is then given by Eq. (9)

$$\sigma_b = \frac{\left(a^2 + b^2\right)}{2b^2} \cdot \sigma_a \quad (10)$$

Hence, the average steel stress, assuming linear stress distribution across the steel section is given by Eq. (10)

$$\sigma = \left\{1 + \frac{\left(a^2 + b^2\right)}{2b^2}\right\} \cdot \frac{\sigma_a}{2} \quad (11)$$

The compressive stress at the inner face is known from the measured steel strain and the modulus of steel (E_s =2.05×10^5 MPa was used).

4.5. Dog bone test

The apparatus for dog bone specimens designed for simple and practical use. By using LVDT sensor, the free shrinkage data were collected automatically and the creep was calculated by the hypothesis that free shrinkage can be subtracted from the deformation of the restrained specimens. Thus the creep can be calculated by

$$\varepsilon_{creep} = \left(\varepsilon_{total} - \Sigma\varepsilon_{elastic}\right) - \varepsilon_{free} \quad (12)$$

where ε_{creep} is the total creep strain, ε_{total} is the total strain from restrained specimen, $\varepsilon_{elastic}$ is the elastic deformation from restrained specimen and ε_{free} is the free shrinkage from unrestrained specimen.

5. Results

5.1. Compressive and tensile strength tests

At 1 day after casting, N42 showed the highest compressive strength which was about 13MPa and the RAC 0 showed the lowest compressive strength. However, as specimens aged until 56 days, the RAC 74 reached the compressive strength of N42. Especially, the RAC 100 showed a lower compressive strength than N42 but at 56 days, the compressive strength of RAC 100 reached the compressive strength of N42.

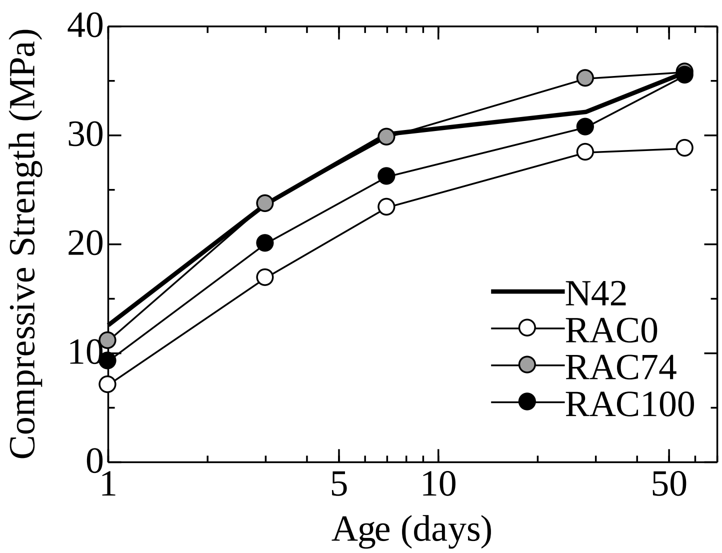

Figure 7. Results of compressive strength of specimens

For the case of tensile strength at 7 days, N42 presented the highest tensile strength than the other RAC specimens. In addition, RAC 0 showed the lowest tensile strength almost half of tensile strength of N42.

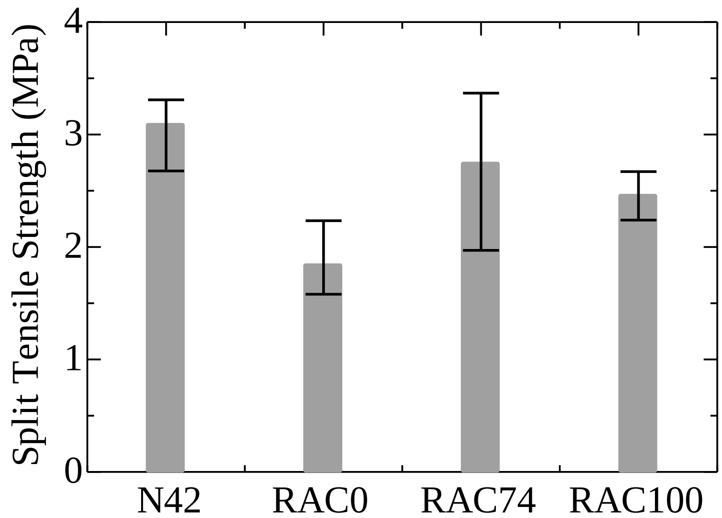

Figure 8. Results of tensile strength of specimens

5.2. Drying shrinkage of ring specimens

Since the ring apparatus collects data from strain of steel ring, steel strain which regards as shrinkage of concrete specimen is shown in Figure 9. Our results indicated that N42 was the highest shrinkage rate which is different from the previous researchers' results [9, 10]. However, in a long term RAC 74 and RAC 100 showed a higher shrinkage rate than N42 after 86 days and 68 days respectively. In addition, the cracking was not developed among all ring specimens.

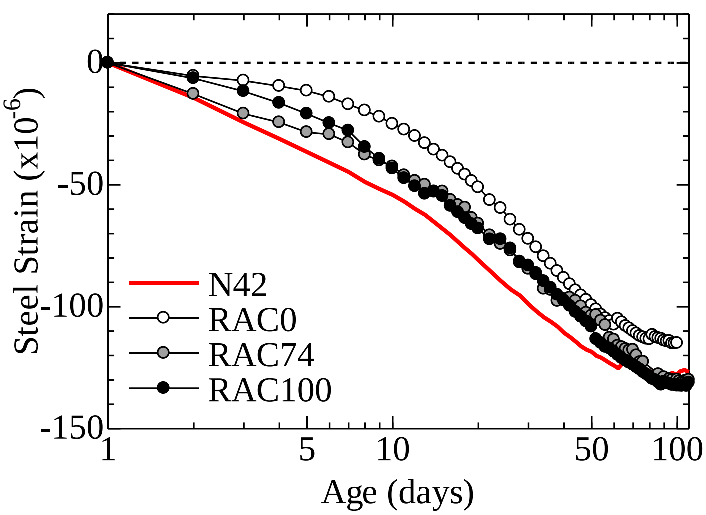

Figure 9. Drying shrinkage of ring specimens

5.3. Dog bone test

At early age, the tensile stress developed substantially but it increased with time. All specimens reached the failure before 7 days because of developing tensile stress to the specimens. RAC 74 failed at a slightly longer age than N42 However, the induced tensile stress in N42 was a higher than RAC 74. The induced tensile stresses at failure were 1.94 MPa for N42 and 1.71 MPa, 1.62MPa, 1.51MPa for RAC 100, RAC 80 and RAC 0 respectively.

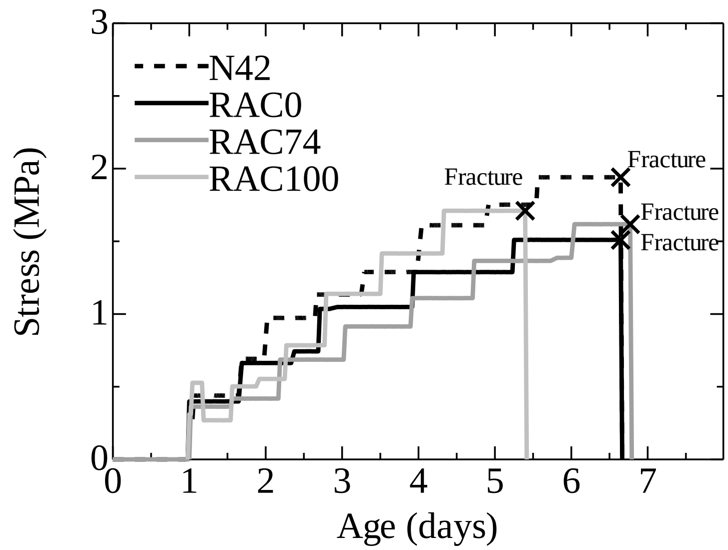

Figure 10. Tensile stress developing of dog bone specimens

Dog bone specimens showed a similar result with ring specimens. All the RAC specimens had a lower shrinkage rate than the N42 specimen in 7 days.

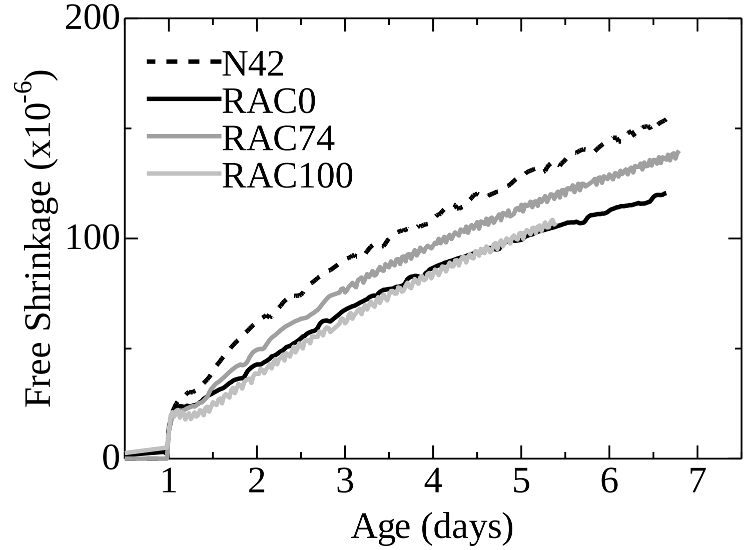

Figure 11. Free shrinkage of dog bone specimens

In the Figure 12, the total tensile creep strain of RAC specimens were lower than that of N42 specimen in 7 days and the creep strain of RAC 74 was similar to the N42.

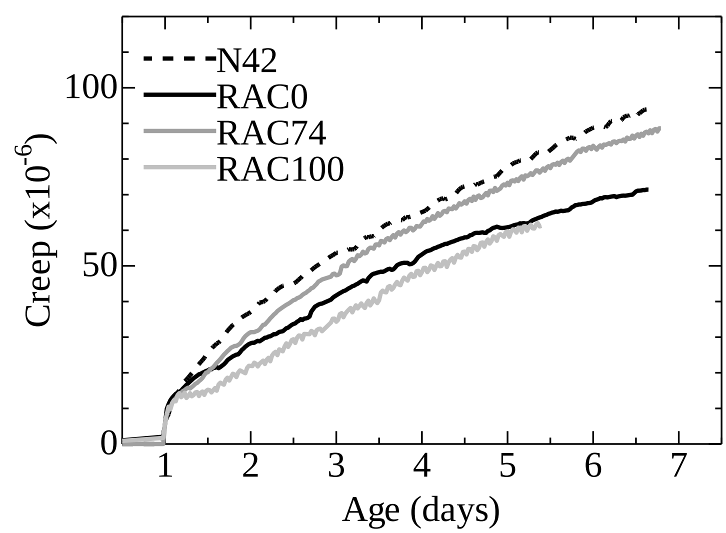

Figure 12. Total creep strain of dog bone specimens

5.4. Free shrinkage of RAC with recycled fine aggregates and fly ash

As increased replacement of sand with recycled fine aggregates, the shrinkage tendencies were increased. In the same way, fly ash could reduce the shrinkage rate.

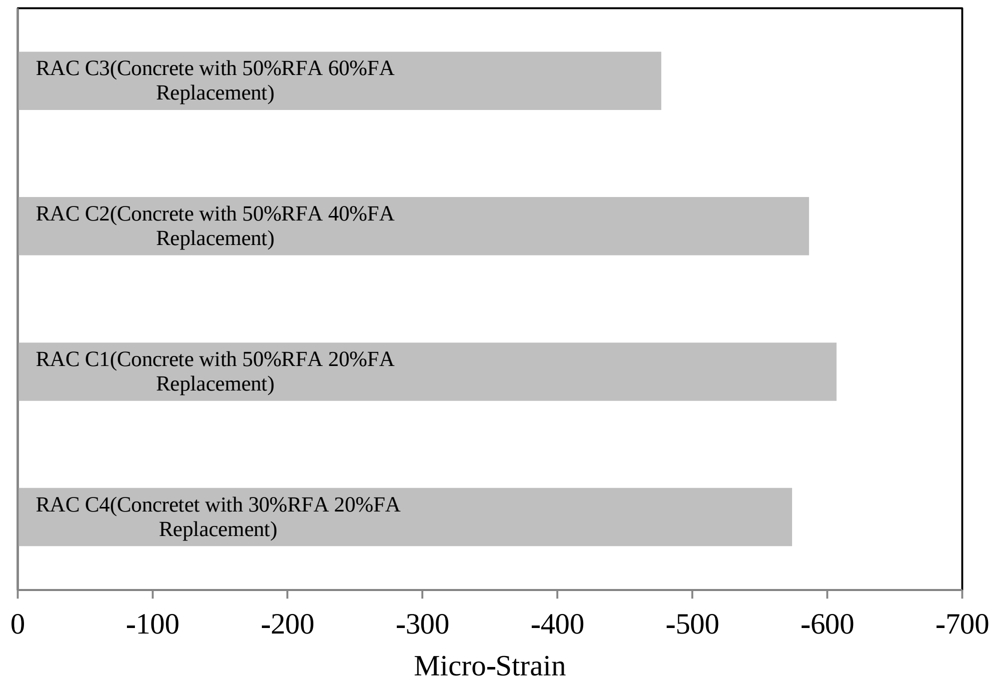

Figure 13. Free shrinkage of series of RAC C at 91days

6. Discussion

6.1. Initial moisture states of recycled coarse aggregates with TSMA

As shown in Figure 7, by TSMA the compressive strength of RAC series were improved. It could be assumed that TSMA produced a denser ITZ than NMA [1]. However, the assumption was not accepted in the case of RAC 0. A denser ITZ can give a higher bonding strength between aggregates and cement paste. During the TSMA, the cementitious materials mixed with aggregates first and water added to impede the hydration of cementitious materials before approaching the aggregates. In other word, the TSMA induces the hydration of cementitious materials on the aggregates at the same time. Thus it could bring a denser ITZ. In the case of RAC 0, probably the oven-dried conditioned recycled coarse aggregates absorbed already the large amount of water first before hydration of cementitious materials during the second stage of mixing in TSMA. In addition, at the mixing period, the actual water to cement ratio was the highest in RAC 0 because of the compensation of water for recycled coarse aggregate. Then the water to cement ratio reached 0.42 with time. Another possible reason is that absorption capacity of recycled aggregates could be variable in every sample. Thus the remains of unhydrated cementitious materials could be increased as absorption capacity of aggregates increases. The compressive strength of RAC 74 and 100 improved by TSMA since the compensation of water for the each initial moisture states of recycled coarse aggregates were a smaller than RAC 0.

6.2. Shrinkage of ring and dog bone specimens

Previous studies indicated that RAC has a higher free shrinkage rate than normal concrete [5, 6]. However, in our experiment, drying shrinkage rate of RAC showed a lower shrinkage rate than normal concrete as shown Figure 9 and 11. Especially RAC 0 showed the lowest shrinkage rate. The possible reason of that, our apparatus can monitor the shrinkage behavior after 1 day thus it cannot detect the shrinkage in 1day. Thus some amount of shrinkage could be missing during 1 day. Autogenous shrinkage of RAC might be a higher than normal concrete before demolding specimens. In addition if the 0% initial moisture states of recycled coarse aggregates tended to hold the water and let the water out from the aggregates later, the hydration process could be accelerated at that time. Thus the shrinkage rate of RAC 0 could be suddenly dropped at later as shown in Figure 9. In long term, the shrinkage behavior of RAC could be a higher than normal concrete. For example, RAC 74 and 100 showed a higher shrinkage rate than N42 after 86 days and 68 days respectively.

6.3. Cracking by restrained stress of ring and dog bone specimens

As shown in Figure 7 and 14, restrained stress of RAC in early age was a lower than N42. The development of the restrained stress increased with time. At the early age, restrained stress in N42 developed faster than RAC. Normally as hardened, the restrained stress can be increased. As previously mentioned, the hydration process could be slow in RAC thus it could give a lower elastic modulus for RAC. This phenomena leads to less induced stress to the RAC by steel ring and actuator of dog bone apparatus. If the restrained stress in ring specimens compared with its tensile strength, the stress to strength ratio was comparatively lower than N42. From this, we could observe that the cracks at outer surface of ring specimens were not presented. Another possible reason of non-visible cracking is that the steel thickness was not sufficient to restrain the ring specimens. Theoretically, if the thickness of steel ring increased, the restrained stress in the specimens could be increased as well. Then, the cracking at outside of the specimen could be detected since a greater residual stress in the specimen is developed.

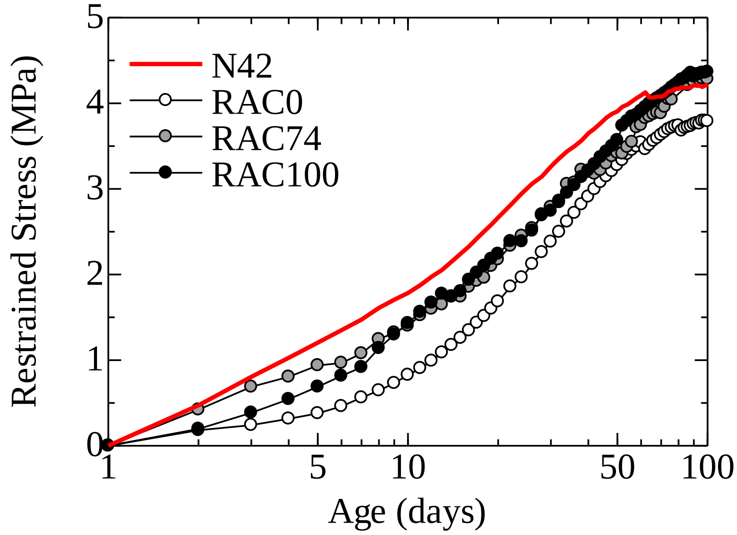

Figure 14. Restrained stress of ring specimens

6.4. Replacements of recycled fine aggregates and fly ash

As shown in Figure 15, it is evident that the free shrinkage rate was increased as amount of using recycled aggregates. Since the weak and less homogeneous parts of old concrete could be departed easily from the concrete in crushing process, the most part of recycled fine aggregates were made of the mortar which has a relatively high volume of porosity than coarse aggregates. Thus, the high volume of porosity in recycled fine aggregates results in a relatively higher free shrinkage rate than normal concrete. In addition, if a greater amount of cement was replaced by fly ash, the free shrinkage rate could be reduced because the hydration products from cement also decrease greatly.

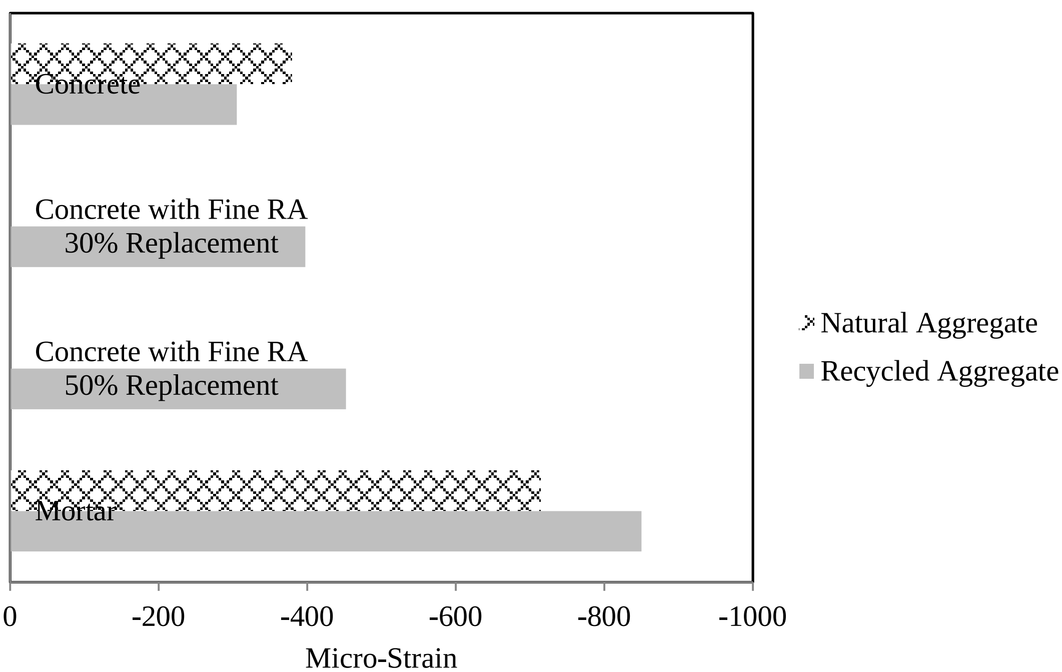

Figure 15. Shrinkage of specimens at 56 days

7. Conclusions

Our experiment was performed to investigate the properties of recycled aggregate concrete (RAC). Specially, shrinkage of RAC was focused on this study when the specimens are drying and restrained by different approaches such as TSMA, different initial moisture states of recycled coarse aggregates, ring and dog bone apparatuses. From these experiments, we concluded that

- TSMA is an effective technique for increasing strength of a given RAC mixture.
- Initial moisture states of RCA is one of the most important variables that impact strength and shrinkage.
- The RCA with using 74% initial moisture states of recycled coarse aggregates reached almost the same compressive strength of normal concrete when using TSMA
- When oven-dried RCA is used, strength is used to be greatly reduced but free shrinkage as measured in this study was low.
- At early age, RCA showed lower shrinkage rate than normal concrete but the trend tended to change in the long term.
- Restrained stress under drying conditions developed slowly in RAC specimens, thus cracking in ring specimens did not occurred.
- The creep to free shrinkage ratio for RAC was similar to that of normal concrete at 7 days under restrained conditions.

- When greater volume of recycled fine aggregates and fly ash was used, free shrinkage of the specimens was reduced.

8. References

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