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# Influence of Type and Replacement Level of Recycled Aggregates on Concrete Properties

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# ABSTRACT

Test results of nine recycled aggregate concrete and a control concrete using only natural aggregates are reported. The replacement levels of recycled grade Ⅰ and grade Ⅲ coarse aggregates and recycled grade Ⅱ fine aggregate were 30, 50 and 100%, respectively. Slump loss and the amount of bleeding against elapsed time were recorded for fresh concrete. Compressive and tensile strengths, moduli of rupture and elasticity, and shrinkage strain were also measured for hardened concrete. The properties of fresh and hardened concrete tested together with a comprehensive database were evaluated according to the relative water absorption of aggregates combining the quality and volume of recycled aggregates used. In addition, the properties of hardened concrete with different replacement level and quality of recycled aggregates were compared with design equations proposed by ACI 318-05 and others. Test results clearly showed that the properties of fresh and hardened concrete containing recycled aggregates were significantly dependent on the relative water absorption of aggregates. In addition, the moduli of rupture and elasticity of recycled aggregate concrete were lower than the design equations specified in ACI 318-05, when the relative water absorption of aggregates is above 2.5 and 3.0, respectively.

**Keywords**: recycled aggregate, properties of concrete, relative water absorption of aggregates, ACI 318-05.

# INTRODUCTION

The global concrete industry will annually require 8~12 billion tones of natural aggregates after the year 2010 as more than three-quarters of volume of concrete is commonly occupied by aggregates[1]. In addition, the amount of waste concrete demolished from old buildings or reconstruction is rapidly rising in the world[2]. Such a large amount of natural aggregate consumption and landfill of waste concrete would be responsible for destruction of the environment. These environmental issues have attracted many researches[1-7] to utilize recycled coarse aggregate; as a result, the partial use of recycled coarse aggregate for low level applications such as fillers in road construction and concrete blocks becomes more common[1]. However, there are still lots of outstanding issues before practical utilization of recycled aggregates for high level applications such as structural concrete, though it was reported that no systematic strength reduction appeared in concrete replaced with below 30% recycled coarse aggregate[8]. Recycled aggregates have commonly poor quality compared with natural aggregates owing to lower stiffness caused by crushing of waste concrete and higher water absorption capacity given by old cement paste attached to the surface of recycled aggregates. The irregularity of particle shape and texture of recycled aggregates would also force concrete properties to be larger fluctuating.

In the past few years, recycled aggregates of high quality have been produced and were successfully used to produce structural concrete, although most of the work has focused on replacing recycled fine aggregate[8]. From the test on high-performance concrete having recycled aggregates with high water absorption, Tu et al.[1] showed that a larger amount of recycled aggregates has a minor effect on the initial slump of concrete but an adverse effect on the workability against elapsed time. In addition, it was proposed by Poon et al.[9] that the replacement level of recycled coarse aggregate controlled at air-dried state should not exceed 50 % to produce concrete having less workability loss and higher compressive strength. On the other hand, it was observed from tests carried out by Khatib[8] that 91-day compressive strength of concrete using recycled fine aggregate with replacement level below 50% was similar to that of concrete with only natural aggregates and a strength reduction by only 10% was recorded for concrete with replacement level of 100%. Rahal[10] also showed that the compressive strength of concrete using recycled coarse aggregate having water absorption of 3.47% was 90% of that of natural aggregate concrete. Therefore, it is noted that workability and compressive strength development of recycled aggregate concrete are significantly dependent on the type, quality and replacement level of recycled aggregates.

The present study investigated the influence of type and replacement levels of nine recycled aggregate concrete and a control concrete using only natural aggregates on the properties of concrete. Slump loss and the amount of bleeding with the elapse of time were recorded for fresh concrete. Compressive and tensile strengths, moduli of rupture and elasticity, and shrinkage strain were also measured for hardened concrete. The properties of concrete tested were evaluated according to the relative water absorption of aggregates combining the water absorption capacity and volume of recycled aggregates. In addition, different properties of hardened concrete tested together with existing results in a database compiled by Chung and Yang[11] were compared with design equations proposed by ACI 318-05[12] and Oluokun[13].

## RESEARCH SIGNIFICANCE

Utilization of recycled aggregates for structural concrete would contribute to the solution of the disposal of construction waste and the difficulty of aggregate production. The influence of the type, quality and replacement level of recycled aggregates on the properties of concrete was studied using ten concrete mixes produced in this investigation and a comprehensive database having a total of 795 test results. The present study clearly showed that the properties of fresh and hardened concrete containing recycled aggregates were significantly dependent on the relative water absorption of aggregates combining the water absorption capacity and volume of recycled aggregates. In addition, the mechanical properties, such as moduli of elasticity and rupture of recycled aggregate concrete having the relative water absorption of aggregate less than 2.5 were higher than those predicted by the formulae specified in ACI 318-05 for concrete with natural aggregate.

# EXPERIMENTAL PROGRAMME

## Materials

Ordinary Portland cement, natural coarse and fine aggregates, recycled coarse and fine aggregates, water, and superplasticizer were used for different concrete mixes. Maximum sizes of coarse and fine aggregates were selected to be 25 mm (1 in.) and 5 mm (0.2 in.), respectively. Locally available crushed granite and sand were used for the natural coarse and fine aggregates, respectively, in saturated surface dried-states. To maintain the saturated surface dried-state condition of aggregates used, the surface of aggregates immersed in water for 24 hours was smoothly rubbed with a dried towel just before aggregates were added to the mixer pan.

To get proper recycled aggregates, waste concrete obtained from columns and beams of old buildings was grounded by impact crusher, and then foreign elements such as small pieces of steel and dust within the crushed aggregates were removed by air blower and finally cleansing process was iteratively carried out until achieving the required quality of recycled aggregates. The washed recycled aggregates were sieved and tested according to the Korean Industrial Standard (KS)[14]. The content of old cement paste on the surface of recycled aggregates, $R_P$, was measured using hydrochloric acid solution method proposed by Kasami et al.[15] as below:

$$R_P = \frac{A_1 - B_1}{A_1} \times 100 \tag{1}$$

where $A_1$ and $B_1$ = weight of original recycled aggregate and weight of recycled aggregate subsided by hydrochloric acid solution for 24 hours, respectively.

The test results on the physical properties of natural and recycled aggregates, such as maximum size, specific gravity, water absorption, content of cement paste on the surface of recycled aggregates and fineness modulus, are given in Table 1. Figure 1 also shows the particle distribution of fine and coarse aggregates that was within the standard grading curves specified in the KS. The specific gravity and water absorption of recycled aggregates were greatly dependent on the content of cement paste on their surface, indicating that the higher the content of old cement paste, the higher the water absorption as shown in Table 1. All aggregate used had a specific gravity above 2.2 as specified by the KS. The grading of coarse and fine aggregates used in the current investigations was finally identified according to their water absorption as specified in the KS: Grade I, II and III coarse aggregates should have water absorption less than 3%, 5% and 7 %, respectively; whereas grade I and II fine aggregates have water absorption less than 5% and 10%, respectively. In addition, the KS recommends the useful application of recycled aggregates according to their grades: grade Ⅰ for structural concrete, grade Ⅱ for non-structural concrete and grade Ⅲ for non-structural concrete or filler for road construction. This indicates that the recycled aggregate of grade Ⅰ has a higher specific gravity, a lower water absorption capacity, and a fewer amount of impurities than those of grades Ⅱ and Ⅲ. The grade of recycled aggregates determined from comparisons of test results and the recommendations of KS is presented in Table 1.

## Mix Proportions

Ten concrete mixes using different recycled and control aggregates given in Table 1 were prepared. Table 2 refers to the details of mixing proportions, based on the saturated surface-dried condition of aggregates, of different concrete mix designed. The replacement levels of recycled aggregates were 30 %, 50 % and 100 %. The designed compressive strength and initial slump of the control mix using only natural aggregates were 40 MPa (5800 psi) and 200 mm (7.87 in.), respectively. As a result, water-cement ratio (W/C) of 50 % by weight and fine aggregate to total aggregate ratio (S/A) of 42 % by volume were employed in all concrete mixes. In addition, to improve initial slump of fresh concrete, commercially available poly carboxylate-based superplasticizer was added by 4.2% relative to the weight of cement as shown in Table 2.

The concrete mix notation given in Table 2 includes two parts except for the control mix. The first part indicates the type of recycled aggregates: RGⅠ for recycled coarse aggregate of grade Ⅰ, RSⅡ for recycled fine aggregate of grade Ⅱ, and RGⅢ for recycled coarse aggregate of grade Ⅲ. The latter part is used to identify the replacement level of recycled aggregates. For example, RGⅠ-30 indicates a replacement level of recycled grade I coarse aggregate of 30%.

## Casting, curing and testing

Natural and recycled coarse aggregate and natural and recycled fine aggregates, respectively, were added into a $0.35m^3$ capacity mixer pan. The aggregates together with cement were dry-mixed in the mixer pan for 3 min, and then water coupled with superplasticizer was added and mixed in for another 3 min. Slump of each fresh concrete mix was measured at 0 (initial), 30, 60 and 90 minutes after mixing. To estimate the amount of bleeding of fresh concrete, 1000 mL graduated cylinder having cover to prevent evaporation of the bleed water was employed. Bleed water on the upper surface of the sample concrete having volume of 800±10 mL within the graduated cylinder was recorded at 10 minutes intervals for the first 60 minutes and thereafter at 30 minutes intervals for another 3 hours. Cylinder specimens of 100 mm (3.94 in.) diameter and 200 mm (7.87 in.) high were cast to evaluate compressive and splitting tensile strengths, and modulus of elasticity of each concrete mix.

Immediately after casting, all specimens were cured at a constant temperature and relative humidity of 23 ± 2 °C and 70 ± 5%, respectively, until tested at the specified age. All steel moulds were removed at an age of one day.

Compressor meter having dial gages and electrical resistance strain gages (ERS) were mounted on the cylinder specimens to determine the modulus of elasticity of concrete, which can be calculated at the 45% of peak stress[12]. The modulus of rupture of concrete was also measured using prismatic beams of 75×75×450 mm (2.95×2.95×17.7 in.) dimensions under a symmetrical one-point top loading system. Compressive strengths of concrete were measured at 1, 3, 7, 28, 56 and 91 days using a 500 kN (112 kip) capacity universal testing machine in order to investigate the strength development with age. On the other hand, splitting tensile strength, and rupture and elastic moduli of concrete were measured at 28 days only. Shrinkage strains of concrete were monitored using 100 mm (3.94 in.) waterproof electrical resistance strain gages (ERS) attached to the center of cylinder specimens of 150×300 mm (5.9×11.8 in.) in size. The shrinkage specimens were kept in the same curing environment as specified above throughout the test. The ERS readings from the cylinder specimens were recorded automatically using a data logger.

The testing procedures for the above experiments were carried out in accordance with the specifications of the KS for testing ordinary Portland cement concrete; that is similar to the American Society for Testing and Materials standards (ASTM standards)[16].

## TEST RESULTS AND DISCUSSION

Table 3 gives the summary of test results of the slump $S_L$ of fresh concrete and mechanical properties of hardened concrete such as compressive $f_c^{'}$ and splitting tensile $f_t$ strengths, and rupture $f_r$ and elastic $E_c$ moduli. The splitting tensile strength, and rupture and elastic moduli are normalized by the square root of compressive strength as proposed by most building codes[12].

To examine the influence of quality and replacement level of recycled aggregates on the workability and compressive strength of concrete, Ohshima et al.[17] proposed relative water absorption $Q_w$ of aggregates defined as below:

$$Q_w = \frac{aQ_{NG} + bQ_{NS} + cQ_{RG} + dQ_{RS}}{a+b+c+d} \tag{2}$$

where $Q_{NG}$, $Q_{NS}$, $Q_{RG}$ and $Q_{RS}$ = water absorptions of natural coarse and fine aggregates, and recycled coarse and fine aggregates, respectively, and $a$, $b$, $c$ and $d$ = mixed unit volumes (in $l$/m$^3$) of natural coarse and fine aggregates, and recycled coarse and fine aggregates, respectively.

The relative water absorption of aggregates in different concrete mixes examined is calculated and given Table 3.

A total of 795 test results of concrete with different quality and replacement level of recycled aggregates, carried out in both Europe and Asia, was originally compiled by Chung and Yang[11]. The database includes 177 concrete mixes with only natural coarse and fine aggregates, 502 concrete mixes with recycled coarse and natural fine aggregates, 45 concrete mixes with natural coarse and recycled fine aggregates, and 71 concrete mixes with recycled coarse and fine aggregates. Details of batching and mixing of concrete are not provided in the database.

Water-cement ratio (W/C) by weight and fine aggregate to total aggregate ratio (S/A) by volume of concrete mixes in the database ranged from 23% to 75% and 29% to 55%, respectively. The replacement level of recycled aggregates varied from 0% to 100%. The water absorptions of natural coarse and fine aggregates used were from 0.54 to 2.47 and 0.76 to 2.7, respectively, and those of recycled coarse and fine aggregates were from 1.12 to 9.87 and 1.28 to 8.9, respectively.

In the following sections, test results obtained from the present study together with the available results collected in the database are examined according to the relative water absorption of aggregates. The mechanical properties of recycled aggregate concrete are also compared with empirical design equations proposed by ACI 318-05[12] and Oluokun[13] calibrated for natural aggregate concrete.

### Initial slump

The initial slump of fresh concrete slightly decreased with the increase of the replacement level of recycled aggregates but was hardly affected by their type as shown in Table 3. As a result, no clear relation between the initial slump and the relative water absorption of aggregates would be drawn. There is no firm conclusion regarding the effect of using recycled aggregates on the initial workability of concrete. Poon et al.[18] observed that the initial slump increased with the increase of the replacement level of recycled coarse aggregates. However, Lin et al.[19] concluded that the initial slump of recycled aggregate concrete was mainly affected by water-cement ratio and volume ratio of recycled coarse aggregate rather than the type of recycled aggregates. In addition, particle distribution and shape of aggregates would also have an influence on the initial slump of fresh concrete[20]. Therefore, various mixing conditions such as water-cement ratio, water-reducing admixture ratio, and grading and volume of recycled aggregates would control the initial slump of recycled aggregate concrete.

### Slump loss

Slump of fresh concrete nearly linearly decreased with the elapse of time as given in Table 3. Yang and Kim[21] showed that the relative slump of fresh concrete against elapsed time, which is valuable index to evaluate workability loss of concrete, can be approximately expressed as below:

$$\frac{S_L}{\left(S_L\right)_i} = kT + 1 \tag{3}$$

where $(S_L)_i$ = initial slump measured immediately after mixing (mm), $S_L$ = slump of fresh concrete tested at optional time $T$ (in minute), and $k$ = rate of slump loss (mm/min).

Figure 2 presents the effect of the relative water absorption of aggregate $Q_w$ on the slope of slump loss $k$ of different concrete mixes tested which is determined by a linear regression analysis. The slope of slump loss increases with the increase of $Q_w$, indicating that higher water absorption capacity and replacement level of recycled aggregates reduce the workability of fresh concrete with the elapse of time. Tests carried out by Chung and Yang[11] showed that recycled aggregates immersed in water can still absorb moisture even after 1 hour although the rate of absorption decreased with the elapse of time. From Table 3 and Fig. 2, therefore, it would be concluded that the type and replacement level of recycled aggregates have much more significant effect on the workability loss than the initial slump of fresh concrete.

## Bleeding

Variation of the amount of bleeding of the control mix and concrete containing 100% recycled coarse or fine aggregate against the elapsed time is shown in Fig. 3. The trend of the bleeding of other specimens tested was similar to that of concrete with 100% recycled coarse or fine aggregate, therefore it is not presented in Fig. 3. No bleeding in the control concrete appeared until early 30 minutes. On the other hand, bleedings in RSⅡ-100 and RGⅢ−100 specimens developed after 60 and 150 minutes, respectively. The increasing rate of the amount of bleeding against the elapsed time decreased with the increase of water absorption of recycled aggregates as shown in Fig. 3.

Figure 4 also shows that the total amount of bleeding of fresh concrete decreases with the increase of the relative water absorption of aggregates. Kim et al.[22] also concluded that the total amount of bleeding of concrete decreased with the increase of replacement level of recycled coarse aggregates as the bleed water would be absorbed by the old cement paste on the surface of recycled aggregates. On the other hand, Poon et al.[18] showed that the total amount of bleeding of concrete slightly increased with the increase of replacement level of air-dried recycled coarse aggregates, a reverse trend to test results obtained from the Kim et al.[22] and present studies. As pointed out by Neville[20], the tendency of bleeding largely depends on the properties of cement, water content, and the addition of pozzolanas or other fine materials. Further investigations would be needed to understand the bleeding characteristics of recycled aggregate concrete as there are very limited test data. From Fig. 2 and Fig. 4, it would be observed that the variation of properties of fresh concrete with the elapse of time is significantly affected by the relative water absorption of aggregates that is directly related to the content of cement paste on the surface of recycled aggregates.

### Compressive strength

Relative compressive strength $f_c'/\left(f_c'\right)_C$ of recycled aggregate concrete against age is represented in Fig. 5, where $\left(f_c'\right)_C$ is the compressive strength of the control specimen. Compressive strength of concrete with RGⅠ aggregate of different replacement levels was similar to that of control concrete. However, compressive strength of concrete containing either RSⅡ or RGⅢ aggregate was lower than that of the control specimen by 20~40%; especially, much lower relative compressive strength is developed at ages of 1 and 3 days as shown in Fig. 5 (b) and (c). On the other hand, relative compressive strength of recycled aggregate concrete increased at ages of 56 and 91 days, indicating that the development of long-term strength of recycled aggregate concrete is more favorable than that of natural aggregate concrete. This may be attributed to further cementing action of unhydrated cement paste on the surface of recycled aggregates as pointed out by Khatib[8]. In addition, the absorbed water in the recycled aggregate may have helped with internal curing by providing a source of water to react with the cement.

Figure 6 shows the influence of $Q_w$ on the relative compressive strength of recycled aggregate concrete at age of 28 days for the current specimens and 275 database specimens having $0.3 \leq W/C \leq 0.64$. The relative compressive strength of recycled aggregate concrete decreases with the increase of $Q_w$, although wide variation is observed for the same $Q_w$ as the relative compressive strength can also be significantly affected by water-cement ratio and curing condition[10]. When $Q_w$ is below 1.8, compressive strength of recycled aggregate concrete maintains more than 80% of that of the control concrete with natural aggregates, while compressive strength of recycled aggregate concrete having $Q_w$ above 5.5 significantly drops by as much as about 40% of that of the control concrete with natural aggregates as depicted in Fig. 6. In particular, a lower relative compressive strength exhibited by concrete using RSⅡ than in concrete with RGⅢ, although $Q_w$ of concrete using RSⅡ was lower than that of concrete with RGⅢ as given in Table 3. Insufficient hydration and a weak interface-zone formed between different components of concrete matrix owing to a large amount of old cement paste on the surface of recycled aggregates can be the cause of a poor development of compressive strength of concrete[1]. In addition, inconsistence surface of recycled fine aggregate would produce lots of micro-cracks between aggregates and cement paste, which would reduce concrete compressive strength.

## Splitting tensile strength

The influence of $Q_w$ on the normalized splitting tensile strength $f_t / \sqrt{f_c^{'}}$ of concrete mixes tested and 134 test specimens from the database, having 0.3≤W/C≤0.64 is plotted in Fig. 7. The empirical equation ( $f_t / \sqrt{f_c^{'}}$ = 0.53) proposed by Oluokun, based on experimental results of natural aggregate concrete, is also presented in the same figure. The splitting tensile strength of concrete with RGⅠ aggregate and control concrete was larger than $0.53\sqrt{f_c^{'}}$, whereas that of concrete containing more than 50% of RSⅡ or RGⅢ aggregate was lower than $0.53\sqrt{f_c^{'}}$ as given in Table 3 and Fig. 7. It is also observed that the normalized splitting tensile strength of recycled aggregate concrete decreased with the increase of $Q_w$ and it was less than 0.53 for most specimens having $Q_w$ larger than about 2.25.

## Modulus of rupture of concrete

Figure 8 presents the effect of $Q_w$ on the normalized rupture modulus $f_r / \sqrt{f_c^{'}}$ of recycled aggregate concrete tested and 197 test results from the database. The normalized rupture modulus $f_r / \sqrt{f_c^{'}}$ of recycled aggregate concrete is commonly decreased with increase of $Q_w$ as presented in Fig. 8. A rupture modulus higher than $0.62\sqrt{f_c^{'}}$ specified in ACI 318-05 is exhibited by the control concrete and concrete with RGⅠ aggregate, regardless of the replacement level of RGⅠ, whereas the rupture modulus of concrete containing more than 50% of RSⅡ or RGⅢ aggregate, is slightly lower than that suggested in ACI 318-05, when $Q_w$ is above about 2.5, as given in Table 3 and Fig. 8. The reduction in tensile strength and rupture modulus as presented in Fig. 7 and Fig. 8 would be attributed to the weaker bond among different components of the concrete matrix owing to the cement paste on the surface of recycled aggregates.

### Modulus of elasticity of concrete

The influence of the relative water absorption $Q_w$ of aggregates on the normalized elastic modulus $E_c / \sqrt{f_c^{'}}$ of the specimens tested in the present study and 162 concrete results from the database is presented in Fig. 9. The modulus of elasticity of concrete tested in the present study except for RGⅢ-100 specimen was above $4700\sqrt{f_c^{'}}$ specified in ACI 318-05 as shown in Fig. 9. In addition, the elastic modulus of concrete containing RSⅡ aggregate was nearly similar to that of concrete with RGⅢ aggregate for the same replacement level. The normalized elastic modulus $E_c / \sqrt{f_c^{'}}$ of recycled aggregate concrete decreased with the increase of $Q_w$, indicating that a lower elastic modulus exhibited by recycled aggregate concrete having $Q_w$ above 3.0 than that proposed by ACI 318-05 for concrete with natural aggregates as presented in Fig. 9. Tavakoli and Soroushian[3] pointed out that the impact effect during the crushing process of waste concrete would result in poor strength and stiffness of recycled aggregate; that would reduce the elastic modulus of recycled aggregate concrete.

## Shrinkage strain

Shrinkage strains of control specimen and concrete containing 100% recycled coarse or fine aggregate against age are plotted in Fig. 10. The behavior of the shrinkage strain of other specimens tested was similar to that of concrete with 100% recycled coarse or fine aggregate; therefore, not presented in Fig. 10. Most shrinkage strains in all concrete tested occurred at the first 10 days after casting and then the increasing rate of shrinkage strain was slowed down. In addition, a lower amount of shrinkage strains developed in recycled aggregate concrete than in control concrete until the age of about 10 days owing to the initial higher water absorption capacity of recycled aggregate. However, the amount of shrinkage strains of recycled aggregate concrete was larger than that of control concrete with the increase of age. This trend was more notable in RSⅡ-100 and RGⅢ-100 specimens than RGⅠ-100 specimen as shown in Fig. 10. The influence of the quality and replacement level of recycled aggregate on shrinkage strains of concrete after 10 and 91 days is presented in Fig. 11. The long-term shrinkage strain of recycled aggregate concrete was more prominent than the short term effect and it increases with the increase of $Q_w$ as shown in Fig. 11. Hansen and Almudaiheem[23] showed that the volume and stiffness of aggregates significantly contributed to the restraint of the amount of concrete shrinkage. Therefore, recycled aggregate with a lower stiffness would cause shrinkage more in concrete at long-term age.

## CONCLUSIONS

Nine recycled aggregate concrete and a control concrete using only natural aggregates were tested to investigate the effect of type and amount of recycled aggregate on fresh and hardened concrete properties. The replacement ratios of recycled aggregates were 30, 50 and 100%. The properties of concrete tested together with existing results in a database were examined according to the relative water absorption of aggregates combining the quality and amount of recycled aggregate and compared with design equations. The following conclusions may be drawn:

1. The initial slump of recycled aggregate concrete was nearly independent on the relative water absorption of aggregates, while the rate of slump loss increased with the increase of the relative water absorption of aggregates.

2. The total amount and increasing rate of bleeding of fresh recycled aggregate concrete decreased with the increase of the relative water absorption of aggregates.

3. Compressive strength of concrete using RGⅠ aggregate was similar to that of control specimen. However, compressive strength of concrete containing either RSⅡ or RGⅢ aggregate was 0.6~0.8 of that of control specimen at early ages of 1 and 3 days and slightly increased with the increase of age.

4. The relative compressive strength of recycled aggregate concrete to that of control concrete with only natural aggregates decreased with the increase of the relative water absorption of aggregates. In particular, a lower relative compressive strength exhibited by concrete containing RSⅡ aggregate than concrete with RGⅢ aggregate, although the water absorption capacity of

RSⅡ aggregate was lower than that of RGⅢ.

5. The normalized splitting tensile strength, and moduli of rupture and elasticity of recycled aggregate concrete decreased with the increase of the relative water absorption of aggregates.
6. The moduli of rupture and elasticity of recycled aggregate concrete were lower than the design equations specified in ACI 318-05, when the relative water absorption of aggregates is above 2.5 and 3.0, respectively.
7. Lower amount of shrinkage strain was exhibited by recycled aggregate concrete than control concrete until the age of 10 days. However, the long-term shrinkage strain of recycled aggregate concrete increased with the increase of the relative water absorption of aggregates, showing a higher shrinkage strain than that of control concrete.

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# Table and Figure

## List of Tables:

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Table 1-Properties of aggregates used.

| Type | | Grade* | Maximum size (mm) | Specific gravity** | Water absorption (%) | $R_P$# (%) | Fineness modulus |
|---|---|---|---|---|---|---|---|
| Coarse aggregate | Natural | - | 25 | 2.6 | 1.6 | - | 7.12 |
| | Recycled | Ⅰ | | 2.53 | 1.93 | 2.17 | 7.22 |
| | | Ⅲ | | 2.4 | 6.24 | 7.2 | 7.36 |
| Fine aggregate | Natural | - | 5 | 2.58 | 1.62 | - | 2.63 |
| | Recycled | Ⅱ | | 2.36 | 5.37 | 6.0 | 3.09 |

* Grade of recycled aggregates according to the Korean Industrial Standard.

** Specific gravity of all aggregates used was measured in a saturated surface-dried (SSD) condition.

\# $R_P$ = content of old cement paste on the surface of recycled aggregates obtained from Eq. (1).

1 mm = 0.039 in.

Table 2-Details of concrete mixes investigated

| Mix | type of aggregates | | $R_{RG}$ | $R_{RS}$ | Mix proportions per a unit volume (1 m$^3$)$^*$(kg/m$^3$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coarse | Fine | (%) | (%) | W | C | G | S | RG | RS | SP |
| Control | Natural | Natural | - | - | 175 | 350 | 1016 | 730 | 0 | 0 | 1.68 |
| RGⅠ-30 | Natural+ Recycled (grade Ⅰ) | | 30 | - | | | 711 | 730 | 297 | 0 | |
| RGⅠ-50 | | | 50 | | | | 508 | 730 | 494 | | |
| RGⅠ-100 | Recycled (grade Ⅰ) | | 100 | | | | 0 | 730 | 989 | | |
| RSⅡ-30 | Natural | Natural + Recycled (grade Ⅱ) | - | 30 | | | 1016 | 511 | 0 | 200 | |
| RSⅡ-50 | | | | 50 | | | 1016 | 365 | | 334 | |
| RSⅡ-100 | | Recycled (grade Ⅱ) | | 100 | | | 1016 | 730 | | 668 | |
| RGⅢ-30 | Natural+ Recycled (grade Ⅲ) | Natural | 30 | - | | | 711 | 730 | 282 | 0 | |
| RGⅢ-50 | | | 50 | | | | 508 | 730 | 469 | | |
| RGⅢ-100 | Recycled (grade Ⅲ) | | 100 | | | | 0 | 730 | 938 | | |

Note: The mix proportions in the above table are given per 1 m$^3$. Each batch was 0.25m$^3$.

$R_{RG}$ and $R_{RS}$ = replacement levels of recycled coarse and fine aggregates, respectively.

* W, C, G, S, RG, RS and SP refer to water, ordinary Portland cement, natural coarse and fine aggregates, recycled coarse and fine aggregates, and superplasticizer, respectively.

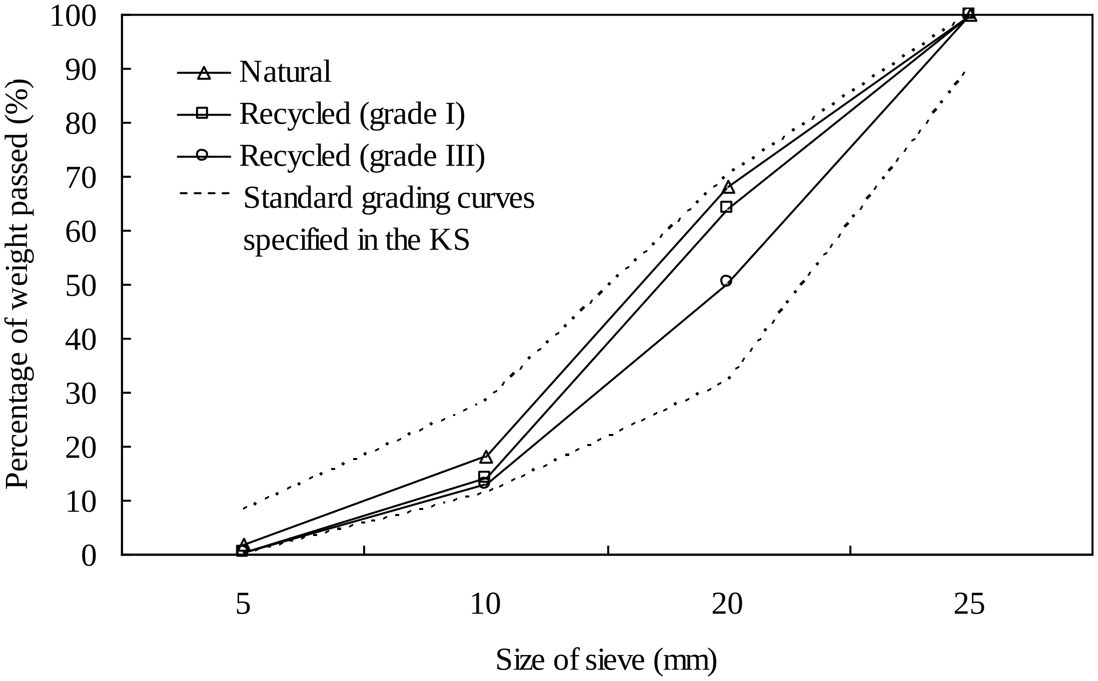
Table 3-Summary of test results

| Mix | $Q_w$ (%) | $S_L$ (mm) |  |  |  | $f_c^{'}$ (MPa) |  |  |  |  |  | $f_t$ (MPa) | $f_r$ (MPa) | $E_c$ (MPa) | $\frac{f_t}{\sqrt{f_c^{'}}}$ | $\frac{f_r}{\sqrt{f_c^{'}}}$ | $\frac{E_c}{\sqrt{f_c^{'}}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Initial | 30 mins | 60 mins | 90 mins | 1 day | 3 days | 7 days | 28 days | 56 days | 91 days |  |  |  |  |  |  |
| Control | 1.61 | 200 | 190 | 178 | 160 | 9.1 | 21.0 | 28.2 | 39.5 | 44.0 | 45.5 | 4.04 | 4.31 | 31722 | 0.64 | 0.69 | 5049.9 |
| RGⅠ-30 | 1.67 | 190 | 180 | 170 | 140 | 9.5 | 22.7 | 30.5 | 36.7 | 44.6 | 45.9 | 4.03 | 4.21 | 30374 | 0.67 | 0.69 | 5013.4 |
| RGⅠ-50 | 1.70 | 180 | 155 | 150 | 125 | 8.9 | 20.2 | 29.0 | 38.0 | 45.9 | 46.6 | 3.65 | 4.01 | 30520 | 0.59 | 0.65 | 4948.3 |
| RGⅠ-100 | 1.80 | 165 | 150 | 127 | 110 | 8.9 | 19.5 | 26.8 | 36.0 | 43.4 | 45.9 | 3.49 | 3.84 | 29223 | 0.58 | 0.64 | 4868.2 |
| RSⅡ-30 | 2.08 | 190 | 160 | 145 | 125 | 9.1 | 18.3 | 23.8 | 30.4 | 35.9 | 39.6 | 3.08 | 3.78 | 27651 | 0.56 | 0.68 | 5015.5 |
| RSⅡ-50 | 2.40 | 175 | 130 | 115 | 95 | 8.0 | 13.5 | 23.5 | 29.3 | 33.9 | 38.4 | 2.80 | 3.27 | 25783 | 0.52 | 0.60 | 4759.7 |
| RSⅡ-100 | 2.72 | 160 | 120 | 80 | 65 | 7.8 | 13.0 | 21.5 | 27.0 | 31.0 | 34.7 | 2.55 | 3.06 | 24465 | 0.49 | 0.59 | 4707.5 |
| RGⅢ-30 | 2.42 | 195 | 135 | 110 | 85 | 7.7 | 16.2 | 22.1 | 32.6 | 37.7 | 39.0 | 3.21 | 3.59 | 28361 | 0.56 | 0.63 | 4966.0 |
| RGⅢ-50 | 2.95 | 185 | 120 | 80 | 65 | 7.3 | 15.0 | 21.3 | 30.4 | 35.9 | 39.0 | 2.85 | 3.40 | 25885 | 0.52 | 0.62 | 4695.3 |
| RGⅢ-100 | 4.30 | 180 | 90 | 70 | 60 | 6.9 | 13.5 | 20.7 | 29.5 | 34.1 | 37.0 | 2.56 | 3.20 | 23717 | 0.47 | 0.59 | 4363.5 |

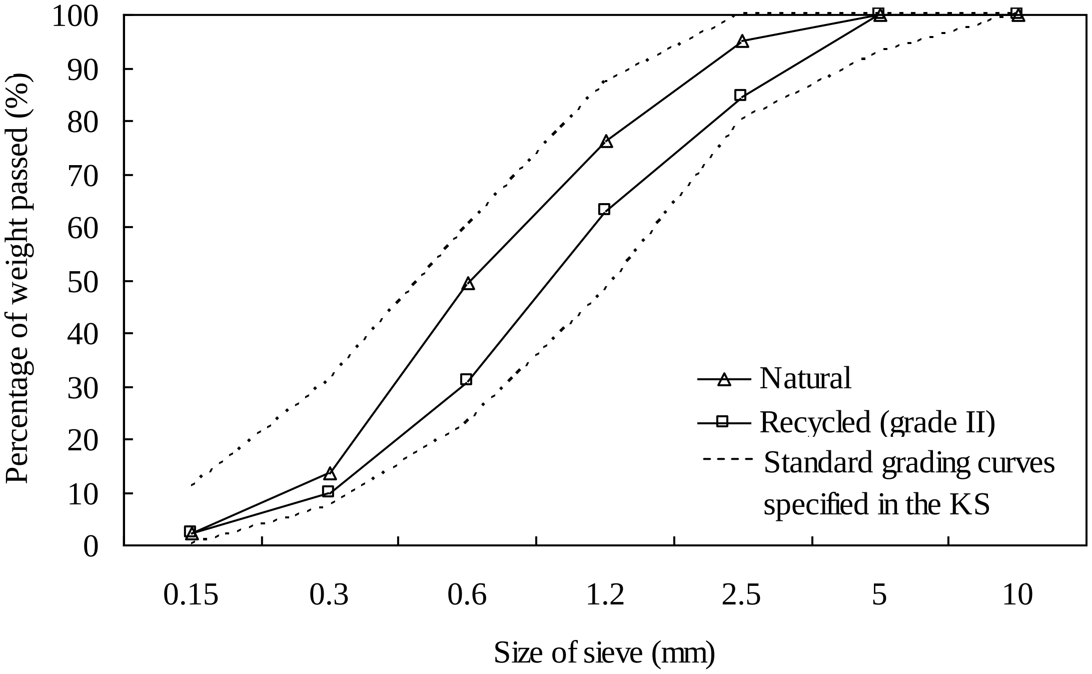
Note: $Q_w$ = relative water absorption of aggregates calculated from Eq. (2), $S_L$ = slump of fresh concrete and $f_c^{'}$ = concrete compressive strength.

Splitting tensile strength, and moduli of rupture and elasticity of concrete measured at 28 days are given in the columns of $f_t$, $f_r$, and $E_c$, respectively.

1 MPa = 145 psi; 1 mm = 0.039 in.



(a) Coarse aggregate



(b) Fine aggregate

Fig. 1-Particle distribution curves of aggregates used in tests.

(1 mm = 0.039 in.)

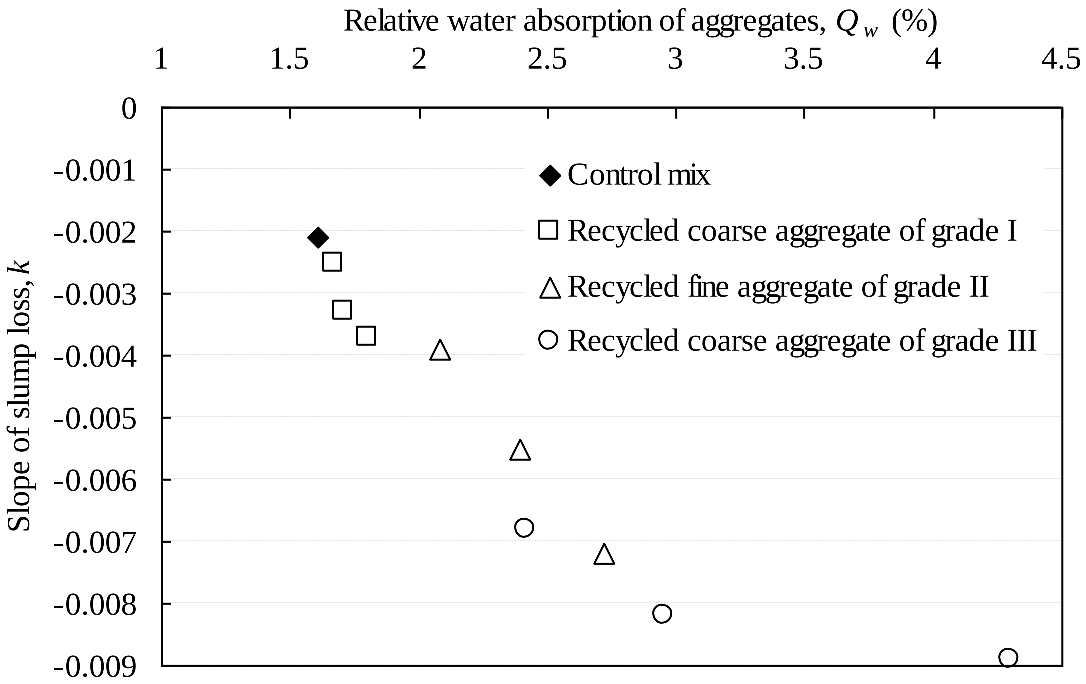


Fig. 2-Influence of $Q_w$ on $k$.

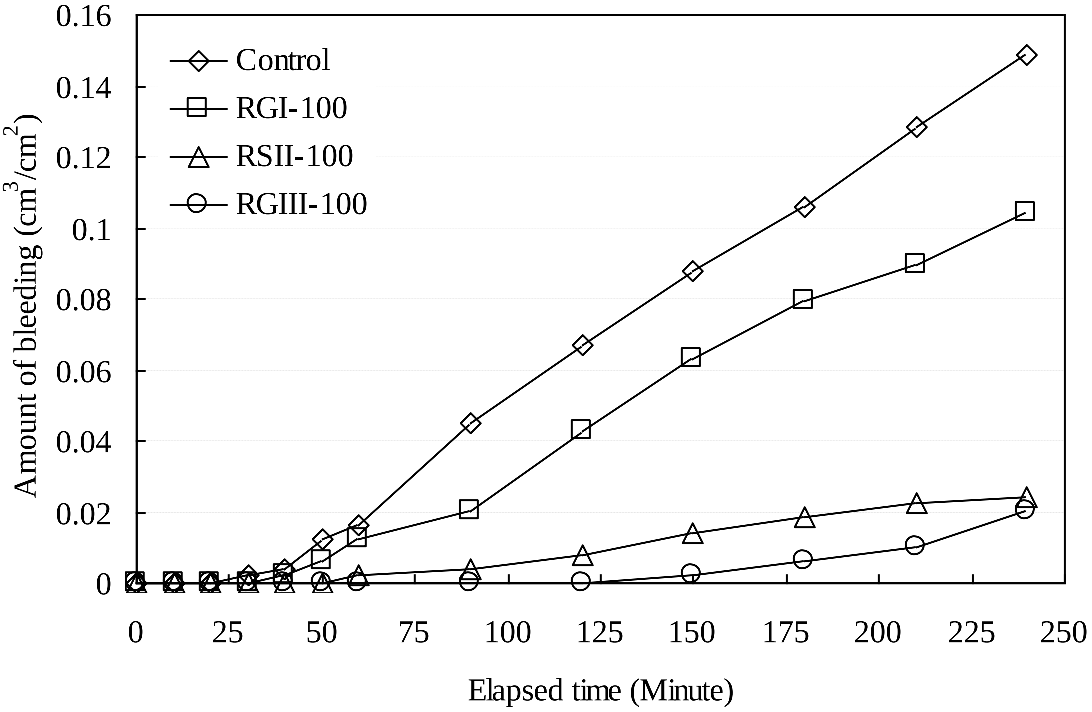


Fig. 3- Variation of amount of bleeding with the elapse of time.

(1 $cm^3$ = 0.059 $in.^3$, 1 $cm^2$ = 0.152 $in.^2$)

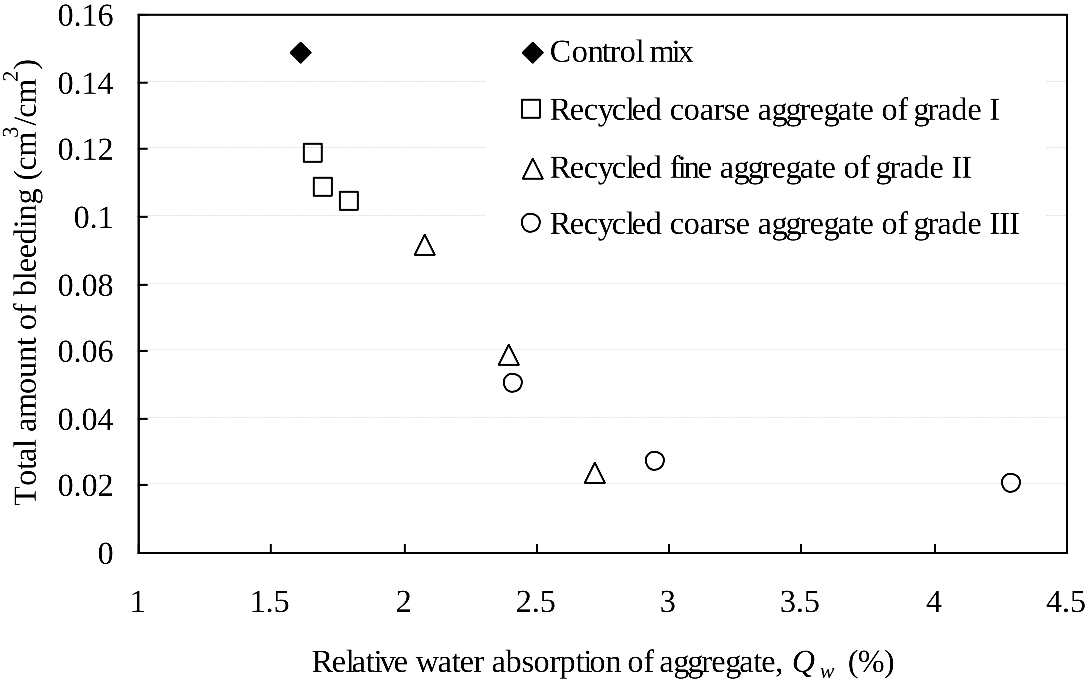
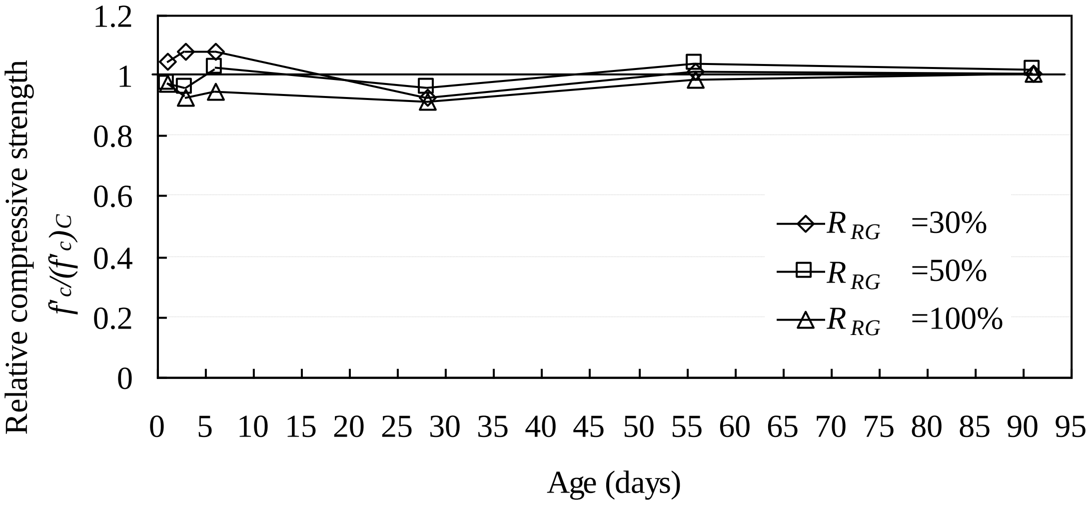
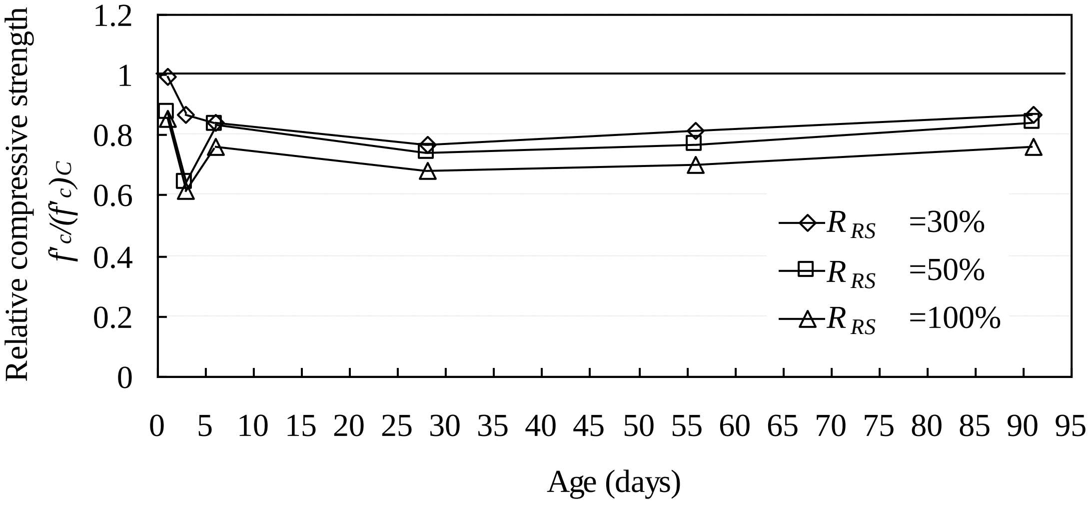


Fig. 4- Influence of $Q_w$ on the total amount of bleeding.

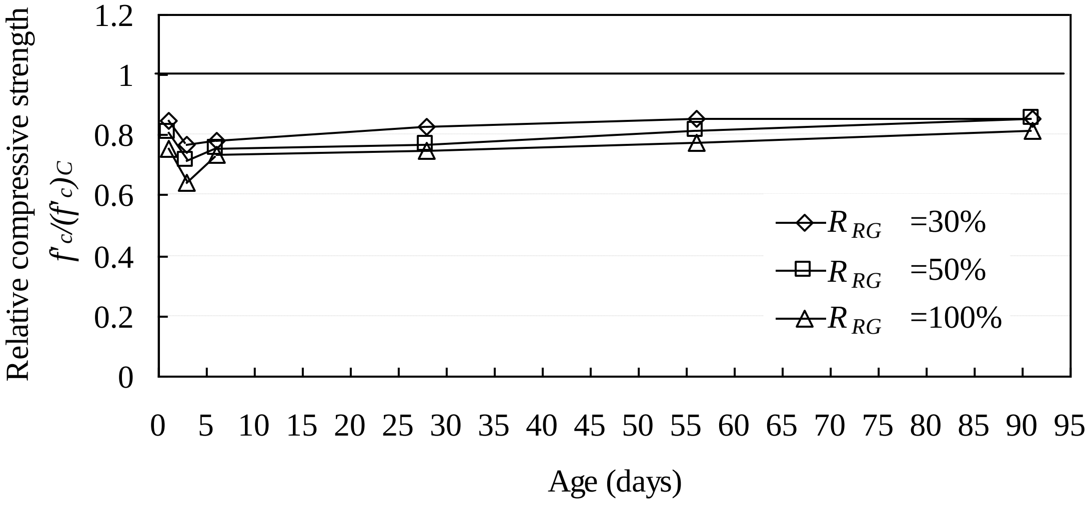
( 1 $cm^3$ = 0.059 $in.^3$, 1 $cm^2$ = 0.152 $in.^2$ )



(a) Recycled coarse aggregates of grade I



(b) Recycled fine aggregates of grade II



(c) Recycled coarse aggregates of grade III

Fig. 5-Relative compressive strength of recycled aggregate concrete against age.

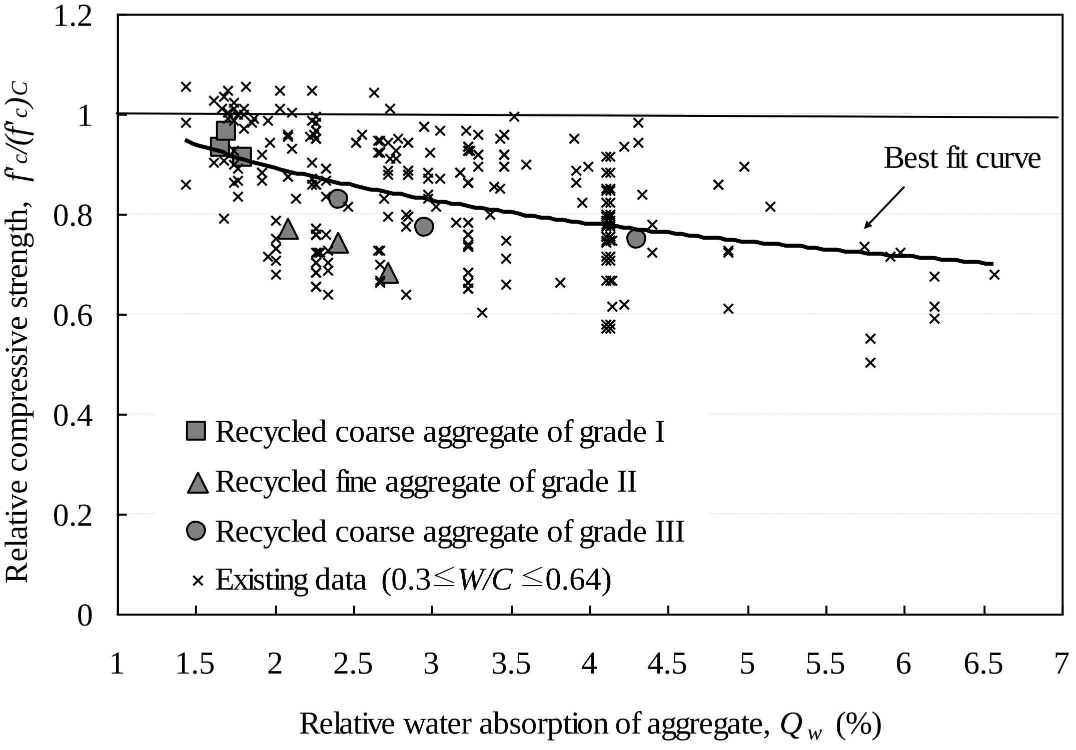


Fig. 6-Influence of $Q_w$ on relative compressive strength at 28 days.

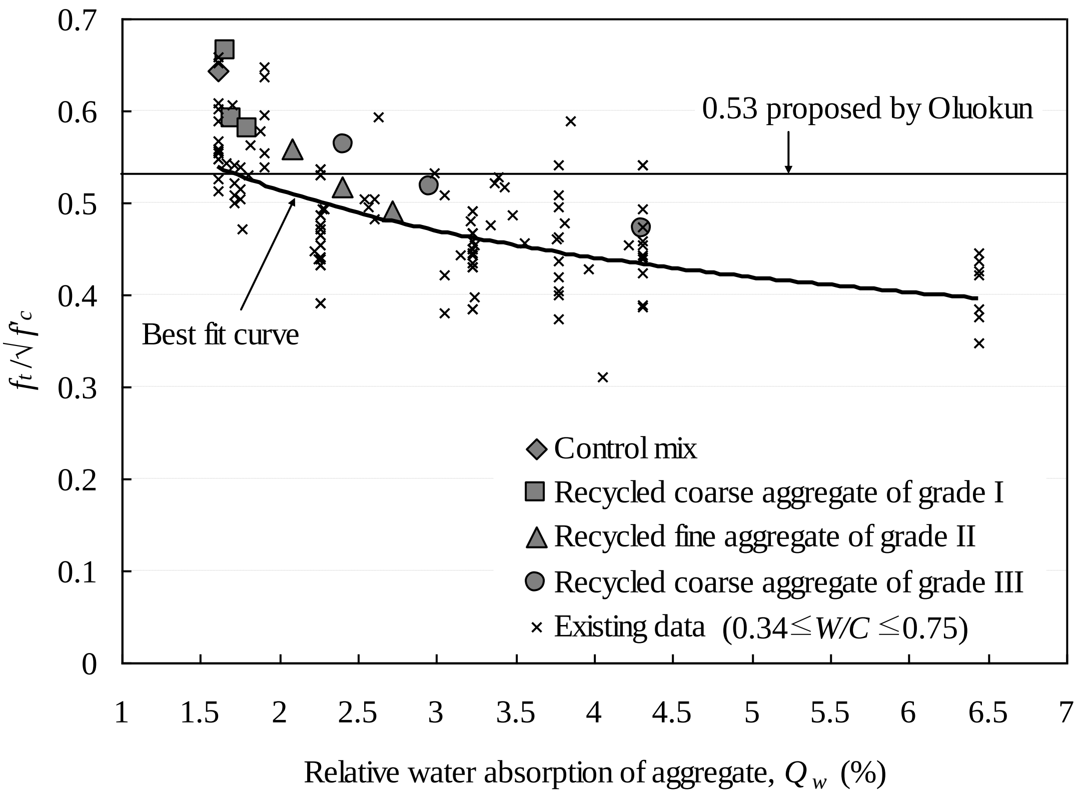


Fig. 7-Influence of $Q_w$ on $f_t/\sqrt{f'_c}$ .

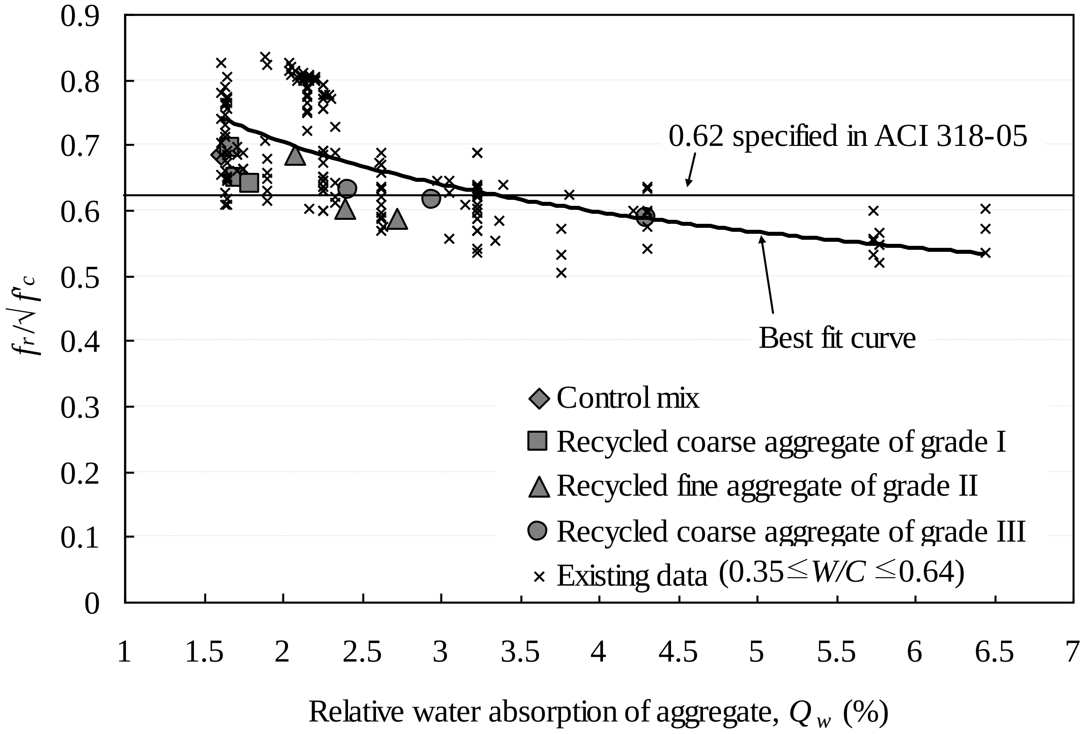


Fig. 8-Influence of $Q_w$ on $f_r / \sqrt{f_c'}$.

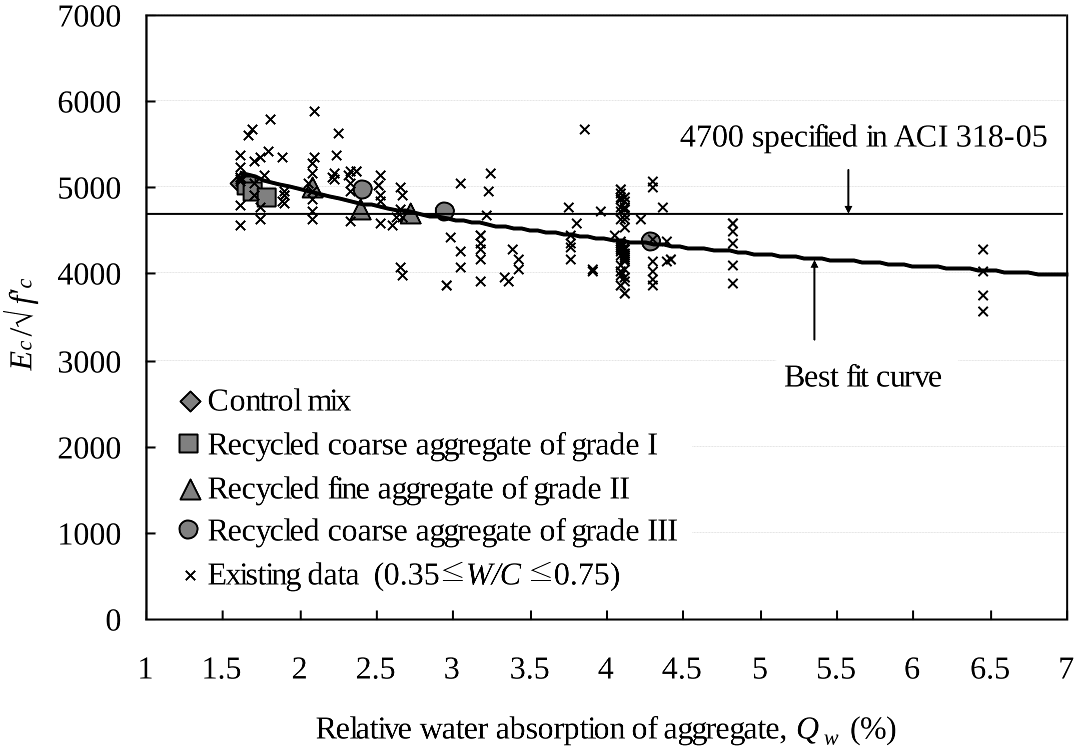


Fig. 9-Influence of $Q_w$ on $E_c/\sqrt{f_c^{'}}$.

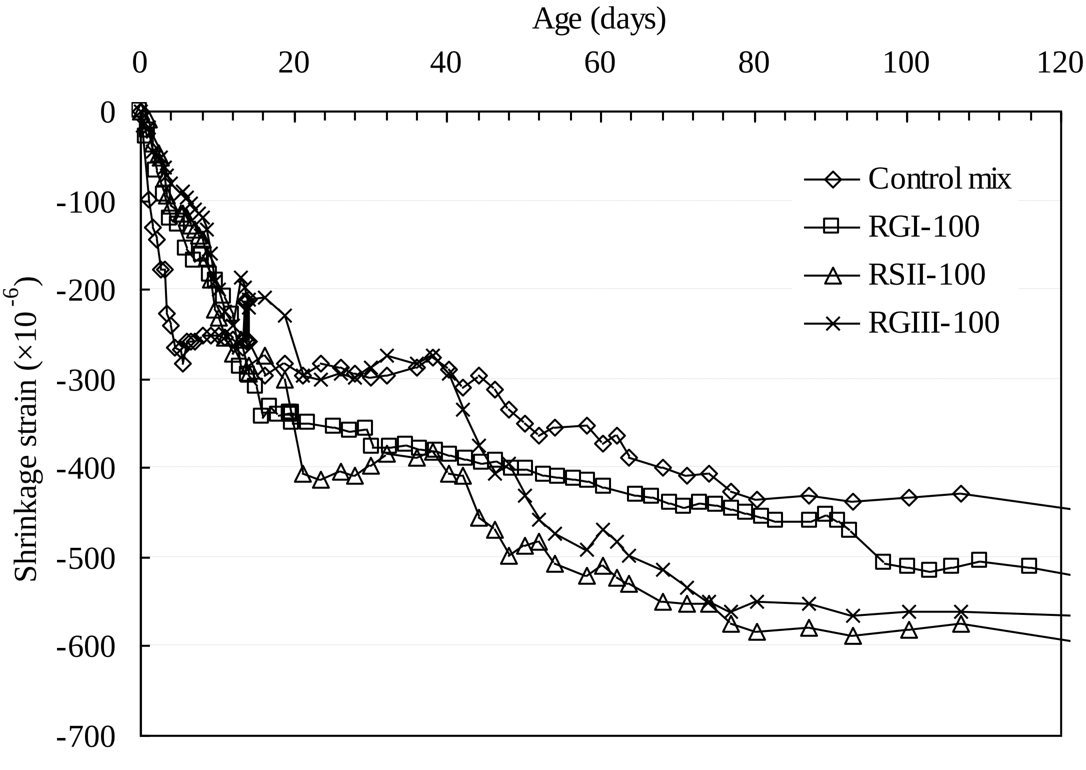


Fig. 10-Behavior of shrinkage strain of concrete against age.

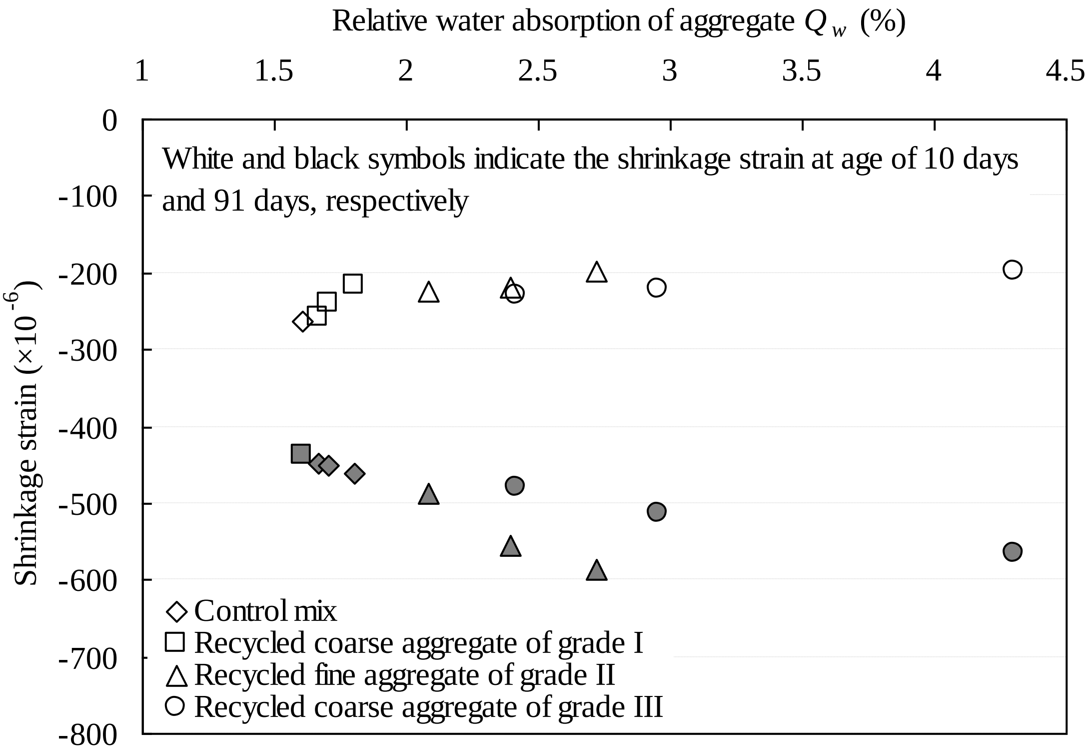


Fig. 11-Influence of $Q_w$ on shrinkage strain at ages of 10 and 91 days.