Abstract

This study concerns high-quality recycled coarse aggregate concrete which was recently specified in Japanese Industrial Standards (JIS). The objective of this study is to determine the basic properties of recycled aggregate concrete when used for the beams of reinforced concrete structures. During a period of one year after the placement of concrete, regular observations were made to identify the magnitude of drying shrinkage cracks generated in the beams. Furthermore, for the beams in which drying shrinkage cracks were generated, the bond splitting strength was investigated. The study found that the drying shrinkage cracks at the material age of one year were slight, showing that the generation of drying shrinkage cracks was suppressed compared with when using an intermediate-quality recycled coarse aggregate. The observed bond splitting strength was equivalent to that of normal concrete, unaffected by the formation of slight drying shrinkage cracks. When the high-quality recycled coarse aggregate of the study was used for reinforced concrete beams, the bond splitting strength was equivalent to that of normal concrete even when recycled coarse aggregate was substituted entirely for normal coarse aggregate. These findings suggest that reinforced concrete beams made using high-quality recycled coarse aggregate can be used as members of architectural structures.

Keywords: high-quality recycled coarse aggregate; recycled aggregate concrete; drying shrinkage crack; bond splitting strength

1. Introduction

Aiming to encourage the use of recycled aggregate, studies on a standard for recycled aggregate concrete have been conducted in recent years in Japan\(^1\). Although recycled aggregate is produced by various methods, that for roadbed material is produced solely by crushing dismantled concrete using a jaw crusher. Since this type of recycled aggregate contains large quantities of attached mortar, the degree of change in length (the rate of drying shrinkage) increases when it is used for concrete, which is likely to induce drying shrinkage cracks in reinforced concrete members\(^2\). Therefore, a technology has been developed to produce high-quality recycled aggregate of a quality similar to that of the original aggregate by crushing the dismantled concrete to remove mortar, followed by further treatment\(^3\). Studies of recycled aggregate concrete using recycled aggregate prepared by this method have attracted interest in materials science.

By removing all the mortar attached to the recycled aggregate, low absorptivity and high quality similar to that of normal coarse aggregate can be attained. A standard for high-quality recycled aggregate, JIS A5021 "Recycled aggregate for concrete-class H\(^4\)" was enforced in March 2005. Since then, it has become accepted that high-quality recycled aggregate has a performance equivalent to that of normal coarse aggregate. Although the standardization of recycled aggregate is progressing, there have been few studies on the properties of drying shrinkage cracks and strength of members when high-quality recycled aggregate is used for the members of full-size architectural structures.

Therefore, this study conducted regular observations of reinforced concrete beams made using high-quality recycled coarse aggregate in terms of the magnitude of generation of drying shrinkage cracks until one year after placement of the concrete. The bond splitting strength of reinforced concrete beams in which drying shrinkage cracks were generated was also investigated.

2. Outline of Experiments

Table 1. shows the details of specimens. Two types of recycled aggregate concrete were used to obtain the basic concrete properties: QM series and QU series. The QM series contains 50% of high-quality recycled coarse aggregate substituting for normal coarse
aggregate (hereinafter "substitution rate"), and the QU series substituted 100% of normal coarse aggregate with high-quality recycled coarse aggregate (100% substitution rate). The high-quality recycled coarse aggregate was prepared by milling using an eccentric rotor mill. The substitution of recycled aggregate concrete was conducted together with specimens that were scheduled to be subjected to load tests at the material ages of five weeks and one year when the generation of drying shrinkage cracks was observed.

For reference, the discussion in the following is given while comparing with the N series of conventional normal concrete and with the R series using the intermediate quality recycled coarse aggregate. The cross section and appearance of the specimen are shown in Figs. 1. and 2., respectively. The main reinforcements were 4-D19 for both the top and the bottom. To determine the bond splitting strength, lap-splicing horizontal to the cross section of the beam was adopted. The main reinforcements were SD685 ($\sigma_y = 732$ N/mm²) so that the bond splitting fracture would occur before bending yield. The shape of the specimen was a simple beam which had a lap-splice length of 30 $d_b$ (570 mm) at the bottom of the pure bend section.

Table 2. Mixing of Concrete

Table 3. Properties of Fresh Concrete

Table 4. Quality of Aggregate
The absorptivity of the aggregate given in the table was obtained from a laboratory test of an aggregate sample at a plant, and the absorptivity of the high-quality recycled coarse aggregate was 2.43%. The mixture absorptivity of a coarse aggregate of the QM series sampled from the fresh concrete at placement was 1.69%. According to the standard for recycled aggregate for concrete-class H of JIS A5021, the density in the oven-dry condition is 2.5 g/cm$^3$ or more, the percentage of solid volume is 55% or more, and the absorptivity is 3.0% or less. All the tested high-quality recycled coarse aggregates satisfied these standard requirements.

3. Young's Modulus

Fig.3 shows the transitions of Young's modulus for the QM series and QU series. For both the QM series and the QU series, observed values of Young's modulus were slightly lower than the calculated values of normal concrete based on the RC standard formula$^6$ at a unit weight, $\gamma = 23$ kN/m$^3$. However, the calculated values based on the observed values of $\gamma$ for individual specimens (22.5 kN/m$^3$ for the QM series, and 22.4 kN/m$^3$ for the QU series) became almost equal to the respective values of observed Young's modulus. The decrease in the observed value of $\gamma$ was presumably caused by the effect of the small amount of mortar attached to the high-quality recycled coarse aggregate. The observed Young's modulus in the N series$^5$ was $2.28 \times 10^4$ N/mm$^2$ and $2.70 \times 10^4$ N/mm$^2$ at five weeks and one year of material age, respectively, giving values close to those of the QM series and the QU series. On the other hand, the R series$^5$ gave the Young's modulus of $2.05 \times 10^4$ N/mm$^2$ and $2.39 \times 10^4$ N/mm$^2$ at five weeks and one year of material age, respectively, giving lower values than those of QM series, QU series, and N series.

4. Rate of Drying Shrinkage

The rate of drying shrinkage of concrete using the high-quality recycled coarse aggregate was investigated focusing on the comparison between the normal concrete (N series) and the concrete in which all the intermediate-quality recycled coarse aggregate having high absorptivity was substituted (R series). The rate of drying shrinkage was determined on a length-change prism specimen having a size of $100 \times 100 \times 400$ mm specified in JIS A 1129 "Method for testing the length change of mortar and concrete". Fig.4 shows the transition of the rate of drying shrinkage. The rate of drying shrinkage at the material age of 56 weeks was $670 \times 10^{-6}$ for the QM series of 50% substitution of high-quality recycled coarse aggregate, and $720 \times 10^{-6}$ for the QU series of 100% substitution. The difference in the rate of drying shrinkage was very small, and a difference caused by the substitution rate of high-quality recycled coarse aggregate was not observed. The R series with 100% substitution of intermediate-quality recycled coarse aggregate gave a drying shrinkage rate of $1120 \times 10^{-6}$, showing a property similar to that of the normal concrete (N series) owing to the suppression of the rate of drying shrinkage by the adoption of high-quality recycled coarse aggregate.

5. Drying Shrinkage Crack Property

Fig.5 shows the drying shrinkage cracks observed at the material age of one year. The drying shrinkage cracks were compared with those which appeared in the R series (00RK)$^5$ in which all the intermediate-quality recycled coarse aggregate having an original absorptivity of 5.05% was substituted. Both the 00QMK of Fig.5 a) and the 00QUK of Fig.5 b) showed several drying shrinkage cracks near the side top in the seventh week. On the 00RK of Fig.5 c),
the drying shrinkage cracks appeared after the fourth week. Thus, the generation of drying shrinkage cracks tended to be delayed by using the high-quality recycled coarse aggregate. Regarding the generation of drying shrinkage cracks at the material age of one year, the 00RK showed a considerable quantity of cracks on the entire side area, while the 00QMK and the 00QUK showed few cracks. Consequently, it was confirmed that the drying shrinkage cracks can be suppressed by using high-quality recycled coarse aggregate, similar to the case of the rate of drying shrinkage. The difference in the shrinkage cracks in Fig.5. comes from the decrease in the generation of drying shrinkage cracks in the high-quality recycled coarse aggregate (having an absorptivity as low as 2.43%) suppressing the drying shrinkage rate compared with the intermediate quality of recycled coarse aggregate (having a high absorptivity of 5.05%). As for the difference in substitution rate of high-quality recycled coarse aggregate, there appeared to be no difference in the generation of drying shrinkage cracks, similar to the case of the rate of drying shrinkage, and no increase in the drying shrinkage cracks occurred even in the case of full substitution with high-quality recycled coarse aggregate. Furthermore, the width of typical drying shrinkage cracks generated at the middle of the beam height was measured. The average width for two observed cracks was 0.04 mm for 00QUK, and that for seven observed cracks was 0.11 mm for 00RK, showing a slightly large average drying shrinkage crack width in the R series.

6. Results of Experiments

Table 5. summarizes the results of the experiments. The specimens having transverse reinforcement ratio, $p_w$, of 0.0% and 0.6% suffered bond splitting fracture of the side split mode in which the bond splitting rapidly propagates in the lap-spliced section (Fig.6.). The specimen having the transverse reinforcement ratio of 1.2% suffered bending yield before bond splitting fracture occurred. The investigation of bond splitting strength of reinforced concrete beams using high-quality recycled coarse aggregate compared with the normal concrete "N series" produced the following results. Table 6. shows the splitting strength of concrete. Compared with the splitting strength at five weeks of material age, that at one year showed an increasing tendency for all the observed series.

| Specimen   | $\sigma_{\text{f}}$ (N/mm$^2$) | $W_{\text{max}}$ (mm) | $P_{\text{max}}$ (kN) | $\tau_{\text{exp}}$ (N/mm$^2$) | Failure mode |
|------------|--------------------------------|------------------------|------------------------|-------------------------------|--------------|
| 1) 00QM    | 0.08                           | 295.0                  | 3.31                   |                               | S            |
| 2) 06QM    | 34.4                           | 364.2                  | 4.09                   |                               |              |
| 3) 12QM    | 0.08                           | 539.4                  | (5.93)$^1$             |                               | FS           |
| 4) 00QMK   | 0.12                           | 299.4                  | 3.36                   |                               | S            |
| 5) 06QMK   | 42.6                           | 433.8                  | 4.87                   |                               |              |
| 6) 12QMK   | 0.09                           | 522.8                  | (5.87)$^2$             |                               | FS           |
| 7) 00QU    | 0.10                           | 274.0                  | 3.08                   |                               | S            |
| 8) 06QU    | 35.5                           | 354.2                  | 3.98                   |                               |              |
| 9) 12QU    | 0.08                           | 587.0                  | (6.13)$^3$             |                               | FC           |
| 10) 00QUK  | 0.13                           | 299.8                  | 3.37                   |                               | S            |
| 11) 06QUK  | 43.6                           | 471.2                  | 5.29                   |                               |              |
| 12) 12QUK  | 0.11                           | 525.4                  | (5.90)$^4$             |                               | FS           |

$\sigma_{\text{f}}$: Compressive strength  
$W_{\text{max}}$: flexural crack width under service loading  
$P_{\text{max}}$: Bond splitting strength  
$\tau_{\text{exp}}$: Bond splitting failure after flexural yield  
FC: Compressive failure after flexural yield  

Table 6. Cylinder Split Tensile Strength

| Series | $\sigma_t$ (N/mm$^2$) |
|--------|----------------------|
|        | 5 weeks | 1 year               |
| QM     | 2.55     | 3.09                 |
| QU     | 2.71     | 3.25                 |
| N$^5$  | 2.75     | 3.35                 |
| R$^5$  | 2.43     | 2.62                 |

$\sigma_t$: Cylinder split tensile strength
cracks appeared at one year, Wmax at that material age did not increase compared with the normal concrete (N series). For all the specimens, Wmax was not affected by the transverse reinforcement ratio, resulting in less than 0.25 mm, which is the crack restriction target of the RC standard.

6.2 Deflection property

Fig.8. shows an example of load–deflection curves at the material age of five weeks. Loading was applied by two-position concentrated reversed cycle loading. The force was applied by increasing the stress $\sigma_{t}$ on the main reinforcements, calculated by the simplified equation of beam flexural strength, at an increment of 100 N/mm$^2$, for each one reversed cycle for each stress level. The deflection was expressed by the deflection at the center of the beam, $\delta$. The specimens of the transverse reinforcement ratio, $p_w$, of 0.0% and 0.6% suffered bond splitting fracture on applying positive loading, followed by a rapid decrease in the strength of members. On the other hand, the 12QM in which the transverse reinforcements were arranged densely, $p_w = 1.2\%$, as shown in Fig.8., showed bending yield, and bond splitting fracture occurred at a deflection of more than $\delta = 30$ mm, thus decreasing the strength of members. The likely cause of the phenomenon is that the compressive strength of the concrete of the QM series, $\sigma_B = 34.4$ N/mm$^2$, was higher than that of the normal concrete, $\sigma_B = 28.8$ N/mm$^2$, and so bending yield occurred before bond splitting fracture.

Fig.9. shows the load–deflection curves (envelope curves) of a specimen of transverse reinforcement ratio $p_w = 0.0\%$. Referring to Fig.9. a), the material at five weeks had equivalent initial rigidity for both the QM series (00QM) giving a 50% substitution rate of high-
quality recycled coarse aggregate and the QU series (00QU), showing no influence of the substitution rate. Also in Fig.9 b), at one year, the initial rigidity was equivalent for both the QM series (00QMK) and the QU series (00QUK). Since the drying shrinkage cracks were slight on the specimens of both the QM series and the QU series, their initial rigidity became equivalent to that of the normal concrete N series (00NK), showing no decrease in rigidity after one year.

7. Evaluation of Bond Splitting Strength

Fig.10. shows the bond splitting strength of the specimens, derived from:

\[
\tau_{u \text{ exp.}} = \frac{M_u}{j \cdot \psi / s} \quad (N/mm^2)
\]  

where,
\( M_u \): Max. bending moment (N · mm)
\( j \): 7/8d (d: Effective beam depth 260.5 mm)
\( \psi \): Perimeter of reinforcement (4-D19 240 mm)
\( l_s \): Length of lap splice (30d, 570 mm)

The concretes of the QM series and the QU series, both using the high-quality recycled coarse aggregate, were manufactured at a ready-mixed concrete plant different from the one that manufactured the N series normal concrete. Owing to the performance of plants, the N series concrete gave lower compressive strength than that of the concretes of the QM series and the QU series, though there was little difference in proportions between them. At the material age of five weeks, as seen in Fig.10 a), the bond splitting strength was almost the same for both the QM series (50% substitution rate of the high-quality recycled coarse aggregate) and the QU series (100% substitution rate) at every transverse reinforcement ratio. Also at the material age of one year, as shown in Fig.10. b), the bond splitting strength was almost the same for both the QM series and the QU series. That is, the QM series and the QU series gave almost the same bond splitting strength. Both the QM series and the QU series, which used the high-quality recycled coarse aggregate, provided the same level of bond splitting strength as the normal concrete N series, and the few drying shrinkage cracks did not affect the bond splitting strength.

8. Conclusions

From the investigations of bond splitting strength of reinforced concrete beams using high-quality recycled coarse aggregate, the following conclusions were drawn within the scope of the experiments.

1) The drying shrinkage cracks at the material age of one year were very slight, and were suppressed compared with the case of using intermediate-quality recycled coarse aggregate, similar to the rate of drying shrinkage.

2) The maximum flexural crack width under service loading on the main reinforcements did not increase compared with normal concrete because few drying shrinkage cracks were generated.

3) The bond splitting strength was independent of the substitution rate of the high-quality recycled coarse aggregate. The bond splitting strength was equivalent to that of normal concrete, showing that the few drying shrinkage cracks had no effect.

Consequently, when the high quality recycled coarse aggregate used in the experiments was applied to reinforced concrete beams, few drying shrinkage cracks were generated. The flexural crack width and the bond splitting strength were equivalent to those of normal concrete even when normal coarse aggregate was entirely replaced by recycled coarse aggregate.

These findings suggest that reinforced concrete beams made using high-quality recycled aggregate can be used as members of architectural structures. The study conducted investigations for material ages up to one year. Further studies will be conducted to assess the propagation of drying shrinkage cracks over longer periods, to improve the drying shrinkage, as well as to investigate neutralization, corrosion of reinforcements, and other variables for materials of longer age.
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