Study on Pore Structure of Coarse Aggregate and Drying Shrinkage Properties

by

Hiroshi YAMADA*, Hiroshi KATAHIRA** and Hiroshi WATANABE***

The factors which affect drying shrinkage of concrete are material properties and environmental conditions, and so on. It is said that the type of coarse aggregate is one of the most dominant factors which affect concrete drying shrinkage. It has also been pointed out that the pore structure of coarse aggregate affects drying shrinkage strain of concrete. From the above backgrounds, in this research, we focused on the pore structure of pore radius of 1 µm or less for coarse aggregate and investigated the relationship between the coarse aggregate pore characteristics obtained by using mercury porosimetry and the drying shrinkage strain of coarse aggregate and concrete. For this study we used 10 types of crushed stone from different regions and of different qualities. As a result, we indicated a mutual relationship could be identified between the pore characteristics of coarse aggregate and the drying shrinkage strain of coarse aggregate or concrete when categorization by rock type was used. We also demonstrated that the average pore size of coarse aggregate, calculated from the pore characteristics obtained by using mercury porosimetry, was related to the drying shrinkage strain of coarse aggregate and concrete, and that it is possible that this relationship could be uniformly expressed by a power function.

Key words:
Drying Shrinkage, Coarse Aggregate, Pore Structure, Average Pore Size, Mercury Porosimetry

1 Introduction

There is a growing interest in controls of cracking of concrete due to shrinkage, therefore concrete drying shrinkage related regulations are being reviewed and revised. In JSCE standard specifications for concrete structures, as a general rule, the design values of the shrinkage strain of concrete must be determined on the basis of the values obtained from shrinkage strain tests of the concrete to be used or past performance data.

The drying shrinkage strain of concrete is determined as the length change strain after 6 months of drying, using the method indicated in JIS A 1129: Methods of Measurement for Length Change of Mortar and Concrete. However, this test takes a long time. There has therefore been a need for a method for simply estimating concrete drying shrinkage strain.

There are many factors which affect concrete drying shrinkage. Among the constituent materials of concrete, it has been reported that the most dominant factor is the type of coarse aggregate1). In the past we have focused on the shrinkage properties of the coarse aggregate, investigating the validity of measuring the drying shrinkage strain using wire strain gauges. We have demonstrated that the mean value of the drying shrinkage strain of coarse aggregate measured by using wire strain gauges can serve as an index for estimating the drying shrinkage strain of concrete2).

Among the qualities of coarse aggregate, it has been reported that the internal specific surface area of the coarse aggregate3), the presence or absence of clay mineral4), and the total amount of voids with pore diameters of 1000 to 100000 Å5) affect the drying shrinkage of concrete. Therefore it is believed that an understanding of the pore structure of coarse aggregate is important to identify coarse aggregate drying shrinkage properties. In our previous research6) we have reported that when categorized by rock type there is a mutual relationship between the specific surface area of coarse aggregate as measured by using water vapor adsorption and the drying shrinkage strain of concrete.

Considering these circumstances, in this research we investigated the relationship between the coarse aggregate pore structure measured by using mercury porosimetry and the drying shrinkage strain of coarse aggregate and concrete.

2 Outline of Experiment

2.1 Coarse aggregate

Table 1 shows the types and characteristics of coarse aggregate used in this research. It has been pointed out that the clay mineral affects drying shrinkage strain4). For this study we selected 10 types of coarse aggregate with a small amount of clay mineral. The selected aggregate have not been confirmed as having a clear impact on concrete drying shrinkage strain5). The selected coarse aggregate consisted of crushed stone from different regions and of different qualities, and in order to cover the impact of a wide range of coarse aggregate quality, some coarse aggregates selected satisfied

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* Member: Hiroshima Pref., Hiroshima Port and Harbor Promotion Office. Engineer, Minami-ku, Hiroshima, 734-0011 Japan

** Public Works Research Institute, iMaRRC. Principal Senior Researcher, Minamihara, Tsukuba, 305-8516 Japan

*** Public Works Research Institute, iMaRRC. Director of Materials and Resources Research Group, Minamihara, Tsukuba, 305-8516 Japan
JIS A 5005: Crushed Stone and Manufactured Sand for Concrete, while others did not. Drying shrinkage strain of a coarse aggregate particle was measured by using wire strain gauges. Waterproof wire strain gauges (gage-length 3mm) were bonded on cut-smooth-surface of the particle. The particle was saturated with water at 20°C. Thereafter length-change test of the particle was started. The particle length-change was measured in an environment at a temperature of 20°C and a relative humidity of 60%, and the strain of change in length at ultimate was evaluated. A number of test pieces were more than 7 particles for each type of the aggregate.

2.2 Mix proportion of concrete and mortar

Ordinary Portland cement was used. River sand shown in Table 1 was used. Coarse aggregate shown in Table 1 was used respectively. AE: water reducing agent (C=0.31%) was used. Mix proportions of concrete were identical as follows except for coarse aggregate to be used. Unit water content was 165 kg/m³. Water-cement ratio was 55%. Sand-total aggregate ratio was 46%. Target air content was 4.5%.

Other than the coarse aggregate, all dosage of the materials for the concrete was identical. Therefore, fresh properties of the concrete were varied dependent on the coarse aggregate. Fresh concrete test results were as follows: slump of 3.5 to 18.6cm, air content of 4.0 to 6.2%.

The mortar was prepared using the river sand shown in Table 1 with the following mix proportion: water-cement ratio of 55%, sand-cement ratio of 2.73. Ordinary Portland cement was used. AE: water reducing agent (C=0.31%) was used.

2.3 Measurement of pore structure of coarse aggregate

The coarse aggregate pore structure was measured by using mercury porosimetry. The coarse aggregate particle drying shrinkage strain measured by using wire strain gauges showed large variations, therefore we paid special attention to samples preparation and selection used to perform pore structure measurement. Some coarse aggregate particles were selected to avoid bias. The test samples for the pore structure measurement are produced with crushing coarse aggregate into the size roughly from 2.5mm to 5mm diameter with mixing uniformly. Each sample was measured twice. The void shape was assumed to be cylindrical. The mercury surface tension was assumed to be 480x10⁻³ N/m. An angle of contact of 130° was used. The measurement range of pore diameter of 6 nm or greater was used.

2.4 Length-change test of concrete prism specimens

The specimens used in concrete length-change test were removed from their molds at the age of 1 day, and then water curing was performed until the age of 7 days. The concrete length-change was measured in accordance with JIS A 1129-3 (Method with Dial Gauge) in an environment at a temperature of 20°C and a relative humidity of 60%, and the strain of change in length after 6 months of drying was evaluated.

3 Results and Discussion

3.1 Pore volume of coarse aggregate and drying shrinkage strain

According to GOTO and FUJIWARA, it has been said that the principal mechanism of volumetric change of aggregate by absorption and drying is due to change of the surface energy. Therefore we assumed that the drying shrinkage of coarse aggregate in this study was due to change of the surface energy.

According to BENTUR, in cement hardened paste, pore diameters of 30 nm or smaller at a relative humidity of
60% are considered to have an impact on drying shrinkage. According to UCHIKAWA, et al\textsuperscript{8),} total amount of capillary voids with pore diameters of 30 nm to 2 µm have an impact on drying shrinkage. In this research, we used pore structure measurement data obtained by using mercury porosimetry with pore diameters of 2 µm or less (that is, pore radius of 1 µm or less) to investigate the relationship between arranged pore structures and the drying shrinkage strain of coarse aggregate and concrete.

Fig. 1 shows an example of the pore volume measurement results of coarse aggregates. The coarse aggregates shown in the result example are G5, which had the highest drying shrinkage strain, and G2, which had the highest pore volume measured by using mercury porosimetry. In this research we measured the pore structure of each sample twice. As the figure shows, little deviation was observed between the first and second measurement results for G5 and G2. Similar results were obtained for the other coarse aggregates. Because of this, for this research we took the average of the first and second measurements.

Fig. 2 shows the pore size distribution of the coarse aggregates. We have also indicated the pore volume per unit logarithmic scale at the lower figure.

Overall we found that pore volume varied by coarse aggregate type. Looking at each rock type separately, we found that for volcanic rock (upper left figure), the pore volume was high in order of G2, G1, and G3, but the coarse aggregate drying shrinkage strain was high in order of G3, G2, and G1, which did not correspond to the results of pore volume. Looking at the lower left figure, the total amount of pore volume with pore radius of 10 nm or less was 5.68 mm\(^3\)/g for G3, 4.88 mm\(^3\)/g for G2, and 1.00 mm\(^3\)/g for G1, corresponding to the drying shrinkage strain. For G2 the peak pore volume was observed to be for pore radius of between 10 and 20 nm, while for G1 and G3 the peak pore volume was observed to be for pore radius of between 100 and 200 nm.

Next, we found that for clastic rock (upper middle figure), the pore volume was high in order of G5, G7, G8, G6, G10, and G9, which also did not correspond to the drying shrinkage strain. For other rock types (upper right figure), the pore volume corresponded to drying shrinkage strain.

It is difficult to uniformly express coarse aggregate type. Looking at each rock type separately, we found that for volcanic rock (upper left figure), the pore volume was high in order of G2, G1, and G3, but the coarse aggregate drying shrinkage strain was high in order of G3, G2, and G1, which did not correspond to the results of pore volume. Looking at the lower left figure, the total amount of pore volume with pore radius of 10 nm or less was 5.68 mm\(^3\)/g for G3, 4.88 mm\(^3\)/g for G2, and 1.00 mm\(^3\)/g for G1, corresponding to the drying shrinkage strain. For G2 the peak pore volume was observed to be for pore radius of between 10 and 20 nm, while for G1 and G3 the peak pore volume was observed to be for pore radius of between 100 and 200 nm.

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and G6, but the coarse aggregate drying shrinkage strain was high in order of G5, G8, G7, and G6, which also did not correspond to the results of pore volume. Looking at the lower middle figure, the total amount of pore volume with pore radius of 10 nm or less was 8.85 mm³/g for G5, 1.54 mm³/g for G8, 3.19 mm³/g for G7, and 0.00 mm³/g for G6, which also did not correspond to the drying shrinkage strain. For G5 the peak pore volume was observed to be for pore radius of between 10 and 20 nm, but no other pronounced peaks were observed for the others.

For other rock types (upper right figure), the pore volume differed by rock type. Looking at the lower right figure, no pronounced peaks were observed for any of the coarse aggregates. The total amount of pore volume with pore radius of 10 nm or less was 4.77 mm³/g for G9, 0.85 mm³/g for G4, and 0.00 mm³/g for G10. The coarse aggregate drying shrinkage strain was, in order, G9, G4, and G10, therefore for these other rock types pore volume corresponded to drying shrinkage strain.

Fig.3 shows the relationship between drying shrinkage strain and pore volume for coarse aggregate and concrete. A mutual relationship was observed for coarse aggregates classified as clastic rock. It was also observed that larger pore volume corresponded to larger coarse aggregate and concrete drying shrinkage strain.

Based on the above, we were unable to determine a quantitative correspondence relationship between pore size distribution and drying shrinkage, but we inferred that the amount of minute voids is affected by the drying shrinkage strain. Also, we found that for coarse aggregates classified as clastic rock, pore volume and drying shrinkage strain are mutually related.

### 3.2 Specific surface area of coarse aggregate and drying shrinkage strain

We inferred that minute voids had an impact on drying shrinkage strain, therefore we investigated their relationship with specific surface area.

It has been pointed out that the specific surface area of coarse aggregate affects concrete drying shrinkage strain. We used pore structure measurement data obtained by using mercury porosimetry to determine coarse aggregate specific surface area, assuming cylindrical voids.

Fig.4 shows the relationship between drying shrinkage strain and specific surface area for coarse aggregate and concrete. The mutual relationships differed between coarse aggregates classified as clastic rock and classified as the others. It was also observed that larger specific surface area corresponded to larger coarse aggregate and concrete drying shrinkage strain.

### 3.3 Average pore size of coarse aggregate and drying shrinkage strain

It is difficult to uniformly express coarse aggregate drying shrinkage strain by the indexes of coarse aggregate pore volume and specific surface area. Generally, average pore size is used as an index to express differences in pore structure. We investigated whether this average pore size
could be used to uniformly express coarse aggregate and concrete drying shrinkage strain. The average pore size \( r \) (nm) can be obtained from equation (1).

\[
r = \frac{2V}{S_p}
\]  

(1)

where, \( S_p \) is specific surface area (m\(^2\)/g), \( V \) is pore volume (mm\(^3\)/g).

Fig.5 shows the relationship between drying shrinkage strain and average pore size for coarse aggregate and concrete. It appears that by using average pore size it is possible to use a power function to uniformly express the drying shrinkage strain of coarse aggregate and concrete. We also determined that an average pore size of 50 nm or more resulted in small drying shrinkage strain for coarse aggregate and concrete.

This indicates the potential for average pore size to be used as a simple index of drying shrinkage strain for coarse aggregate and concrete.

4 Conclusions

We investigated the relationship between the coarse aggregate pore structure measured by using mercury porosimetry and the drying shrinkage strain of coarse aggregate and concrete. Our results were as follows.

1. The pore size distribution of pore radius of 1 \( \mu \)m or less for coarse aggregate varied by coarse aggregate type, and the amount of pore volume did not necessarily correspond to the drying shrinkage strain of the coarse aggregate or concrete. We found that the coarse aggregate pore volume and the drying shrinkage strain of coarse aggregate and concrete were only mutually related for coarse aggregate classified as clastic rock.

2. We found that the specific surface area of coarse aggregate with pore radius of 1 \( \mu \)m or less, as determined from pore structure measurement data obtained by using mercury porosimetry, and the drying shrinkage strain of coarse aggregate and concrete were mutually related when the coarse aggregate was separated into the categories of clastic rock and the others.

3. There is potential for uniform expression of the drying shrinkage strain of coarse aggregate and concrete using a power function of the average pore diameter of coarse aggregate with pore radius of 1 \( \mu \)m or less, as determined from pore structure measurement data obtained by using mercury porosimetry.

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