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Evaluation of Effect of Aggregate Properties on Drying Shrinkage of Concrete

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ABSTRACT

In this paper, the effects of aggregate properties on drying shrinkage of concrete were experimentally and analytically investigated in order to quantitatively estimate contributions of elastic modulus and shrinkage of aggregate on concrete shrinkage. As results, the measured aggregate properties of the elastic modulus and the shrinkage in each obviously proportionally related to the drying shrinkage of concrete. It was found that the dominant factor of concrete shrinkage was the aggregate shrinkage rather than the elastic modulus by multiple regression analysis. The three-phase composite model was demonstrated that the drying shrinkage of concrete made with various aggregates could be predicted in a practical and realistic manner with good accuracy.

Keywords. Drying Shrinkage, Properties of Aggregate, Multi Regression Analysis, Composite Model

INTRODUCTION

Drying shrinkage of concrete often induces cracking in reinforced concrete members which may result in a deterioration of durability in concrete structures. In order to enhance a longevity of structures, it is very important to quantitatively estimate shrinkage of concrete as well as to control cracking at the design stage. Concrete shrinkage is due primarily to shrinkage of cement paste. The presence of aggregates reduces the concrete shrinkage because of restraining the paste shrinkage. However, concrete shrinkage is not only related to aggregate contents, but also aggregate mechanical properties such as elastic modulus, shrinkage itself and so on(Goto and Fujiwara 1976). Empirical equations for predicting concrete shrinkage is generally adopted in design code(JSCE 2007), which is based on a large amount of experimental data. On the other hand, as an entirely different approach, composite models for estimating influence of aggregate contents and properties on concrete shrinkage has been proposed(Pickett 1956; Hansen and Nielsen 1965).

The purpose of this study is to quantitatively evaluate the influences of aggregate properties such as elastic modulus and shrinkage to drying shrinkage of concrete as well as to verify the applicability of the composite model for predicting concrete shrinkage.

OUTLINE OF EXPERIMENTS

Materials and Mixture Proportions. The density under absolute dry condition and water absorption of coarse aggregate used in the present study are tabulated in **Table 1**. A total of 23 crushed stones in different production area were prepared, which were classified into 4 types of igneous rock and 4 types of sedimentary rock. Maximum size of all coarse aggregates was 20mm. The physical properties of fine aggregates used are listed in **Table 2**.

The mixture proportions and aggregate combinations for all of the investigated mixtures are given in **Table 3**. Ordinary Portland cement was used as cement. The water-to-cement ratio was set at 50% and the unit water content was fixed at 170kg/m^3.

Table 1. Properties of Coarse Aggregate

No.	Symbol	Rock types		Density (g/cm^3)	Water absorption (%)	Elastic modulus (kN/mm^2)	Shrinkage (x10^{-6})
G1	GB	Igneous	Basalt	2.79	1.42	77.2	-120
G2				2.66	1.99	53.6	-166
G3				2.93	0.42	77.3	-101
G4	GA		Andesite	2.62	2.13	54.3	-224
G5				2.54	2.47	42.7	-234
G6				2.65	2.14	63.5	-133
G7				2.57	2.93	38.6	-262
G8	GR		Ryolite	2.58	1.10	76.5	-154
G9				2.61	0.65	62.4	-74
G10	GG		Gabbro	2.75	0.44	89.2	-50
G11	GL	Sediment -ary	Lime stone	2.71	0.43	78.1	-17
G12				2.70	0.41	79.3	4
G13				2.69	0.63	82.1	1
G14				2.69	0.60	84.4	-18
G15	GS1		Sand stone	2.66	0.74	68.6	-237
G16				2.61	1.88	44.7	-756
G17				2.67	0.96	66.0	-455
G18				2.73	0.55	81.0	-142
G19				2.72	0.88	64.5	-400
G20				2.68	0.73	67.4	-174
G21				2.59	1.84	67.6	-870
G22	GT		Tuff	2.87	0.54	78.7	-154
G23	GS2		Slate	2.68	0.58	66.4	-180

Table 2. Properties of Fine Aggregate

No.	Types (mix ratio)	Density (g/cm^3)	Water absorption (%)
S1	Sea sand /Crushed sand (45:55)	2.60 / 2.70 (Ave. 2.66)	1.23 / 1.17 (Ave. 1.20)
S2	Mountain sand / Crushed sand (40:60)	2.50 / 2.59 (Ave. 2.55)	3.17 / 1.34 (Ave. 2.07)

Table 3. Mixture Proportions and Aggregate Combinations

W/C (%)	Water content (kg/m^3)	Type of cement	Fine aggregate	Coarse aggregate
50	170	Ordinary Portland cement	S1	G2, G4, G5, G8-G10, G12-G14, G22, G23
			S2	G11, G15-G19

Table 4. Test Programs

Objects	Test items	Specimen/ Sample
Concrete	Drying shrinkage	Prism (100 x 100 x 400mm)
Fine aggregate	Moisture absorption	Granules
Coarse aggregate	Moisture absorption	Particles
	Elastic modulus	Core cylinder (ϕ32 x 64 mm)
	Shrinkage	Particles

Test Method. Test programs are tabulated in **Table 4**. Drying shrinkage of concrete prism with a specimen size of 100 x 100 x 400mm was measured in accordance with JIS A 1129 by using a contact-type strain gauge. After demolding at 1 day, the specimens were cured in water at 20 ^oC until the age of 7 days. After 7 days, the specimens were cured in the laboratory at 20 ^oC and 60% R.H. until 182 days. The elastic modulus of coarse aggregates was measured with core cylinder specimens of ϕ32 x 64mm, which were removed from its base rock. Wire-strain gauge were used for measuring a longitudinal strain of core specimen under loading test. Shrinkage of coarse aggregate particles was measured by using wire-strain gauge, as shown in **Figure 1**. The wire-strain gauge was covered with a butyl type waterproof materials. The aggregate were soaked in water at 20 ^oC for more than 7days. After soaking, it was left in air 20 ^oC and 60% R.H. until strain change was settled down. The shrinkage of aggregate was defined as difference between the strain just after soaking and the saturated strain in air. Moisture absorption of fine and coarse aggregate was measured in a wet box saturated vapor at 20 ^oC for 24 hours, which was proposed as physical properties related to an internal surface area of aggregate(Fujiwara 1988).

Figure 1. Measurement method for shrinkage of aggregate

EXPERIMENTAL RESULTS AND DISCUSSION

Drying Shrinkage of Concrete. Drying shrinkage of concrete at the age of 182 days after drying is shown in **Figure 2**. The concrete shrinkage was significantly different depending on aggregate types, and was ranging from approximately -500×10^{-6} to over -1000×10^{-6}. Shrinkage of concrete made with limestone were relatively less than that of others. On the other hand, in the case of sandstone, the extent of shrinkage was remarkably wide. As a results, these could indicate that the drying shrinkage of concrete was determined by not only rock types, but also properties of aggregate.

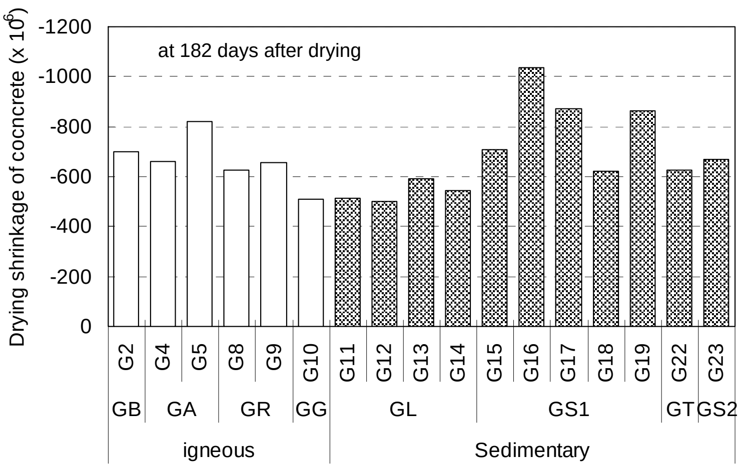

Figure 2. Drying shrinkage of concrete

Elastic Modulus of Aggregate. Elastic modulus of coarse aggregate measured with core cylinder is listed in **Table 1**. The results were ranging from approximately $40kN/mm^2$ to $90kN/mm^2$. It was marked that the elastic modulus of limestone were averagely larger than that of other aggregates. **Figure 3** shows the relationship between the elastic modulus of aggregates and the drying shrinkage of concrete. As generally recognized, the both relations had a relatively high-correlation, and the larger elastic modulus of aggregates, the smaller drying shrinkage of concrete.

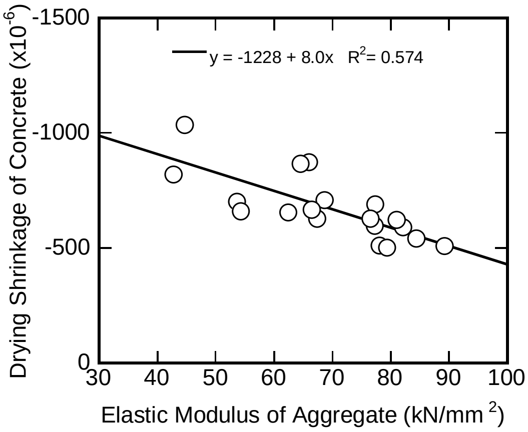

Figure 3. Relationship between drying shrinkage of concrete and elastic modulus of aggregate

Shrinkage of Aggregate. Shrinkage of coarse aggregate measured with wire-strain gauge is listed in **Table 1**, where the mean value of 5 to 60 particles in each aggregate was used. The largest one measured approximately -900 x 10^{-6} in strain. This value is not necessarily small compared with shrinkage of cement paste which is generally ranging from 3000 to 4000 x 10^{-6}. It was found that non-negligible shrinkage possibly occurred in aggregates. In a comparison with rock types, sandstone ranged widely in various shrinkage, on the contrary, limestone hardly shrunk. As shown in **Figure 4**, it was showed that the relationship between the aggregate shrinkage and the concrete shrinkage had a remarkably high linear correlation.

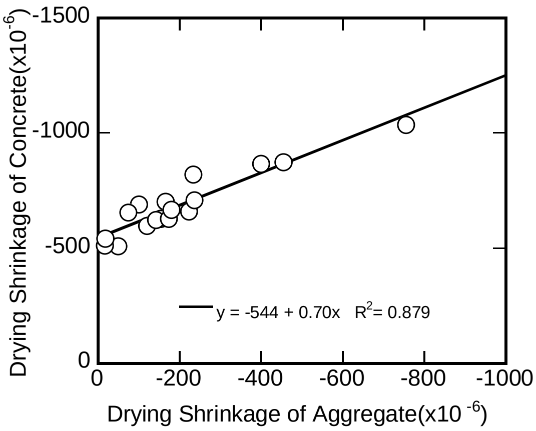

Figure 4. Relationship between concrete shrinkage and aggregate shrinkage

Multiple Regression Analysis. In order to estimate the respective contribution of the elastic modulus and shrinkage of aggregate on concrete shrinkage, multiple linear regression analysis was conducted. The calculated partial regression coefficients, standard errors, P-values as well as multiple correlation coefficients by the analysis are tabulated in **Table 5**. According to correlation coefficient, the experimental results could be accurately explained, therefore, the evaluation taking into account both aggregate properties together was appropriate and reasonable. However, in comparison with analytical results of each variable, it was indicated that the elastic modulus has only a minor influence on concrete shrinkage, rather, aggregate shrinkage could be dominant factor.

Table 5. Multiple linear regression analysis

Variables	Partial regression coefficient	Standard error	P-values(%)
Elastic modulus	2.68	1.00	1.82
Shrinkage	0.59	0.07	0.00
Constant	-747	-	-
Square multiple correlation coefficient R^2			0.931

COMPOSITE MODEL FOR CONCRETE SHRINKAGE

Composite Model. As mentioned above, a composite model for predicting concrete shrinkage considering effects of aggregate has been developed. Recently, three-phase composite model regarding concrete as hardened cement paste, fine aggregate and coarse aggregate was proposed (Teranishi and Sato 2006). This model was derived from the theory of spherical shells based on which concrete shrinkage was determined from relative volume content, elastic modulus and shrinkage in each phase. In this section, applicability of this model is verified by comparison between measured values and predicted values. Then, for the purpose of enhancing a practical use, aggregate properties formulae with simple indicators are also suggested based on the experimental results obtained above.

Formulation of Elastic Modulus. The relationship between water absorption and elastic modulus of aggregate is shown in **Figure 5**. High-absorption is associated with a low-elastic modulus, and the both properties was expressed as a power function, regardless of rock types.

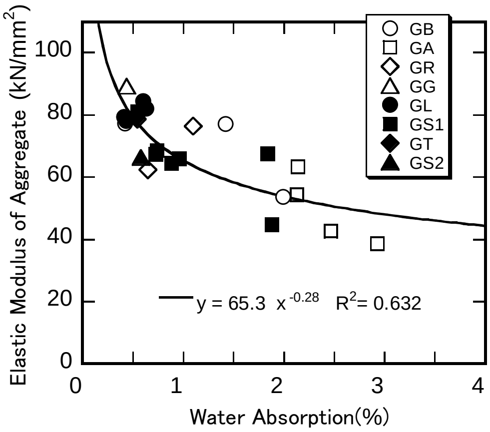

Figure 5. Relationship between water absorption and elastic modulus of aggregate

Formulation of Shrinkage. As shown in **Figure 6**, the moisture absorption is strongly lineally related to the aggregate shrinkage, while the relation was clearly different depending on rock types. The shrinkage of sedimentary rock sensitively increased with increasing of the moisture absorption, as compared with that of igneous rock. Although the cause of this different tendency are not fully understood, it is thought that pore structure could be important factor.

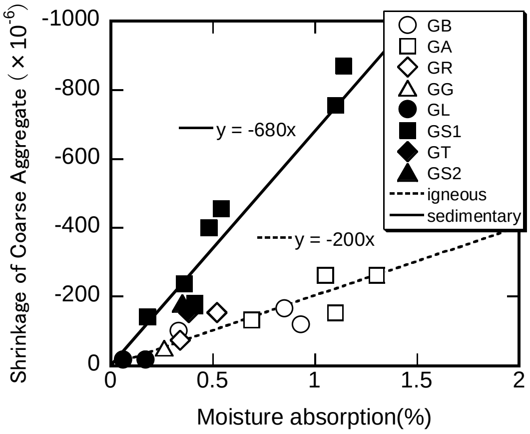

Figure 6. Relationship between moisture absorption and shrinkage of aggregate

Examination by Composite Model. The composite model (Teranishi and Sato 2006) used in this examination is written as follows,

$$\varepsilon_c = \varepsilon_p \frac{1-(1-m_s n_s))V_s - (1-m_g n_g)V_g}{n_c} \quad (1)$$

$$n_c = 1 + \frac{2(n_s - 1)V_s}{n_s + 1 - (n_s - 1)(V_s + V_g)} + \frac{2(n_g - 1)V_g}{n_g + 1 - (n_g - 1)(V_s + V_g)} \quad (2)$$

$$\varepsilon_c(t) = \frac{t}{R_s(\alpha W/C + \beta) + t} R_h(\lambda W/C + \delta) \quad (3)$$

$$R_s = 3.29 \log(V/S) + 1.17 \quad (4)$$

$$R_h = 1.28\{1-(h/100)^3\} \quad (5)$$

$$E_p = \frac{100}{W/C}\gamma + \eta \quad (6)$$

$$\alpha = 0.322, \beta = 4.77, \lambda = 86.3, \delta = 54, \gamma = 5.9, \eta = 4.2$$

Where, ε: shrinkage(x10^{-6}), E: elastic modulus(kN/mm^2), V: relative volume content, t: time after drying (=182days), W/C: water to cement ratio (%), V/S: volume-surface ratio(cm), h: relative humidity(%), m_s: $\varepsilon_s/\varepsilon_p$, m_g: $\varepsilon_g/\varepsilon_p$, n_s: E_s/E_p, n_g: E_g/E_p, (suffix of c, p, s, g is concrete, cement paste, fine aggregate and coarse aggregate, respectively).

The elastic modulus and drying shrinkage of cement paste were calculated from proposed equation, and was 16.0 kN/mm^2 and 3414 x 10^{-6}, respectively. On the other hand, those of aggregates was determined by substituting the water and the moisture absorption into the formulated equation above. Concerning with shrinkage of sea and mountain sand, because rock type of those was unknown, the averaged values between sedimentary rock and igneous rock were used.

As shown in **Figure 7**, the predicted shrinkage values were in excellent agreement with those measured. The error range between both values were within approximately 100 x 10^{-6}, and it was demonstrated by using the composite model that the drying shrinkage of concrete made with various aggregates could be predicted in a practical and realistic manner with good accuracy.

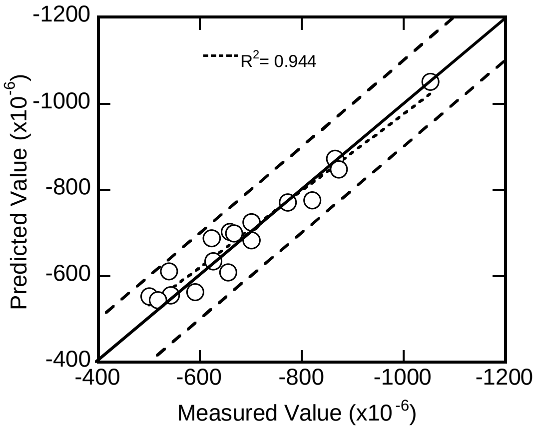

Figure 7. Comparison between experimental values and predicted values by composite model

CONCLUSION.

In this paper, the effects of aggregate properties on drying shrinkage of concrete were experimentally and analytically investigated in order to quantitatively estimate contributions of elastic modulus and shrinkage of aggregate on concrete shrinkage. The following conclusion can be drawn from the present study.

The measured aggregate properties of the elastic modulus and the shrinkage in each obviously proportionally related to the drying shrinkage of concrete. It was found that the dominant factor of concrete shrinkage was the aggregate shrinkage rather than the elastic modulus by multiple regression analysis. The three-phase composite model was demonstrated that the drying shrinkage of concrete made with various aggregates could be predicted in a practical and realistic manner with good accuracy.

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