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Strength and Young's modulus change in concrete due to long-term drying and heating up to 90 °C

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ABSTRACT

Understanding changes in the strength and Young's modulus of concrete under long-term drying or heating less than or equal to 90 °C is crucial for managing the aging of industrial buildings. We collected experimental data on changes in the physical properties of concrete components, aggregates, cement pastes, and concretes containing different aggregates and mortar under different heating and drying conditions. The change in compressive strength of concretes under various drying or heating conditions was explained by the behavior of the cement paste matrix and damage accumulation caused by differences in volume changes between the aggregate and mortar. In contrast, the variation in the Young's modulus of concrete caused by the drying or heating conditions was mainly explained by the increase in the number of voids due to internal cracking in the concrete.

1. Introduction

Occasionally, industry requires concrete structures that can withstand heating or drying for a long time, for example, in chimney structures, kilns, metal refining plants, and nuclear power plants. In nuclear power plants, the temperature of the concrete is regulated for normal long-term operation. The concrete surface temperatures should not exceed 65 °C except for localized areas, such as around penetrations, which are allowed to reach temperatures of up to 90 °C [1,2]. The regulations are based on experimental data that show a drop in compressive strength of heated concrete compared with that of concrete in saturated in lime water or sealed conditions. These data have recently been compiled by the U.S. Nuclear Regulatory Commission [3]. These data show that concrete components affect the changes in the behavior of the compressive strength of concrete in response to drying or heating. In some cases, concretes do not show a reduction in strength at temperatures of up to 100 °C [4].

Kishitani et al. conducted a series of studies to evaluate the drying effect of elevated temperatures on the properties of concrete [5]. The exposure periods were 10, 100, and 1000 days, and the temperature, compressive strength, Young's modulus, and water content were recorded. Although the exposure period affected the relationship between temperature and compressive strength, the relationship between water content and compressive strength was identical. The results indicate that concrete specimens require a considerable amount of time to achieve equilibrium, even at elevated temperatures, and suggest the importance of experiments under equilibrium conditions. This is consistent with the results reported by Pihlajavaara [6]. For this reason, our experiments on the properties of concrete, mortar, and cement paste were at equilibrium conditions. Pertaining to the effects of heating and drying conditions, from sealed conditions to heating at 90 °C, data on the strength and Young's modulus of cement paste, mortar, and concrete containing different types of aggregates should directly contribute to the management of aging nuclear plants.

The mechanism behind these effects is important for cement chemistry and concrete science. Concrete is composed of an aggregate and cement paste. The majority of research has focused on cement paste, although the volume percentage of cement paste is usually about 30% in concrete. Recently, we have investigated the mechanism of the bending strength and Young's modulus of cement paste during the first drying [7]. The changes in strength and Young's modulus were explained by a combination of the colloidal and porous properties of the cement paste. However, the contribution of these results to concrete engineering was limited because the effect of the changes in the cement paste on the concrete properties was not investigated.

The volume percentage of aggregate in normal concrete is about 70%, although its volume stability is rarely investigated, except in relation to the alkali–silica reaction. Aggregate shrinkage has been investigated by Roper [8], and Goto and Fujiwara [9]. It has also been reported that the volume stability of aggregate has a large impact on concrete shrinkage [10]. In addition, studies have shown that aggregate size is a factor in concrete shrinkage [11,12]. In Japan, the Tarui viaduct

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in Wakayama prefecture required a large-scale repair because numerous cracks appeared in the concrete one and a half years after its completion. The cracking was linked to the volume stability of aggregate, and this has led to research into the properties of aggregate [13]. Concrete aggregates that are examined and deemed acceptable under the Japanese Industrial Standards show a large variety of shrinkage behavior [14].

Differences in the volumetric behavior of aggregates and cement pastes and the resultant microcracking have been recently investigated both experimentally and theoretically [10,12,15–18]. Microcracking affects the physical properties of concrete; therefore, the volume stability of the aggregate and aggregate size should be parameters for investigating the physical properties of concrete.

In this study, we examine the concrete components, such as the paste and coarse aggregates, and the compressive strength and Young's modulus of mortar and concretes containing five different sizes or types of aggregates. In addition, we evaluate the damage accumulation by the digital image correlation method (DICM) [18]. Based on these data, we discuss the importance of the properties of cement for the physical properties of concrete, the difference in the changes in volume of coarse aggregates and mortar, and the effect of the resultant accumulated damage on the physical properties of concrete. Our results highlight the importance of aggregate performance in concrete.

2. Material and methods

2.1. Aggregate experiments

Five different coarse aggregates were prepared and their properties are shown in Table 1. There were four crushed aggregate (C-G1–C-G4) and one river gravel (C-G5) sample. The maximum aggregate sizes of C-G3 and C-G4 were 20 and 13 mm respectively, although they are made of the same type of rock.

The aggregates were identified by polarization microscope images of the original rocks, powder X-ray diffraction (XRD) and Rietveld analysis [19–21]. For XRD analysis, a sample of the aggregate was finely ground with a vibration pulverizer. Corundum (α-Al_2O_3, 50 mass %) was mixed with the sample as an internal standard. XRD was performed on a diffractometer (D8 Advance, Bruker AXS) with a Cu-Kα X-ray source, a tube voltage of 40 kV, a tube current of 40 mA, a scan field of 2θ = 5–65°, a step size of 0.02° and a scan speed of 5°/min. Rietveld analysis was performed with TOPAS version 4.2 (Bruker AXS) and the effects of the preferred orientation and particle size were optimized. The target minerals were quartz [22], calcite [23], dolomite [23], albite [23], anorthite [23], microcline [23], orthoclase [23], chlorite [24,25], sericite [26], biotite [27], illite [23], and the internal standard, corundum [23].

Volume change properties of coarse aggregates were measured with a thermomechanical analyzer (TMA; TMA4000SA, Bruker AXS) coupled to a relative humidity generator (HC9700, Bruker AXS). Three samples with dimensions of 3 × 3 × 6 mm were cut from each aggregate specimen with a diamond saw in three orthogonal directions. Before the experiment, the samples were soaked in water under depressurized conditions for 30 min. The samples were placed in the apparatus, and the experiment was initiated after attaining a stable condition was reached. The target relative humidity (RH) for the samples were 80%, 60%, 40%, and 20% RH, as well as 0% RH, which was achieved under N_2 gas (99.999%) flow. The temperature was increased under N_2 gas flow to 40, 60, and 90 °C. The change in the length of the samples was measured by a linear variable differential transformer with a precision of 0.5 μm and a contact load of 0.098 N. The thermal expansion coefficient (TEC) was calculated from the linear regression of the strain at 20, 40, 60, and 90 °C under N_2 flow, and the length change isotherm under shrinkage 20 °C was calculated.

The Young's modulus and Poisson's ratio of the aggregate are also important for preventing large shrinkage of the cement paste. Therefore, these were obtained by measuring the ultrasonic velocity. The ultrasonic pulse velocities of the P-wave (longitudinal elastic wave) and the S-wave (transverse elastic wave) of the water-saturated aggregate samples were measured using an ultrasonic probe (V103-RM and V153-RM, Panametrics-NDT), and a pulser-receiver (5077PR, Panametrics-NDT). The voltage of the pulse oscillator was −400 V, the frequency was 1.0 MHz, and the pulse repetition frequency was 100 Hz for the transmission method. The width of the samples was measured as 10 mm with a digital micrometer caliper with an accuracy of 0.020 mm. The reference curves were obtained by direct contact, and the period of the pulse peak in the reference curve was subtracted from the period of the pulse peak in the sample record to determine the propagation time. The pulse velocities of the P-wave (V_p) and S-wave (V_s) were calculated from the sample width and propagation time. Using the saturated aggregate density (ρ), the Poisson's ratio and Young's modulus were determined by using V_p and V_s in the following equations:

$$\nu = \frac{1-2\left(V_s/V_p\right)^2}{2-2\left(V_s/V_p\right)^2} \tag{1}$$

$$E = V_p^2 \rho \frac{(1+\nu)(1-2\nu)}{1-\nu}. \tag{2}$$

2.2. Cement paste experiments

The details of specimen preparation have been reported elsewhere [7]. White cement provided by the Taiheiyo Cement Corporation was used. Cement type is BL I according to EN 197. The properties of the cement are shown in Table 1 (cement C1) and Table 2. The water/cement ratio was 0.55, and the paste (10 L) was mixed in a 20 L Hobart mixer for 3 min after the water was added, and then remixed for a further 3 min after the paste was scraped from inside the mixer. To minimize segregation, the paste was remixed every 30 min until 6 h, after which it had a creamy consistency. The specimens were placed in a thermostatic chamber at 20 ± 1 °C. They were demolded after 4 days and cured under lime-saturated water until they were 6 months old. The specimen size was 3 × 13 × 300 mm. After 6 months, the specimens were placed in RH-controlled humidity chambers at 95%, 80%, 60%, 40%, or

Table 1
Properties of the materials.

Material	Notation	Property
Cement	C1	White cement; density, 3.05 g/cm^3; Blaine value, 3480 cm^2/g;mortar strength, 63.7 MPa.
	C2	High early strength Portland cement; density, 3.14 g/cm^3; Blaine value, 4400 cm^2/g; mortar strength, 71.4 MPa.
Fine aggregate	S	River sand; density, 2.57 g/cm^3; absorption, 2.51%; solid volume ratio, 68.3 %; F.M., 2.60
Coarse aggregate	C-G1	Limestone; max. size, 20 mm; density, 2.71 g/cm^3; absorption, 0.24%; solid volume ratio, 62.3%; F.M., 6.65.
	C-G2	Sandstone; max. size, 20 mm; density, 2.64 g/cm^3; absorption, 0.89%; solid volume ratio, 62.5%; F.M., 6.70.
	C-G3	Sandstone; max. size, 20 mm; density, 2.70 g/cm^3; absorption, 0.65%; solid volume ratio, 61.3%; F.M., 6.68.
	C-G4	Sandstone; max. size, 13 mm; density, 2.70 g/cm^3; absorption, 0.57%; solid volume ratio, 59.8%; F.M., 6.25.
	C-G5	River gravel; max. size, 20 mm; density, 2.65 g/cm^3; absorption, 0.90%; solid volume ratio, 64.3%; F.M., 6.76.
Chemical admixture	A	High water reducing and air-entraining agent,lignin, sulfuric acid oxide, and polycarboxylic acid oxide.