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Influence of reinforcement configuration on the shrinkage and cracking potential of high-performance concrete

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HIGHLIGHTS

- Investigated the restrained shrinkage behavior of high-performance concrete (HPC).
- Precise and complete information of HPC obtained by automatic measurement system.
- The effect of reinforcement to restrain concrete shrinkage decreases with distance.
- Bars at the corners decrease the cracking potential with same reinforcement ratio.
- Dry condition increased the shrinkage gradient and cracking potential of HPC.

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ABSTRACT

This study experimentally investigated the effects of the reinforcing bar configuration on the shrinkage behavior of high-performance concrete (HPC), including the restrained shrinkage strain, shrinkage gradient, restrained stress, and cracking potential. The deformation in high-performance concrete specimens was measured with four different reinforcement ratios, two different reinforcement configurations, and two different curing conditions. The results demonstrated that the restraining effect of the reinforcement on concrete shrinkage decreased with the distance from the reinforcing bar. For the same reinforcement ratio, the four reinforcing bars placed at the corners of a concrete member better restrained the shrinkage all throughout the concrete cross-section and decreased the concrete cracking risk better than a single reinforcing bar placed at the center. A formula was put forward to predict the restrained shrinkage strain distribution in the concrete cross-section. In addition, the restrained specimens under the dry curing condition have higher decrease rate of restraining effect, shrinkage gradient, restrained stress, and cracking potential than those under the sealed condition.

1. Introduction

The internal humidity of concrete decreases during hydration and drying, thereby leading to concrete shrinkage without any applied external load. Tensile stresses are generated in the concrete if the shrinkage is restrained by reinforcing bars, studs, steel plates, and other structural components. These stresses can result in cracks when they exceed the concrete's tensile strength. The shrinkage in the high-performance concrete (HPC), particularly autogenous shrinkage, is significantly higher than that in normal concrete because of its low water/cement ratio [1–4], which results in the increased cracking risk in the HPC.

So far, the restrained shrinkage of concrete is investigated by theoretical derivation [5], laboratory scale experiment [6–8] and in-suit experiment [9]. According to present theory [5], the restraining effect of the reinforcement on the concrete shrinkage is influenced by the elastic modulus of the concrete and reinforcement and the reinforcement ratio. However, it is not influenced by the reinforcement configuration. Furthermore, some studies observed that the reinforcement configuration influences the shrinkage behavior of the reinforced concrete [6–8]. Unfortunately, no explanation was provided for this observation, and this issue has not attracted the attention of researchers. On the contrary, engineering practice shows that this issue is worth studying. In the presence of multiple constraints limiting the concrete shrinkage, reinforcing bars not only contribute to shrinkage stress, but also help the concrete to resist the shrinkage stress caused by other constraints. In the design of reinforced concrete structures that

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experience a large shrinkage stress, the Chinese design criteria require additional reinforcing bars near the concrete surface to help the concrete resist the shrinkage stress caused by the other constraints [10]. The ability to resist concrete deformation is essential for the reinforcement to be able to help the concrete resist external loads. Therefore, in practice, reinforcements that have been placed cannot restrain the concrete near the surface. Some clauses of the Chinese design code are derived from engineering experience and ignore the stresses caused by the reinforcement because of the lack of related research. These clauses have been proven to fail in many cases. Thus, the influence of the reinforcement configuration on the restraining effect of the reinforcement should be investigated to precisely predict the shrinkage behavior of the reinforced concrete and reduce the risk of concrete cracking.

In the past, the deformation of the concrete was measured by the mechanical dial gauge and record by the manual reading, the earliest reading were taken 24 h after the specimens were casted. There were three main disadvantages of this measurement method: the error caused by the reader, the discontinuousness of the data, and the lack of information of the concrete in the early age. In order to overcome these disadvantages, some computerized measurement system have been designed to automatically measure and record the information of concrete by using the sensor [9–14], *VWSG*(vibrating wire strain gages) or *LVDTs*(linear variable differential transducers)for example. The character of HPC was rapidly changed in the early age, and the precise and complete information of HPC in the early age were very important. Thus, in present study, an automatic system is used to measure and record the shrinkage, relative humidity (RH), and temperature of the HPC to investigated the shrinkage and restrained shrinkage of the HPC. The main variables considered were the reinforcement ratio(values of 0%, 1.00%, 1.57%, and 2.45%), reinforcement configuration (one reinforcement bar placed in the center of the concrete cross-section versus four reinforcement bars placed at the four corners of the concrete cross-section), and curing conditions(sealed versus dry). The specific objectives included the evaluation of the effects of the reinforcement ratio, reinforcement configuration, and curing condition on the shrinkage strain, restraining effect of the reinforcement on the concrete shrinkage, restrained stress, and cracking potential of the HPC.

2. Experimental program

2.1. Materials and mix proportions

Table 1 shows the details of the mix proportions in this study. Portland cement and fly ash were used as the cementitious materials. Table 2 presents the chemical compositions and the physical properties of the cementitious materials used. Crushed limestone with a maximum nominal size of 20 mm was used as the coarse aggregate. The fineness modulus of the fine aggregate (quartz sand) was 3.0. A water/binder (W/B) ratio of 0.27 was used for all the test specimens. In addition, a high-performance water-reducing agent, polycarboxylate superplasticizer (SP) with a density of 1.09 g/cm^3, was added to improve workability.

2.2. Basic properties

Table 2
Chemical compositions and physical properties of the cementitious materials.

Composition% (mass)	Cement	Fly ash
SiO_2	21.47	49.47
CaO	65.77	4.45
Al_2O_3	5.47	20.67
Fe_2O_3	4.28	14.32
MgO	1.44	1.17
SO_3	0.52	1.40
Specific surface(cm^2/g)	3471	4680
Density(g/cm^3)	3.10	2.22

The cube compressive strength, splitting tensile strength, and elastic modulus of the concrete mixes under the sealed and dry curing conditions were tested. The concrete specimens were tested at ages of 72, 168, 336, 504, and 672 h Table 3 shows the test results.

2.3. Shrinkage, relative humidity, and temperature

The mold used to cast the specimens was made of Plexiglas with inner dimensions of 100 mm × 200 mm × 800 mm. The four sides of the mold were covered with removable Plexiglas sheets. The bottom of the mold was covered with a Teflon sheet that was 1 mm thick, such that the specimens would only be restrained by the reinforcement after the removable Plexiglas sheets are lifted (Fig. 1). The reinforcement ratios of 0%, 1.00%, 1.57%, and 2.45% were obtained for the specimens with reinforcing bars diameters of 10 mm, 16 mm, 20 mm, and 25 mm, respectively (Table 4). Table 5 presents the properties of the reinforcing bars. The two following reinforcement configurations were used: one with a reinforcing bar placed at the center and one with four reinforcing bars placed at the four corners of the concrete cross-section. The sealed and dry curing conditions were used. Accordingly, the specimens were immediately covered with aluminum tape after the removable sheets were lifted to create the sealed curing conditions. The specimen shrinkage was measured at 0, 45, and 90 mm from the specimen centers. These measurement positions were referred to hereinafter as the “0 position”, “45 position”, and “90 position”, respectively. Shrinkage was measured using the LVDTs mounted on the two long ends of each specimen. The measurement range of the LVDTs was 2 mm. The measurement accuracy was 1 μm. Nuts were precast in the concrete to ensure that the LVDTs were in good contact with the specimen. Plastic bolts were screwed into the nuts after the removable sheets were lifted. The sensory bars of the LVDTs were then brought into direct contact with the bolt. The bolts and the LVDTs for the sealed curing conditions were installed after the seal work. All the tests were performed at a constant RH of 60 ± 5% and a temperature of 22 ± 1 °C. The internal temperature and the RH of the concrete were measured according to the methods suggested by J. Zhang [14].

An automatic system was used to obtain the precise and complete information about the shrinkage strain, RH and temperature of the HPC. The system includes four parts: sensor(LVDTs or Temperature/Humidity sensor), multiplexer, computer and supporting software. The sensors measure the shrinkage strain, RH and temperature of the HPC, then transfer the information through the multiplexer to the computer. The software was provided by the sensor supplier. And the function of the software was to record and store these information. After the sensor has been set, using the data lines to connect the sensor, multiplexer and computer.

Table 1
Mix proportions.

Materials (kg/m^3)	Cement	Water	Fly ash	Sand	Course aggregate	Superplasticizer
HPC	480.0	146.0	50.0	605.0	1075.0	12.4