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Shrinkage characteristics of high-strength concrete for large underground space structures

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ABSTRACT

This study forms part of a research project that was carried out on the development and application of high-strength concrete for large underground spaces. In order to develop 50 MPa high-strength concrete, eight optimal mixtures with different portions of fly ash and ground granulated blast furnace slag, which make the pozzolanic reaction, were selected. For assessments of shrinkage characteristics, free shrinkage tests with prismatic specimens and shrinkage crack tests were performed. The compressive strength was more than 30 MPa at 7 days, and stable design strength was acquired at 28 days. High-strength concrete containing blast furnace slag shows large autogenous shrinkage, while large shrinkage deformations and cracks will occur when mixtures are replaced with large volumes of cementitious materials. Hence, for these high-strength concrete mixtures, the curing conditions of initial ages that affect the reaction of hydration and drying effects need to be checked.

1. Introduction

The need for the creation of large underground space structures is due not only to the lack of sufficient terrestrial surface, but also to complex factors such as rapid economic growth, the development of construction technologies, and changes to peoples' lifestyles. In industrialized countries, attempts have been made to apply large underground space structures as national major projects (Boniface, 1999; Rienzo et al., 2008; Monnikhof et al., 1999; Romer et al., 2003; Yuan et al., 2000).

However, concrete structures applied to underground spaces should be adjusted by external forces, and durability problems should also be satisfied for the duration of the structure's service life. Because the assessments of both durability and rehabilitation of underground concrete structures are more difficult than those of cases above ground, the required capacities must be considered during the design and construction stages. Moreover, because underground environmental conditions are more stable than those above ground, the service lives of underground concrete structures are more affected by the corrosion of reinforcing steel compared to the durability of concrete itself (Tongeren and Tonnisen, 1988). In concrete structures, the corrosion of reinforcement progressively accelerates the volumetric expansions of reinforcing steel, the development of cracks, and the rate of corrosion, rapidly reducing the service life of the structure.

In order to improve the durability of concrete structures, the probability of cracks occurring should be minimized during the design and construction stages. However, the guidelines of specifications used for the prevention of cracks are limited to unit water weight and allowable width of cracks, and these cannot be applied ubiquitously for underground structures. Since the 1990s, studies have been carried out on methods of preventing cracks, and have focused more on structural performances than on material behaviors. Studies on materials have fundamentally been carried out for the development of non-shrink cements using expansive materials, and methods of reducing capillary water. However, expansive materials can create problems with the quality of concrete, and the method for reducing capillary water can reduce the workability of concrete due to the reduction the water content. Therefore, such methods do not provide adequate solutions.

Due to the development in the 1980s of chemical admixtures, robust, 40 MPa strength concrete can now be produced without the need to apply special quality controls in the field. Although there is a need and a demand for concrete higher than that strength, such high-strength concrete cannot fundamentally be used due to the difficulties of quality controls and lack of applicable cases. In addition, with a lower water–cement ratio, high-strength concrete shows large autogenous shrinkages; adjustment evaluations should therefore be performed in order to effectively reduce initial shrinkage cracks. Hence, in this study, as part of

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the research towards the development and application of high-strength concrete for large underground spaces, particularly with respect to the development of 50 MPa high-strength concrete, optimal mixtures with different portions of fly ash and ground granulated blast furnace slag, which make the pozzolanic reaction, were selected. These pozzolanic materials, which are hardened by the pozzolanic reaction with the hydration product, $Ca(OH)_2$, improve the water-tightness and the long-age strength because they fill pores in the concrete matrix. In addition, as admixtures (pozzolanic materials, fly ash, and blast furnace slag) are added to the concrete matrix, the hydration heat is reduced. For the assessments of shrinkage characteristics, free shrinkage tests with prismatic specimens and shrinkage crack tests were then performed.

2. Experimental programs

2.1. Mix proportions

For the application of high-strength concrete to large underground structures, all mixtures were proportioned to give the 28-day design strength of 50 MPa. Considering the design strength, the water to cementitious materials ratio (w/b or w/cm) was maintained at 36% for all mixtures. The amount of superplasticizer varied in order to determine the desired level of workability while maintaining a slump and slump flow of 230 ± 25 and 500 ± 50 mm, respectively. To enable the development of durable concrete, the air content of all mixtures was maintained at 5.0 ± 1.0% by adjusting the dosage of the air-entraining admixture. The determined unit water content and fine aggregate ratio are 170 kg/m^3 and 50%, respectively. Ordinary Portland cement (OPC), fly ash (FA), and blast furnace slag (BS), of which the chemical compositions and the physical properties are given in Table 1, were used as cementitious materials in the tests. With different constituents of binders, eight mixtures of OPC, binary mixtures (FA10, FA20, BS30, and BS50), and ternary mixtures (F10S40, F15S35, and F20S30) were determined and are summarized in Table 2. OPC refers to ordinary Portland cement, and FA and BS refer to fly ash and blast furnace slag (ternary mixtures were used with F and S), respectively. The following figures in the designation represented the percentage mass of the cementitious materials in the total binder contents; for example, Mix FA20 contains 20% fly ash and 80% OPC, and F15S35 contained 15% fly ash, 35% slag, and 50% OPC.

The specific gravity and fineness of ordinary Portland cement were 3.16 and 341 m^2/kg, respectively, while those of fly ash and blast furnace slag were 2.16, 348 m^2/kg and 2.91, 453 m^2/kg, respectively. The coarse aggregate used was crushed granite, with the specific gravity, fineness modulus and maximum particle size of 2.63, 6.6 and 20 mm, respectively. The fine aggregate was sea sand with a specific gravity and fineness modulus of 2.59 and 2.8, respectively. Chemical admixtures of the polycarboxylic acid high range AE water reducing agent and air-entraining agent were used to acquire the properties.

Table 1
Physical properties and chemical composition of binders.

	OPC	FA	BS
SiO_2	21.3	52.8	34.3
Al_2O_3	4.7	22.5	12.7
Fe_2O_3	3.1	13.4	0.5
CaO	63.1	4.1	41.3
MgO	2.9	0.8	5.93
SO_3	2.2	0.4	2.53
K_2O	–	0.9	0.5
Na_2O	–	0.4	0.4
Loss on ignition	0.8	3.8	0.48
C_3S	59.8	–	–
C_2S	13.7	–	–
C_3A	5.1	–	–
C_4AF	9.3	–	–
Specific gravity	3.15	2.13	2.91
Fineness (m^2/kg)	341	348	453

2.2. Compressive strength and splitting tensile strength

Generally, in the design of reinforced concrete structures, the tensile strength of concrete is disregarded due to its small proportion. However, in order to reduce cracks and to enhancing the serviceability, evaluation and consideration of tensile strength of concrete has been considered. In normal strength ranges, the tensile strength of concrete is proportional to the compressive strength, but in high-strength ranges, these relationships are not possible (Carrasquillo et al., 1981; Kovler et al., 1999). Because of the difficulty in straightforwardly maintaining direct tensile strengths, and due to the imperfection of fixing between equipment and the end of specimens, the tensile strength of concrete has been evaluated by splitting the tensile strength and the flexural tensile strength.

After casting, the specimens were covered with plastic sheets, and left in the casting room for 24 h at 20 ± 2 °C, and were then demolded and stored in water at 20 ± 3 °C until tested. The compressive strength and splitting tensile strength were tested on φ 100 × 200 mm cylinders at 7, 28, and 56 days after casting, according to ASTM C 39 and ASTM C 496. For 24 h after casting, the specimens were cured in a curing room at 20 ± 3 °C.

2.3. Shrinkage of concrete

Shrinkage of concrete can be expressed by the summation of autogenous shrinkage and drying shrinkage as Eq. (1). In particular, for high-strength concrete, the effect of autogenous shrinkage should be considered using the following equation for the calculation of shrinkage deformation (CEB-FIP, 1999; JCI, 1996)

$$\varepsilon_{sh}(t) = \varepsilon_{as}(t) + \varepsilon_{ds}(t) \tag{1}$$

where $\varepsilon_{sh}(t)$ = total shrinkage deformation, $\varepsilon_{as}(t)$ = portion of autogenous shrinkage, $\varepsilon_{ds}(t)$ = portion of drying shrinkage.

Table 2
Mix proportions.

Mixture	w/b (%)	S/a (%)	Unit weight (kg/m^3)					
			Water	Cement	FA	BS	Fine Agg.	Coarse Agg.
OPC	36	50	170	472	–	–	842	855
FA10				425	47	–	833	846
FA20				378	94	–	825	838
BS30				331	–	142	835	847
BS50				236	–	236	830	843
F10S40				236	47	189	824	836
F15S35					71	165	821	833
F20S30					94	142	818	830