

Engineering Properties of Environmental Friendly Concrete using Hwangtoh Binder

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ABSTRACT: This study presents the testing of 7 hwangtoh-based cementless concrete mixes to explore the significance and limitations of the development of environmental friendly concrete without carbon dioxide emissions while maintaining various beneficial effects. Hwangtoh, which is a kind of kaolin, was incorporated with inorganic materials, such as calcium hydroxide, to produce a cementless binder. Mechanical properties of hardened concrete were measured: including compressive strength gain, splitting tensile strength, moduli of rupture and elasticity, and stress-strain relationship. In addition, the recorded mechanical properties were compared with those of ordinary portland cement (OPC) concrete and predictions obtained from the design equations specified in ACI 318-05 and CEB-FIP for OPC concrete, wherever possible. Test results showed that the developed hwangtoh-based concrete have highly effective performance and great potential as an environmental-friendly building material.

Keywords: hwangtoh, engineering properties, eco-friendly concrete.

1. INTRODUCTION

Ordinary portland cement (OPC) is generally known as an essential component of concrete. However, the production of OPC generates excessive carbon dioxide and cause massive environmental pollution. Recent survey [1] shows that approximately 7% of total emission of greenhouse gases (GHS) in the earth's atmosphere is produced because of the production of OPC. Thus, production of cement-less binder using pozzolan materials, such as fly-ash, and ground granulated blast-furnace slag, has attracted the concrete industry to minimize carbon dioxide emissions. Alkali-activated or geopolymer binder has been commonly regarded as a new class of engineering materials for use in the production of environmental friendly mortar and concrete [2, 3].

Hwangtoh, whose physical characteristics and activation process are

fully covered in a companion paper [4], is the primary clay created by the weathering of rocks and is mainly available in South Korea. Hwangtoh is commonly known as an eco-friendly material with various beneficial properties, including high absorbency, self-purification, and radiation of far infrared rays. As proved by Yang et al. [4], the main ingredients in hwangtoh are kaolinite and halloysite, which have a few layers containing linked Si-tetrahedral sheets and Al-octahedral sheets, indicating that hwangtoh is a kind of kaolin having a 1:1 layer structure with an amorphous microstructure. Therefore, hwangtoh has been considered for production of inorganic pastes with no cement using an alkaline activator. Yang et al. [4] showed that hwangtoh-based cementless mortars have various applications as an environmental friendly building material, and proposed empirical formulas to evaluate the initial

flow and 28-day compressive strength of hwangtoh-based mortars.

In the present study, 7 concrete mixes were produced and tested to explore the significance and limitations of the development of hwangtoh-based cementless concrete. The amount of high-range water-reducing admixture added to meet the designed initial slump and slump loss with time were recorded for fresh concrete. Different properties of hardened concrete, such as compressive strength gain with age, splitting tensile strength, moduli of elasticity and rupture, stress-strain relation, and bond resistance, were also measured. Mechanical properties of hwangtoh-based cementless concrete were compared with those of OPC concrete examined from the database established by Yang et al. [4]. In addition, mechanical properties of concrete tested were compared, whenever possible, with the predictions obtained from the design equations specified in ACI 318-05 [5] or CEB-FIP [6] for OPC concrete.

2. EXPERIMENTAL DETAILS

2.1 Materials

The chemical compositions of hwangtoh evaluated by x-ray fluorescence (XRF) analysis are given in Table I. Hwangtoh has very low calcium oxide (CaO) content, but is rich in silicon oxide (SiO₂) and aluminum oxide (Al₂O₃), so the SiO₂-to-Al₂O₃ ratio by mass is 1.6. Hwangtoh was incorporated with inorganic materials, such as calcium hydroxide, to produce a cementless binder.

The physical properties of hwangtoh and aggregates used were also measured. The specific gravity and specific surface area of the hwangtoh were 2.48 and 5800 cm²/g, respectively. The specific gravity and fineness modulus for sand used as a fine

aggregate were 2.54 and 2.82, respectively, and those for crushed granite used as coarse aggregate having maximum size of 25 mm were 2.61 and 7.06, respectively.

2.2 Mixture Proportions

Seven cementless concrete mixtures using the hwangtoh-based binder were prepared. Water-binder (W/B) ratio by weight varied between 20 and 70% when the volumetric fine aggregate-to-total aggregate ratio was fixed at 40%. All aggregates were batched in a saturated surface dried state. To meet the designed initial slump of 180±10 mm, high-range water-reducing admixture, whose threshold dosage recommended to minimize the change of concrete properties was 2% with respect to the weight of binder, was added.

2.3 Casting, Curing and Testing

Fine and coarse aggregates together with the hwangtoh-based binder were dry-mixed in a 0.35m³ capacity mixer pan for 1 minute and then water was added and mixed for another 1 min. If the initial slump of concrete did not meet the designed value, high-range water-reducing admixture was added until the designed slump was obtained.

Various steel moulds were cast to evaluate the mechanical properties of each concrete mix. Immediately after casting, all specimens were cured at a constant temperature and relative humidity of 23 ± 2 °C and 70 ± 5%, respectively, until tested at a specified age. All steel moulds were removed at the age of one day.

The slump of fresh concrete was measured at 0 (initial), 30, 60, 90, and 120 minutes after mixing of concrete to evaluate the workability loss of hwangtoh-based concrete. Compressive and splitting tensile strengths, stress-strain relation, and modulus of elasticity were measured using 100×200 mm cylinder specimens. A compressor meter having dial gages and electrical resistance strain gages (ERS) was mounted on the cylinder specimens, to obtain the

Table I: Chemical composition of hwangtoh (Mass %)

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	F ₂ O ₃	TiO ₂	MnO
52.5	32.9	4.3	4.3	0.4	0.7	0.6	0.2
		1	7			9	4

Note : Loss on ignition=3.89

stress-strain relationship and modulus of elasticity of concrete, which was calculated at 45% peak stress [5]. The modulus of rupture of concrete was also measured using prismatic beams of 150×150×550 mm dimensions under a symmetrical two-point top loading system. The bond stress-slip relationship of a 16 mm diameter deformed bar with yield strength of 820 MPa incorporated in a cubic specimen of 150 mm was measured from the pullout test under monotonic loads. The above tests of hardened concrete specimens were conducted using a 500 kN capacity universal testing machine with a servo-control system. The compressive strength of concrete specimens was measured at 1, 3, 7, 28, 56 and 91 days, while other properties were measured at the age of 28 days only. The testing procedure was carried out in accordance with the specifications of the KS [7].

3. TEST RESULTS AND DISCUSSION

Splitting tensile strength, and moduli of elasticity and rupture of OPC concrete are generally proportional to the square root of compressive strength in the range of normal concrete strength [5, 6]. Thus, these mechanical properties of hwangtoh-based (HB) concrete tested also need to be normalized by square root of the compressive strength. As there is little, if any, available test results on HB concrete, the effects of main variables on different properties of the concrete specimen is compared with that recorded for OPC concrete database compiled by Yang et al. [4]. In addition, various measured properties of HB concrete are compared, wherever possible, with the predictions obtained from design equations specified in ACI 318-05 or CEB-FIP building codes for OPC concrete.

3.1 Slump Loss

The slump loss $S_L(t)/(S_L)_i$ of concrete with elapsed time is shown in Fig. 1, where $S_L(t)$ and $(S_L)_i$ are the slump values at a

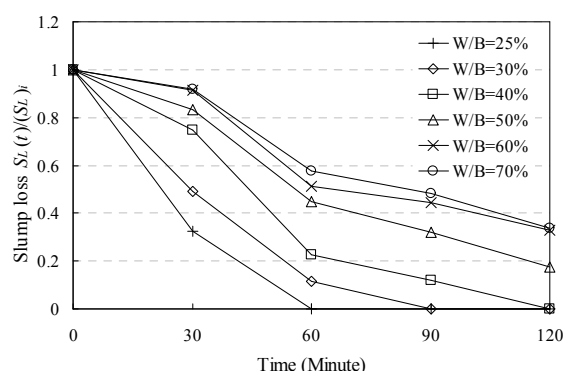


Figure 1: Slump loss with time

specified time (in minutes) and initial slump, respectively. The slump of specimen having W/B ratio of 20 or 25% after 30 minutes and 60 minutes, respectively, could not be measured due to the rapid setting. The slump of the HB concrete decreased linearly with time, regardless of W/B ratio. The decreasing rate was more notable with the decrease of W/B ratio.

3.2 Compressive Strength at 28 days

The effect of W/B ratio on the 28-day compressive strength f'_c of HB concrete is plotted in Fig. 2. On the same figure, the test results of OPC concrete and best fit curves obtained from nonlinear regression analysis are also given. The compressive strength of concrete specimens tested increased with the decrease of W/B ratio, showing that the W/B ratio is one of the most important factors that affect the compressive strength of HB concrete. This is also true for OPC concrete [8] and HB mortar [4]. The increasing rate of the compressive strength against the W/B ratio was slightly lower for HB concrete than for OPC concrete. In addition, for the same W/B ratio, a lower compressive strength generally developed in HB concrete than in OPC concrete. A compressive strength greater than 20 MPa was not achieved in HB concrete with W/B ratios above 40%. Therefore, W/B ratio should be less than 40% for structural application of HB concrete.

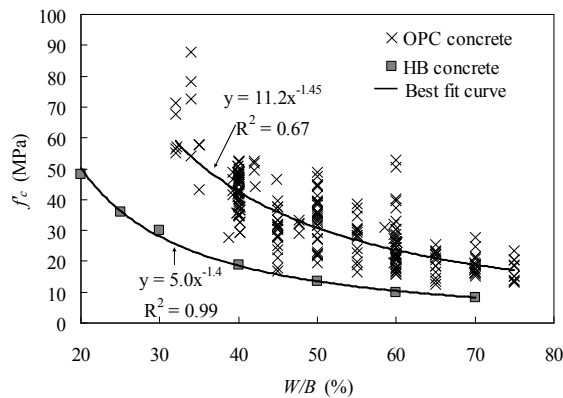


Figure 2: Compressive strength at 28-days.

3.3 Compressive Strength Development

To examine the compressive strength gain of HB concrete with age, the relative compressive strength $f'_c(t)/f'_c$ with age is shown in Fig. 3, where $f'_c(t)$ is the compressive strength at age t (in days). The development of the compressive strengths of different HB concretes according to age showed a typical parabolic shape, indicating that the increasing rate of compressive strength development decreased with the increase of age. The compressive strength at age of 1 day ranged between 25% and 45% of the 28-day strength, and more than 80% of the 28-day strength developed within age of 7 days. The compressive strength development at age of 1 day was slightly increased with the increase of W/B ratio. On the other hand, the compressive strength development at age of 91 days increased minimally with the decrease of the W/B ratio.

3.4 Splitting Tensile Strength

Fig. 4 shows the normalized splitting tensile strengths $f_{sp}/\sqrt{f'_c}$ of HB concrete and OPC concrete. The $f_{sp}/\sqrt{f'_c}$ of HB concrete decreased with the increase of the W/B ratio, but that of the OPC concrete was nearly independent of the W/B ratio. In general, a lower $f_{sp}/\sqrt{f'_c}$ appears in HB concrete than in OPC concrete. When the W/B ratio was below 30%, however, the

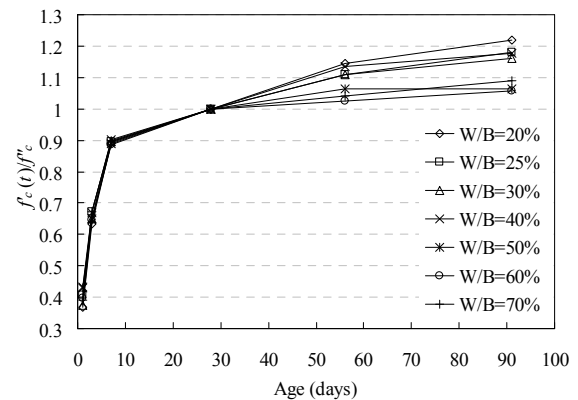


Figure 3: Compressive strength gain

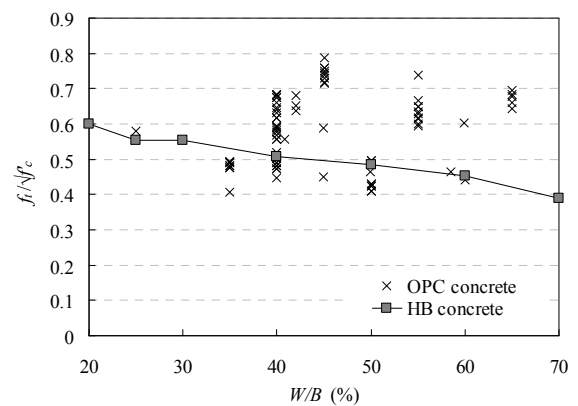


Figure 4: Splitting Tensile Strength

$f_{sp}/\sqrt{f'_c}$ of HB concrete was higher than 0.53, which is the empirical value proposed by Oluokun [9] based on test results of OPC concrete.

3.5 Modulus of Rupture

The effect of W/B ratio on the normalized modulus of rupture $f_r/\sqrt{f'_c}$ of HB concrete is shown in Fig. 5. Test data obtained from OPC concrete database are given in the same figure. The $f_r/\sqrt{f'_c}$ of HB concrete decreased with the increase of the W/B ratio. In addition, when the W/B ratio was above 30%, the $f_r/\sqrt{f'_c}$ of HB concrete was lower than that of OPC concrete and the design equation of ACI 318-05. Based on Fig. 4 and Fig. 5, the tensile resistance capacity of HB concrete is commonly lower than that of OPC concrete.

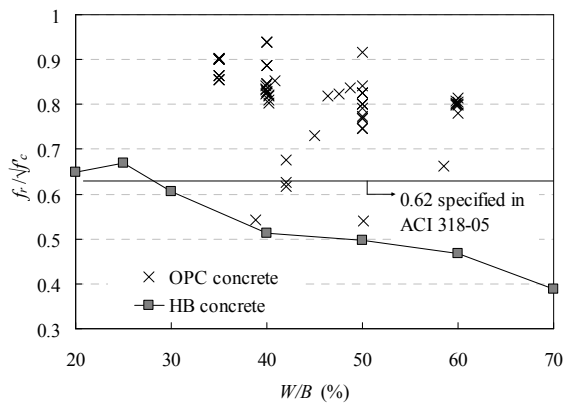


Figure 5: Modulus of Rupture

3.5 Modulus of Elasticity

Fig. 6 shows the normalized modulus of elasticity $E_c / \sqrt{f'_c}$ of HB concrete with the increase of W/B ratio. $E_c / \sqrt{f'_c}$ of HB concrete was independent of W/B ratio. The average value of $E_c / \sqrt{f'_c}$ of HB concrete tested was about 4540, indicating that the modulus of elasticity of HB concrete is generally lower than the predictions obtained from ACI 318-05 by an average of 3.5% as shown in Fig. 6.

3.6 Stress-Strain Relationship

Typical stress-strain curves of different HB concrete mixes are plotted in Fig. 7. On the same figure, predictions obtained from formulas specified in CEB-FIP for OPC concrete are also given for comparison purposes. The characteristic of the stress-strain curve of HB concrete was significantly influenced by W/B ratio,

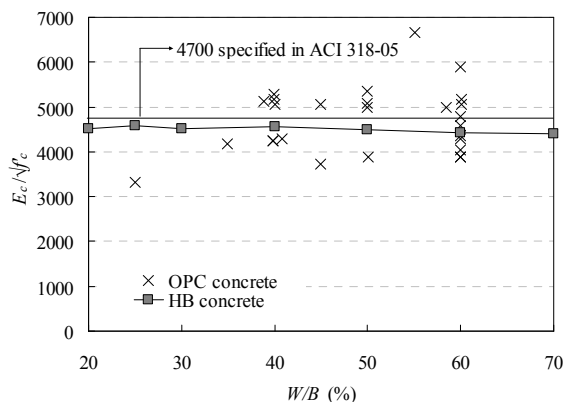
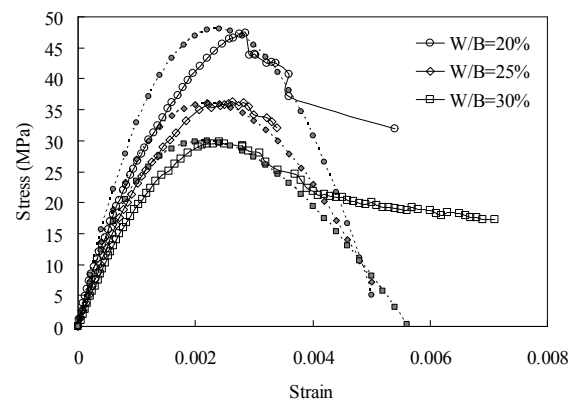


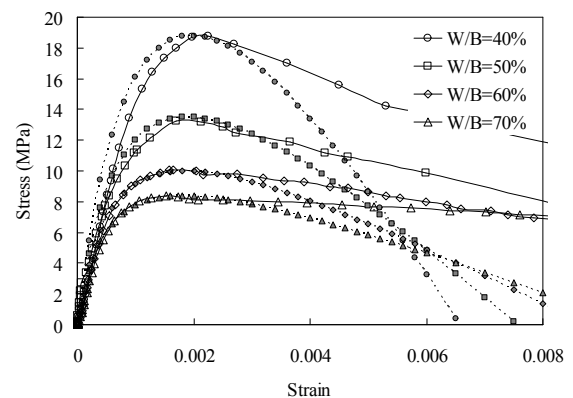
Figure 6: Modulus of Elasticity

which has a significant effect on the compressive strength. With the decrease of W/B ratio, that is, the increase of compressive strength, the initial stiffness and strain at the peak stress of HB concrete increased. For W/B ratio below 30% (for medium strength), the descending branch of the stress-strain curve dropped sharply showing the brittleness failure mode, and the dropping rate was more prominent for high concrete strengths as shown in Fig. 7 (a). However, the descending branch for HB concrete having W/B ratios greater than 30% (for low strength lower than 20 MPa) showed ductile behavior.

The characteristic of the stress-strain curve measured for HB concrete generally



(a) For medium strength



(b) For low strength

Figure 7: Stress-strain curves

(White symbol with solid line and black symbol with dotted line indicate test results and predictions obtained from CEB-FIP for OPC concrete, respectively.)

disagreed with the predictions of the CEB-FIP model. Lower stiffness in the ascending branch and larger strain at the peak stress were observed for the test specimens than for the CEB-FIP model, showing an increase of discrepancy with the increase of W/B ratio. In addition, the slope of the descending branch of the stress-strain curve was slower for the test specimens than for the CEB-FIP model, showing an increase of discrepancy with the decrease of W/B ratio.

4. CONCLUSION

- 1) The slump of HB concrete decreased linearly with time, showing that the decreasing rate was more notable with the decrease of water-to-binder ratio.
- 2) The compressive strength of HB concrete increased with the decrease of water-to-binder ratio. However, the increasing rate was slightly lower for HB concrete than for OPC concrete.
- 3) HB concrete showed rapid and high strength development at an early age, but the compressive strength development at long-term age was similar to that of OPC concrete.
- 4) The normalized splitting tensile strength, and normalized modulus of rupture of HB concrete decreased with the increase of water-to-binder ratio.
- 5) The normalized modulus of elastic modulus of HB concrete was almost independent of water-to-binder ratio.
- 6) The initial stiffness of the ascending branch and the dropping rate of the descending branch in the stress-strain curve, and the strain at peak stresses of HB concrete increased with the decrease of water-to-binder ratio.
- 7) The moduli of rupture and elasticity of HB concrete with water-to-binder ratios above 40% were generally lower than those of OPC concrete and predictions obtained from design equation specified in ACI 318-05 for OPC concrete. In addition, the stress-strain relation measured for HB concrete showed little agreement with the predictions

obtained from the design model specified in CEB-FIP.

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