Mixture and Material Factors Affecting the Strength and Shrinkage of High Performance Concrete

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Abstract
This paper reports experimentally investigated effects of mixture proportion and material factors on strength, drying and autogenous shrinkage of high performance concrete (HPC). Based on numerous trial mixtures by the authors, HPC mixtures incorporated 5% expansive additive (EA) and 1% shrinkage reducing admixture (SRA). Water to binder ratio (W/B) and water content were varied from 20% to 35% and 145 kg/m$^3$ up to 175 kg/m$^3$, respectively. Cement type, such as ordinary Portland cement and high belite cement, as well as superplasticizer type, including melamine based, naphthalene based and polycarboxylate based superplasticizers, were chosen as experimental parameters. Drying and autogenous shrinkage were reduced by increasing the W/B and decreasing water content. Additionally, drying and autogenous shrinkage were reduced by using high belite cement. In order to secure volumetric stability, HPC mixtures must incorporate, within a range of possible limits, fly ash (FA), silica fume (SF), EA and SRA, high W/B, low water content and a high C$_2$S content cement.

Keywords: mixture proportion; autogenous shrinkage; drying shrinkage; High Performance Concrete (HPC)

1. Introduction

The demand for High Performance Concrete (HPC) has gradually increased since its development. HPC can be defined as concrete that is, according to specific performance requirements, stronger, more durable, and more fluid than traditional concrete. HPC has been internationally recognized as the new generation of concrete.

Despite the well known benefits of HPC, engineers and designers have difficulty making decisions regarding the proper strength level and compatibility between cement and superplasticizer (SP) for particular construction applications. Furthermore, shrinkage of HPC is increasingly recognized as a design stage consideration.

Although HPC has exceeds the performance of conventional concrete in all engineering properties, many researches have revealed that HPC is prone to a large amount of autogenous shrinkage, which leads to concrete structure cracking. Autogenous shrinkage has been attributed to the combination of chemical shrinkage and self desiccation of the cement paste. This combined effect is due to the excessive hydration reaction that results from high amounts of cement and faster hydration reactions resulting from improved dispersion of mixture by SP.

It was previously reported that the risk of autogenous shrinkage of HPC could be reduced by combining HPC with a specific proportion of a mineral admixture, such as silica fume (SF) and fly ash (FA), an expansion admixture (EA) and a shrinkage reducing admixture (SRA). The SF-FA-EA-SRA mixture was found to aid in the reduction of autogenous shrinkage and improve the mechanical characteristic of HPC.

The present paper builds on previous researches by experimentally investigating the effect of mixture proportions including water to binder ratio (W/B), water content and material factors, such as cement and SP type, on the strength characteristic, drying and autogenous shrinkage of the HPC system incorporating FA-SF-EA-SRA.

2. Experimental Program and Methodology

2.1 Experimental Program

The experimental program of the present study is shown in Table 1. To determine the proper incorporation ratio of mineral admixtures for reducing shrinkage in HPC, initial trial mixtures with FA contents from 0% to 30%, SF contents from 0% to 15%, SRA contents from 0% to 2% and EA contents from 0% to 20% were tested.

Initial tests resulted in a mixture incorporating FA of 20%, SF of 10%, EA of 5% and SRA of 1%. This mixture was tested with W/B ranging from 20% to 35%. The effect of water content on the strength...
and shrinkage of HPC was confirmed by fabricating HPC with a W/B of 30%, which was achieved by varying water content from 145 kg/m$^3$, 155 kg/m$^3$, 165 kg/m$^3$ and 175 kg/m$^3$. The effect of cement type and SP type on the properties of HPC was investigated by fabricating OPC and HBC with a W/B of 30% and a water content of 175 kg/m$^3$. Naphthalene based SP (NS), Melamine based SP (MS) and Polycarboxylate acid based SP (PS) were used to make separate mixtures of HPC, each with a W/B of 30% and a water content of 175 kg/m$^3$. The mixture-specific SP dosages required to achieve the target slump flow were determined by mixing ten batches of HPC. HPC targets for slump flow and air content were set to 60±10 cm and 4.5±1.5%, respectively. Mixture proportions of HPC are summarized in Table 2.

### 2.2 Materials

Korean produced OPC and HBC were used in this experiment, the physical properties of which are shown in Table 3. The mineral compositions of these cements, as calculated by Bogue's equation, are given in Table 4. River sand from Chungnam, Korea was used as fine aggregates and crushed stone from Chungbuk, Korea, with a maximum size of 25 mm, was used as coarse aggregates. The physical properties of aggregates are shown in Table 5.

FA produced in Korea and SF produced in Norway were used as mineral admixtures. CSA based EA, produced in Japan, and Glycol based SRA, produced in Germany, were used as chemical admixtures. NS, MS and PS from Korea were used as SP. The physical properties of these admixtures are shown in Tables 6–10.

### 2.3 Test method

Concrete was mixed in a forced mixer. The slump test was carried out in accordance with Korean Industrial Standards (KS) F 2402 and slump flow was measured after the slump value was taken. Air content was measured in accordance with KS F 2421.

Compressive strength specimens were prepared using $\Phi 100 \times 200$ mm cylindrical moulds in accordance with KS F 2403 and compressive strength was measured at the design age in accordance with KS F 2406. Drying shrinkage was measured in accordance with KS F 2424. Autogenous shrinkage was tested in accordance with the method set forth by the Japan Concrete Institute (JCI). As shown in Fig.1., prisms of $100 \times 100 \times 400$ mm were prepared for autogenous shrinkage measurement. Two studs for mounting a

### Table 1. Experimental Program

| Factors considered | Parameters investigated |
|--------------------|-------------------------|
| Slump flow (cm)    | 1, 60 ± 10              |
| Air content (%)    | 1, 4.5 ± 1.5            |
| W/B (%)            | 4, 20, 25, 30, 35       |
| Water content (kg/m$^3$) | 4, 145, 155, 165, 175 |
| Cement type        | 2, Ordinary Portland cement (OPC) High belite cement (HBC) |
| SP type            | 3, Naphthalene based SP Melamine based SP Polycarboxylate based SP |
| Fresh concrete     | 4, Slump, Slump flow, Air content, Unit weight |
| Hardened concrete  | 4, Compressive strength (7, 28, 91, 180 days) Tensile strength (28 days) Drying shrinkage (1, 2, 3, 7...180 days) Autogenous shrinkage (0.5, 1, 2, 3...48 days) |

### Table 2. Mixture Proportions of HPC

| W/B (%) | Water content (kg/m$^3$) | Cement type | SP type | S/a (%) | SP (Bx%) | AE agent (Bx%) | Unit weight (kg/m$^3$) |
|---------|--------------------------|-------------|---------|---------|----------|---------------|-----------------------|
| 20      | 175                      | OPC         | PS      | 43      | 0.85     | 0.006         | 560 529 680 175 88 44 8.8 |
| 25      | 175                      | OPC         | NS      | 44      | 2.50     | 0.018         | 448 616 761 140 70 35 7.0 |
| 145     | 175                      | OPC         | NS      | 45      | 2.50     | 0.025         | 309 761 902 97 48 24 4.8 |
| 155     | 175                      | OPC         | NS      | 45      | 2.40     | 0.023         | 331 735 871 103 52 26 5.2 |
| 165     | 175                      | OPC         | NS      | 45      | 2.30     | 0.020         | 352 708 839 110 55 28 5.5 |
| 30      | 175                      | OPC         | NS      | 45      | 2.00     | 0.018         | 373 681 808 117 58 29 5.8 |
| 175     | HBC                      | NS          | 45      | 2.00     | 2.20     | 0.015         | 373 681 808 117 58 29 5.8 |
| 35      | 175                      | OPC         | MS      | 45      | 3.00     | 0.006         | 373 681 808 117 58 29 5.8 |
|         |                          |             | PS      | 45      | 0.55     | 0.007         | 373 681 808 117 58 29 5.8 |
detachable mechanical gauge were glued 200 mm apart on the side surfaces of each specimen.

To prevent moisture loss, the autogenous shrinkage specimens were sealed with two layers of polyester film. Measurements were conducted at a temperature of 20 ± 3°C and a relative humidity of 60 ~ 80%. The first measurement was taken after the approximate completion of initial setting because autogenous shrinkage is assumed to occur at the beginning of the hydration reaction. After final setting, specimens were demolded and sealed with aluminum tape to prevent moisture movement. Mass loss was also measured.

3. Results and Discussion

3.1 Fundamental properties of fresh concrete

Fluidity and air content

The test results of fresh concrete with mixture and material variation are summarized in Table 11. All HPC mixtures were proportioned by trial batches to secure the slump flow and air content targets of 60 ± 10 cm and 4.5 ± 1.5%.

SP dosage was increased in response to reduced slump flow resulting from specific mixture proportion factors, including fluidity, W/B and water content reduction. Air content remained relatively constant with W/B variation for given water contents and cement types. The dosage of AE agent was increased with decreases in water content due to associated decreases in air content. Given a set W/B and water content, HPC using HBC showed lower fluidity than HPC using OPC. These results differ somewhat from those of previous research, which showed HBC to be more fluid than OPC due to its ability to more rapidly adsorb chemical agents. The chemical adsorption rate of HBC is more rapid than that of OPC due to its having a more spherical particle shape and smaller fraction of C₃A and C₄AF than OPC.

Reductions in water demand afforded by SP type were shown to be PS>NS>MS. The air content of HPC with HBC was greater than that of HPC with OPC, which resulted in a decrease of AE agent dosage in HPC with HBC.

3.2 Setting time

Decreases in W/B and water content generally resulted in slower setting times. More specifically, increases in SP dosage for achieving target slump flow and associated decreases in W/B and water content lead to retardation of setting times. However, a W/B of 20% tended to result in a setting time shorter than that of other HPC mixtures. This is because the HPC mixture with a W/B of 20% uses PS, which does not require a large amount of SP to achieve its target slump flow, and also contains a comparably large amount of cement. Cement type did not significantly affect the setting time. For a given slump flow, reductions in setting time afforded by SP type were shown to be NS>PS>MS.

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4. Properties of Hardened Concrete

4.1 Compressive strength

Compressive strength depending on B/W (inverse of W/B) and water content is shown in Fig. 2. In this paper, compressive strength may be considered as apparent, rather than potential compressive strength because all of the HPC mixtures described herein contain varieties of mineral admixture, EA and SRA. Apparent compressive strength was enhanced by increasing B/W and age, but not by altering water content.

Fig. 3. illustrates the relationship between apparent compressive strength and cement and SP type, respectively. The apparent compressive strength achieved before 28 days was lower for HBC than for OPC. However, the apparent compressive strength of HBC achieved after 28 days was comparable to that of OPC. The initially retarded, but eventual comparable compressive strength of HBC, relative to OPC, can be explained by the relatively high amount of C$_2$S in HBC, which aids in long term strength development but retards the hydration reaction at early age. Also, the retarded formation of Ca(OH)$_2$ that results from the delayed hydration reaction of HBC at early age decreases apparent compressive strength due to the prolonged pozzolanic reaction of fly ash and silica fume. However, the combination of the hydration reaction of HBC and corresponding pozzolanic reaction by silica fume and fly ash improved the apparent compressive strength of HBC to a level comparable to that of HPC with OPC at 91 days.

Although the SP dosages required to achieve a target slump flow were different for every SP type, SP type did not markedly affect the apparent compressive strength of any of the mixtures.

4.2 Splitting tensile strength

The apparent splitting tensile strengths at 28 days for various B/W and water contents, and for various combinations of cement and SP types, are illustrated in Figs. 4. and 5., respectively. Apparent tensile strength depending on variations in mixture and material factors exhibited a similar tendency with apparent compressive strength gain.

5. Shrinkage Properties

5.1 Drying shrinkage

In Fig. 6., the drying shrinkage of HPC depending on W/B and water content is shown as a function of time. HPC swelled for the first 7 days of the water curing period. HPC showed rapid drying shrinkage after 7 days, and shrinkage development decreased after 28 days. It is interesting to note that a decrease in W/B led to an increase in drying shrinkage. This
may be because drying shrinkage in low W/B HPC is mainly responsible for autogenous shrinkage, and thus the large amount of autogenous shrinkage caused by the increased binder content results in increased corresponding drying shrinkage. It is also interesting to note that for HPC with W/B of 20% and 25%, shrinkage occurred even after 2 days of water curing.

As expected, an increase in water content led to an increase in drying shrinkage. This is because, for a given W/B, the capillary pore pressure that occurs during desiccation increases with elevated water contents, and significant autogenous shrinkage occurs due to correspondingly large cement contents. The degree of drying shrinkage was found to increase by \(-0.8 \times 10^{-4}\) for every 10 kg/m\(^3\) increase in water content.

The drying shrinkage of HPC by cement and SP type is presented as a function of time in Fig.7. The drying shrinkage of HPC using HBC was as much as 45% smaller than that of OPC. Research conducted by Tazawa\(^{12,13}\) showed that because HBC has a greater C\(_2\)S content and smaller C\(_3\)A and C\(_4\)AF contents than OPC, HBC has reduced chemical shrinkage during the hydration reaction. In other words, the presence of an interlayer composed of C\(_3\)A and C\(_4\)AF in the hydration product increases autogenous shrinkage and thereby decreases corresponding drying shrinkage of concrete using HBC to a level lower than that using OPC. Additionally, the delayed pozzolanic reaction of fly ash and silica fume that results from the prolonged hydration reaction of HBC at early age leads to reduced autogenous shrinkage, and may also be responsible for decreased drying shrinkage.

Although the SP dosages required to secure the same slump flow were different for every SP type, SP type did not affect the drying shrinkage. However, it is thought that for a given SP dosage, the use of PS makes it possible to reduce the drying shrinkage due to the superior water reducing effect.

5.2 Autogenous shrinkage

The autogenous shrinkage of HPC depending on W/B and water content as a function of time is presented in Fig.8. A decrease in W/B resulted in an increase of autogenous shrinkage. This effect can be explained by the degree of hydration associated with the high self desiccation of low W/B HPC mixtures with large cement contents. The self desiccation in the cementitious matrix results in a greater capillary pore pressure, which causes elevated levels of autogenous shrinkage of HPC.\(^{14}\) Capillary pore pressure affects autogenous and drying shrinkage, but in different ways. In the case of drying shrinkage, moisture loss via evaporation results in tensile forces developing within capillaries, while moisture loss is through the hydration reaction of cementitious materials for autogenous shrinkage.\(^{14}\)

Autogenous shrinkage of HPC tended to decrease with decreasing water content, as a reduced hydration reaction resulted from the reduction of cement content with decreasing water content for a given W/B. Due to the use of EA and SRA, autogenous shrinkage did not occur during the measurement period for HPC with a W/B of 35% and a water content of 145 kg/m\(^3\).

Autogenous shrinkage depending on cement and SP types is illustrated as a function of age in Fig.9. HBC showed lower autogenous shrinkage than OPC, as HBC contains larger amounts of C\(_2\)S than OPC, which retards hydration reaction at early age. The prolonged Ca(OH)\(_2\) formation due to the retardation of the hydration reaction in HBC resulted in a delayed pozzolanic reaction of fly ash and silica fume. The retardation of hydration reaction was also responsible for delayed degree of hydration associated with corresponding strength development at early age. The
Pozzolanic reaction and the fast degree of hydration are known to increase autogenous shrinkage by bringing about self desiccation by consuming water in the cement matrix. For this reason, the use of HBC results in less autogenous shrinkage than is seen with OPC.

SP type may not directly affect autogenous shrinkage for a given slump flow. According to Holt\[13\], the use of SP increases autogenous shrinkage not because SP affects the hydration reaction, but because SP contributes to heterogeneities, such as cluster formations between aggregates, and aids the dispersion and reaction speed of cement during the early hours. Accordingly, SP is not considered to directly affect autogenous shrinkage, regardless of SP type.

Mass loss caused by evaporation of moisture was measured to monitor the region of autogenous and drying shrinkage (Figs.10. and 11.). A loss in mass of 0.036–0.046% of the autogenous shrinkage specimens was observed 49 days after the first measurement. Mass loss satisfied the requirement for autogenous shrinkage being less than 0.05%, as required by the JCI.\[11\]

However, results of autogenous shrinkage readings taken after 49 days were not included because some readings exceeded the requirement range provided by the JCI.\[11\]

6. Conclusions

This paper investigates experimentally the effects of mixture and material factors on strength and shrinkage of HPC. The following conclusions can be drawn from the experimental results.

1. An Increase in B/W enhanced apparent compressive strength, while water content did not affect apparent compressive strength. At 28 days, use of HBC showed an apparent compressive strength lower than that of OPC. However, after 28 days, the compressive strengths of HBC and OPC based HPC were comparable. The SP dosages required to achieve the target slump flow were different for every SP type, but SP type did not markedly affect apparent compressive strength.

2. Drying shrinkage increased with decreasing W/B in the high performance region due to increased autogenous shrinkage. The use of HBC decreased drying shrinkage due to its reduction of autogenous shrinkage. Autogenous shrinkage was reduced by the combined effect of a large amount of C₃S in HBC and the retarded pozzolanic reaction of fly ash and silica fume resulting from prolonged Ca(OH)₂ formation at early age.

3. Decreased W/B and increased water content increased autogenous shrinkage. HBC reduced autogenous shrinkage. By achieving proper mixture proportioning through increasing W/B and lowering water content within a given range, and by selecting high contents of C₃S cement and MS, HPC may secure improved engineering properties and reduce the risk of drying and autogenous shrinkage.
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