IMPROVING THE QUALITY OF SLAG CONCRETE VIA HIGH ALITE CEMENT

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Abstract - Concrete containing ground granulated blast furnace slag (GGBFS) has many advantages but it is easily subjected to cracking and has low quality when cured in poor conditions. For the sustainability of slag concrete structures, these disadvantages need to be overcome. In this study, the effectiveness of high alite cement (HAC) in improving cracking and the quality of covercrete of slag concrete is investigated. The cracking resistance ability is examined via the tensile strength of concrete, while the surface water absorption test is applied to study the quality of covercrete. The results reveal the capacity of HAC in improving the tensile strength of slag concrete. The high bond strength between aggregate and HAC mortar contributes significantly to larger tensile strength. HAC slag concrete also exhibits high resistance against water absorption.

Key words - slag concrete; high alite cement; direct tensile strength; bond strength; SWAT (surface water absorption test); water absorption rate at 10 minutes (p_{600}); covercrete

1. introduction

Nowadays, because of its advantages, which include better workability, high compressive strength, environmental conservation, and high durability [1], concrete using ground granulated blast furnace slag (GGBFS) is being widely used all over the world. However, Son and Hosoda found that slag concrete is also easily subjected to more severe nonstructural microcracks than OPC concrete *(cần giải thích từ viết tắt OPC)* under temperature variation at early ages [2]. It has also been recognized that slag concrete has lower resistance against carbonation. To solve these disadvantages of slag concrete, a new type of cement named high alite cement has been proposed. In a past study about compressive strength development of HAC [3], HAC slag concrete showed good performance in terms of long-term continuous strength development as well as early age strength.

For long-term service of reinforced concrete structures, not only strength but also durability is one of the key factors. Soon after the hydration of cement has begun, the protective passivity layer on the surface of reinforcing bar, which consists of γ-Fe_2O_3 tightly adhering to the steel, is self-generated. This oxide film keeps the steel bar intact. Nonetheless, when this layer is destroyed, e.g., by chloride ions, corrosion will occur with the presence of water and oxygen [4]. In this case, therefore, the quality of covercrete is an important factor for resisting against the corrosion of reinforcement and it needs to be improved.

There are many nondestructive methods to inspect the quality of covercrete. Some tests are based on air permeability such as Schönlin air permeability test [5], autoclam air permeability test [6], or Torrent permeability tester [7]. The others are based on water permeability such as initial surface water absorption test (ISAT) proposed by Levitt in 1969 [8], autoclam water permeability test proposed in early 1980s [9] and modified in early 1990s [10]. Recently, a new method, surface water absorption test (SWAT), has been developed by Hayashi and Hosoda [11]. One of the main indices obtained from SWAT is water absorption rate. It has been found that water absorption rate at 10 minutes could evaluate the quality of covercrete up to 10 to 30 mm. Moreover, the 10-minute SWAT results have a good relationship with that of long term absorption test results. Therefore, the 10-minute SWAT result is enough for the inspection of covercrete quality [12].

In this research, the effectiveness of HAC in improving cracking and water absorption resistance of slag concrete is investigated. The cracking resistance ability is examined via tensile strength of concrete, while SWAT is applied to study the water absorption resistance of covercrete.

2. Experimental programs

2.1. Materials

Three types of binders were used in this study: Ordinary Portland Cement (OPC), HAC, and GGBFS. HAC is a newly developed cement with very high alite ($3CaO.SiO_2$) content and almost no belite ($2CaO.SiO_2$) [13]. The mineral compositions HAC are calculated from the chemical composition through Bogue's equations and the main compounds of HAC and some types of cements [14] are compared in Figure 1. The physical properties of the binders are presented in Table 1. The coarse aggregate was andesite with the maximum particle size of 19 mm. Pit sand was the fine aggregate. All the materials were placed in a curing room with a temperature of around 20°C before mixing.

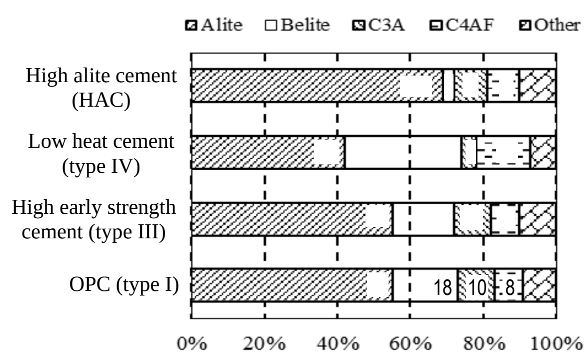

Figure 1. *Main compounds of cements*

Table 1. *Physical properties of binders*

Binder	Density(g/cm^3)	Specific area(cm^2/g)
OPC	3.16	3310
HAC	3.11	5480
GGBFS	2.90	4030

2.2. Direct tensile strength test

The mix proportions of the mortars and concretes for direct tensile strength test are given in Table 2. As mentioned above, in terms of compressive strength, HAC showed the best results when it was combined with GGBFS with a slag replacement ratio of around 50 percent.

Thus, in this study, the proportion of cement and GGBFS was set at 50-50. The mix proportions of the respective mortars for each kind of concrete were determined by just removing the coarse aggregate from the concrete while retaining the other proportions.

Table 2. *Mix proportions for direct tensile strength test.*

Mixture	M-O-30	M-H-30	C-O-30	C-H-30
Water	251	250	165	165
OPC	418	-	275	-
HAC	-	417	-	275
GGBFS	418	417	275	275
Pit-sand	1229	1225	810	808
Andesite	-	-	816	814
SP	4.2	5.8	2.8	3.9

Figure 2. *Direct tensile strength test*

The specimens were cylinders 100 mm in diameter and 100 mm high. Right after finishing concreting, the specimens were sealed by polyethylene film and placed in a temperature-controlled chamber, which had been maintained at 20ºC. The heating began at 2 hours after adding water into the mix. Firstly, the temperature was increased from 20ºC to 50º Cover one hour, and then maintained at 50ºCfor 5 hours. After that, the temperature was cooled down to 20º Cover 6 hours and kept at 20ºCfor 10 hours. The direct tensile strength of concretes and mortars was investigated at the age of one day following heat curing. The direct tensile strength test method was the same as that proposed by Son and Hosoda [2] (Figure 2). Three specimens were tested for each mix proportion and the mean value was taken.

2.3. Surface water absorption test (SWAT)

The mix proportions of the concretes for SWAT are given in Table 3. In all mixes, the cements were replaced by GGBFS with the replacement ratios of 40% by mass. W/B ratios were 0.4, 0.5, and 0.6 to cover from good concrete to poor concrete. The air content of concrete was controlled at 6 ± 0.5% to prevent concrete from scaling under freeze/thaw cycles. Ten cylindrical specimens of 100 mm in diameter and 200 mm high for each type of concrete were placed.

Table 3. *Mix proportions for SWAT*

Mixture	O-40	H-40	O-50	H-50	O-50	H-50
Water	165	165	165	165	165	165
OPC	248	-	198	-	165	-
HAC	-	248	-	198	-	165
GGBFS	165	165	132	132	111	111
Pit-sand	745	745	776	776	798	797
Andesite	921	920	960	959	986	986
101	1.24	1.44	0.99	0.99	0.83	1.38
AE	2.1	2.5	0.7	-	-	-

Ten specimens of each type of concrete were cured in 5 different conditions covering from very good to very poor curing conditions as shown in Figure 3. Two specimens were prepared for each condition.

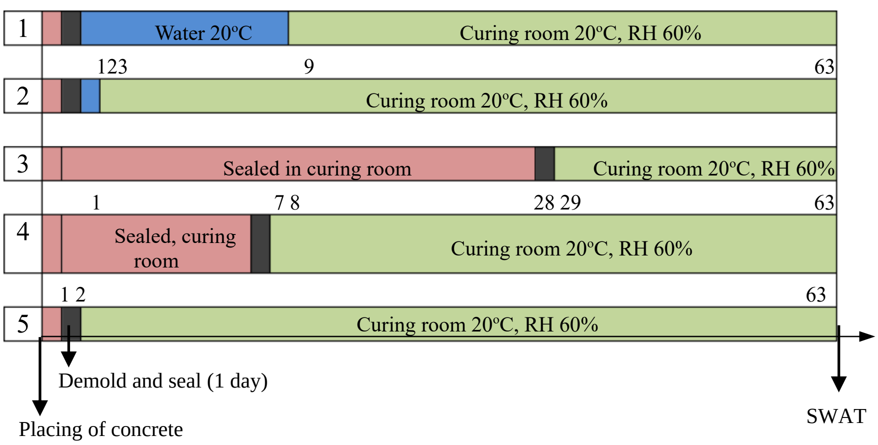

Figure 3. *Curing conditions and experimental process*

Right after demolding, the surface and side of the specimens were sealed (the bottom was opened) to ensure that evaporation or permeation of water just occurred in one direction, i.e., moisture was evenly distributed in the specimen. Iwamoto [15] explored that only epoxy resin coating could not perfectly prevent moisture transportation from inside the concrete to the ambient. Thus, the specimen was wrapped by alumina tape firstly and then coated by epoxy resin. It took one day for hardening epoxy resin. After that, the curing process was continued.

After the curing process, all the specimens were dried in a room with a temperature of 20ºC and RH of 60%. Because the moisture content of concrete is the most influential factor on water absorption of concrete [16], all the specimen were dried until the water contents inside the specimens reached stable situations. According to the ASTM C140-11a [17], the stable situation can be determined when two successive weighings at intervals of 2h show an increment of water lossnot larger than 0.2% of the last previously detected weight of thespecimen.Before conducting SWAT measurement, the moisture content of concrete was measured at the surface by moisture tester HI-520, and then SWAT using pure water was applied to obtain SWAT indices. For cylindrical specimens, a frame was employed to fix the water cup to the surface of the specimen (Figure 4).

Figure 4. *SWAT testing*

3. Results and discussion

3.1. High tensile strength of HAC slag concrete

It is well known that tensile strength is one of the main factors governing the cracking resistance of concrete. The larger tensile strength, the larger cracking resistance of concrete is. Figure 5 shows that the direct tensile strength of HAC slag concrete was much larger than that of OPC slag concrete.

Generally, the tensile strength of concrete depends on three factors: tensile strength of mortar, tensile strength of coarse aggregate, and bond strength between mortar and aggregate. Cracking will be initiated at the point that has the lowest strength.

Some evidences pointed to the existence of high bond strength in HAC slag concrete. The first evidence is the direct tensile strength of concretes and respective mortars with W/B of 0.3 subjected to steam curing, as shown in Figure 5. In this experiment, mortar was made in two ways: in the first way, mortar was directly mixedfrom binders, sand, and water; while in the second way, mortar was taken from the respective concrete by removing coarse aggregate. However, the direct tensile strengths of two kinds of mortarsshowed almost no difference. It can be seen in Figure 5 that while the tensile strengths of OPC mortar and HAC mortar were nearly similar, the tensile strength of OPC concrete was much smaller than that of HAC concrete. Furthermore, the tensile strength of HAC concretes was larger than that of the respective mortars. This improvement in the tensile strength of HAC concrete must be due to the strong bond between HAC mortar and coarse aggregate.

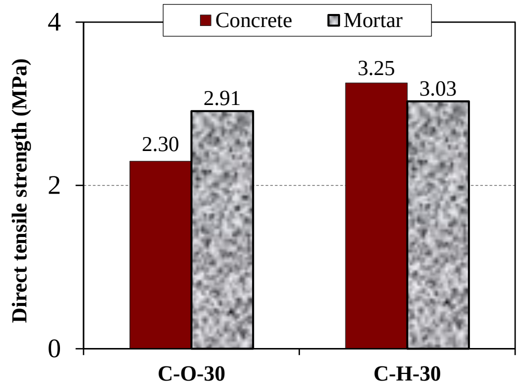

Figure 5. *Direct tensile strength of concretes and mortars*

The second evidence of high bond strength in HAC concrete was revealed from visual observation. The broken sections of OPC and HAC concrete under visual observation are shown in Figure 6. Clearly, more numbers of debonding at interface transition zone (ITZ) were seen in C-O-30 than in C-H-30. Inversely, more broken coarse aggregate was noted in C-H-30 than in C-O-30. This means that the bond strengthh in HAC concrete was larger than that in OPC concrete.

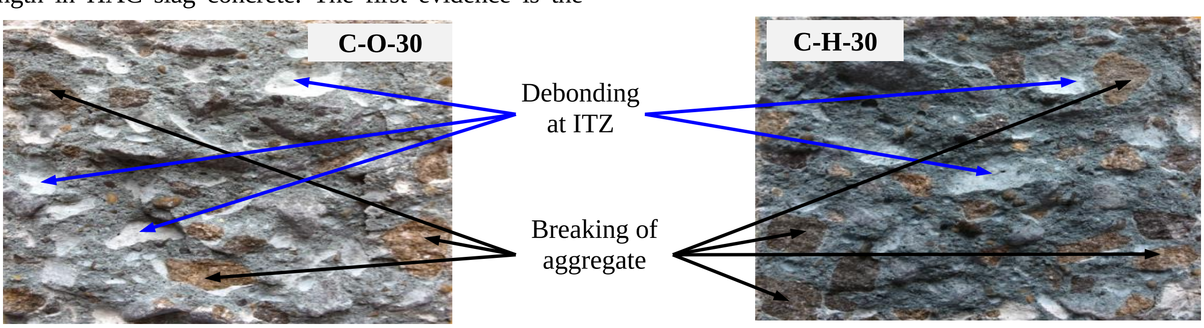

Figure 6. *Visual observation at broken section of HAC and OPC slag concrete.*

The high bond strength in HAC concrete might be explained by the large amount of CH produced through the hydration of HAC. CH reacts with the active SiO_2 component in GGBFS and creates secondary CSH gel. The CSH gel located in pores near the ITZ enhances the bonding capacity between the HAC mortar and coarse aggregate.

Due to the strong bond between HAC mortar and aggregate, it can be inferred that HAC can improve the cracking resistance of slag concrete and this was confirmed elsewhere [18]. This is very significant because one of the worst disadvantages of slag concrete is that it is vulnerable to cracking.

3.2. High resistance against water absorption of HAC slag concrete

The comparisons of water absorption rate at 10 minutes (p_{600}) of slag concretes with OPC and HAC is presented in Figure 7. In the graph, the values of HAC slag concretes are connected by solid lines while those of OPC slag concretes are linked by dash lines.

Apparently, p_{600} remarkably varied with the variation of curing conditions. The specimens cured one day in mold presented the highest p_{600}, i.e., the worst quality of covercrete, while the specimens cured 7 days in water or 28 days in mold, which showed the best covercrete quality. It can be said that p_{600} can clearly differentiate the curing conditions of the specimens.

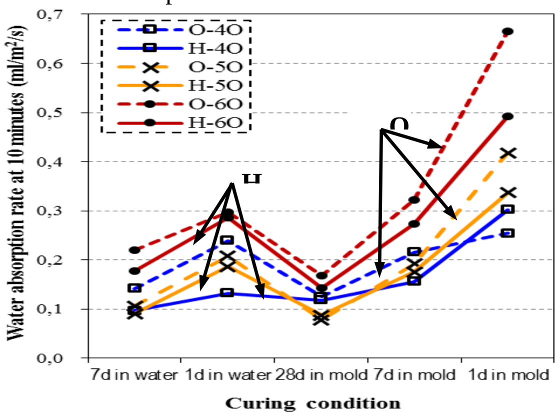

Figure 7. *Water absorption rate at 10 minutes of concretes*

Moreover, concrete containing slag was very sensitive to the curing condition. Concrete subjected to the poor curing condition (e.g, one day in mold) exhibited very bad quality of covercrete. The concretes with W/B of 0.4 cured 1 day in mold even showed the much lower coverete quality than the concretes with W/B of 0.6 cured 28 days in mold (Figure 7). It implies that slag concrete needs sufficient curing condition to achieve good quality.

Considering the type of cement, HAC slag concretes showed the smaller p_{600} than OPC slag concretes. The difference in p_{600} was not significant in concretes subjected to good curing but very clear in concretes subjected to poor curing condition. Clearly, HAC slag concretes were less sensitive to curing condition than OPC slag concrete. It can be said that HAC can improve resistance against water absorption of concrete.

Denser matrix and better bond between aggregate and mortar might be the reasons for this advantage of HAC slag concrete.

4. Conclusions

Through the use of the direct tensile strength test and SWAT, the effects of HAC on improving the resistance against cracking and water absorption of slag concrete were investigated. The conclusions obtained from this study are as follows:

- HAC can improve the tensile strength of slag concrete. The reason for the high tensile strength of HAC slag concrete was the strong bond between mortar and coarse aggregate. The high bond strength of HAC slag concrete was verified through mechanical test and visual observation. The strong bond in HAC slag concretes might be due to the formation of secondary CSH gel from the reaction of CH and active SiO_2 in slag at pores near the ITZ. The increase of tensile strength will lead to the high resistance against cracking of slag concrete.

- HAC can improve resistance against water absorption of slag concrete, particularly in concrete subjected to poor curing condition. Denser matrix and better bond between aggregate and mortar might be the reasons for small water absorption of HAC slag concrete. High quality of covercrete ensures the sustainability of reinforced slag concrete structures for long-term service.

Acknowledgement: The author wish to express sincere gratitude to DC CO., LTD for supplying the high alite cement used in the research.

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(The Board of Editors received the paper on 10/23/2014, its review was completed on 10/28/2014)