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Experimental Study on Internal RH of BFS Mortars at Early Age

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Abstract. A caution procedure to use embedded sensor to measure internal RH of low W/C ratio mortars is proposed in this paper. Specimens made from OPC mortar and the one made with 40% BFS replacement cured under a sealed condition at 20°C. The results showed higher internal RH decrement when BFS was applied. The slag content, the creation of the early hydrated products, pore structures of OPC mortars introduced with BFS are considered as the main factors.

Introduction

An indecisiveness of using BFS in concrete, particularly its application at low W/C ratio, is necessary to be investigated through a comprehensive study. The mechanical stability of concrete is affected by shrinkage, especially if it contains supplementary cementitious material such as fly ash or slag [1, 2]. It is reported that the properties improve slowly in comparison to ordinary Portland cement (OPC). The hydration rate of this supplementary material is less reactive. Therefore, inadequate water supply in the mixture or water that evaporated from the product at the early age results in lower performance [3].

In addition, it is expected discovering that using Blast Furnace Slag (BFS) with a low water to cement ratio in the mixture to improve concrete performance can cause an early-age crack due to autogeneous shrinkage. Moisture loss due to self-desiccation is thought to induce the additional stress under restrained shrinkage. When there is no moisture movement allowed with the environment, shrinkage in concrete at early ages will occur due to cement hydration. Water consumption of un-hydrated cement results relative humidity in the concrete pores (IRH) reduced. This phenomenon is known as self-desiccation. It causes volume change so-called autogeneous shrinkage. This deformation may cause micro cracking due to restrained autogeneous shrinkage. It forms macro-cracks after connecting into a continuous crack pattern. Problems such as autogeneous shrinkage and change of IRH have been a great concern on using high performance concrete with a low water-binder ratio.

In practice, measuring RH inside the concrete at early ages is a tough work because of its accuracy. From a saturated condition to dry condition, measurable reduction in RH will only occur after pores with radii of 50 nm to 100 nm have been emptied. Therefore, RH measurement also is necessary to indicate the performance of the mixture with a low W/C ratio when weight loss is impossible to be measured in practical.

Fundamental Theory

There are many types of hygrometers for relative humidity measurement. Chilled mirror, resistive and capacitive sensors seem to be most popular in concrete research. In this paper, this kind of sensor is adopted. The capacitive used for IRH needs was proposed by Z.C. Grasley [4]. It has accuracy $\pm 1.8\%$ for RH and ± 0.3°C for the temperature.

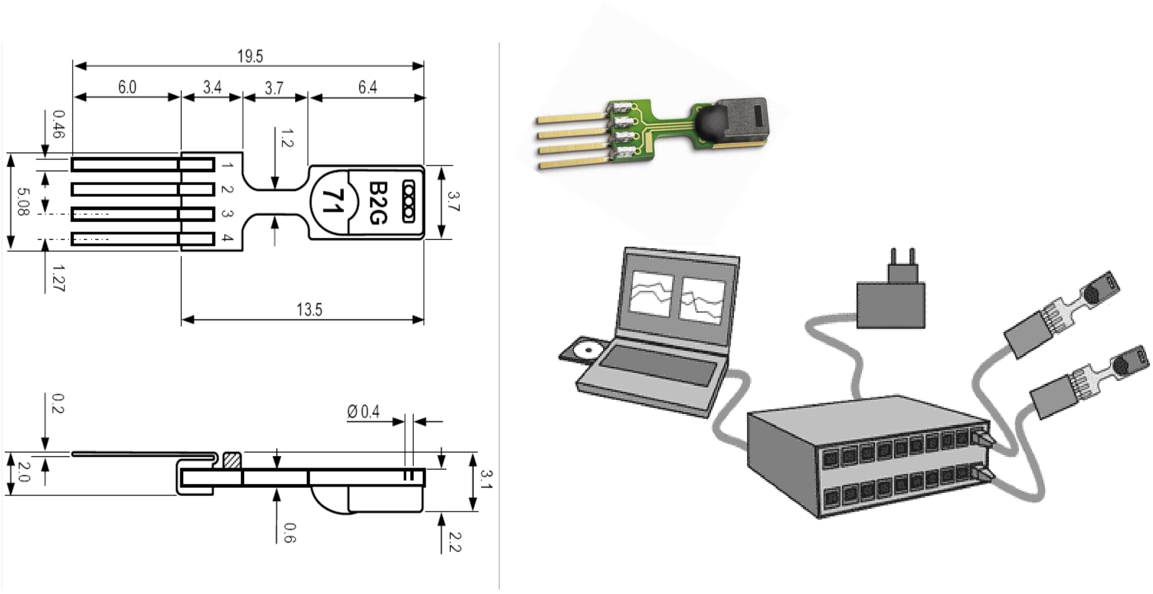

Figure 1. Sensor and IRH measurement set up

It is not simple to measure IRH, because to get a reliable reading value, it is necessary to wait until the probe and surrounding concrete pore vapor are stable. The sensor includes a capacitive polymer-sensing element for relative humidity and a band-gap temperature sensor is used in this research. The data logger has 20 channels, which can be connected to the personal computer for data record as illustrated in Fig 1.

Methods

Physical and Chemical Composition of OPC. To investigate the internal moisture, an ordinary Portland cement (OPC) containing 40% of cement weight partially replaced with BFS was used. The chemical composition of OPC is listed in Table 1.

Table 1. Chemical composition (%)

Code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
OPC	21.36	5.28	2.66	65.02	1.46	2.08	1.77

Mix Proportion of Specimens. Mortar specimens made with OPC, and 40% weight of OPC replaced with BFS were prepared to have W/C ratio of 35% and 25%. Some additional mortars made with pure OPC were adopted as the control system. Mix proportion of each specimen is listed in Table 2. The compositions included the use of water reducer (SP) to aid the workability of fresh mortar. Sand with a density of 2.63g/cm^3 was applied as the fine aggregate with 40% volume.

Table 2. Mix proportion of specimen (kg/m^3)

No	Code	W/C (%)	Cement	Water	Sand	SP	BFS
1	OPC -25%	25	995.70	248.90	988.88	14.90	0
2	OPC+BFS -25%	25	597.40	248.90	988.88	11.90	398.30
3	OPC-35%	35	846.27	296.19	988.88	4.65	0
4	OPC+BFS -35%	35	507.76	296.19	988.88	4.65	338.51

Internal Relative Humidity (IRH) Measurement. This measurement is used to investigate the effect of W/C ratio and BFS application in mixture. Mortar specimens with W/C ratio of 25% and 35% were prepared as shown in Table 2. The experiment was conducted at sealed condition in environment controlled room at 20^{o}C and a constant 60% of RH. This method was conducted by inserting the sensor directly into the measuring point after the concrete is sufficiently hardened by providing inserting path (pre-embedded pipe) before casting [5]. Cylindrical molds with a diameter of 10 cm and 20 cm in height was used for internal RH measurement. An acrylic pipe with an inner diameter of 11 mm was fixed by two small wires at the center of the mold by making two small holes in the mold. One end of the pipe was wrapped whit waterproof/breathable fabric (Gore-Tex) made from polytetrafluoroethylene (PTFE). It allows vapor from mortar to be captured by sensors but prevents the hydration products reaching the sensors during the hydration process [6]. A rubber cap was inserted through the pipe until an end to prevent vapor flow into the pipe during casting. After 6 to 12 hours, depends on setting time of specimens, the rubber was replaced by RH sensor immediately not to disturb moisture equilibrium inside the pipe. An average value was obtained from two readings. Then, measurement was monitored as shown in Fig 2.

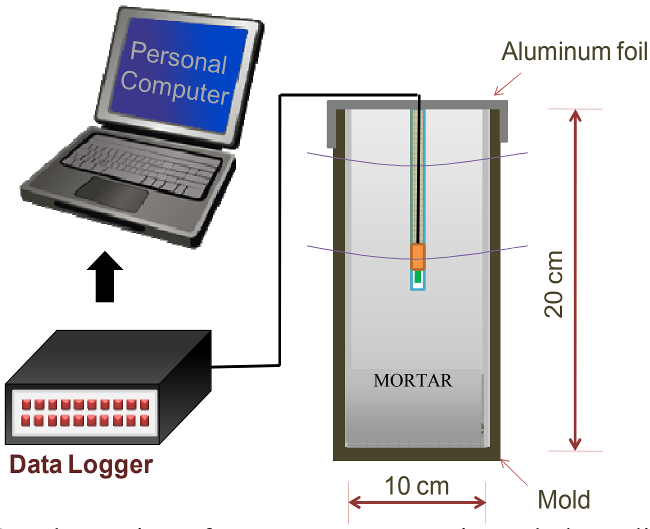

Figure 2. The setting of IRH measurement in sealed condition

The experimental results were then compared with the analytical ones by the thermo-hygro simulation system named DuCOM, which has been developed in author`s research group [7]. The finite element mesh for specimen with 1/12 cylindrical model was used in simulation. It has the same geometric conditions, mix proportions, and the atmospheric condition as those used in the experiment.

Experimental Results

The Effect of Water to Binder Ratio. The internal RH measurement result in the specimen due to self-desiccation is shown in Fig 3.

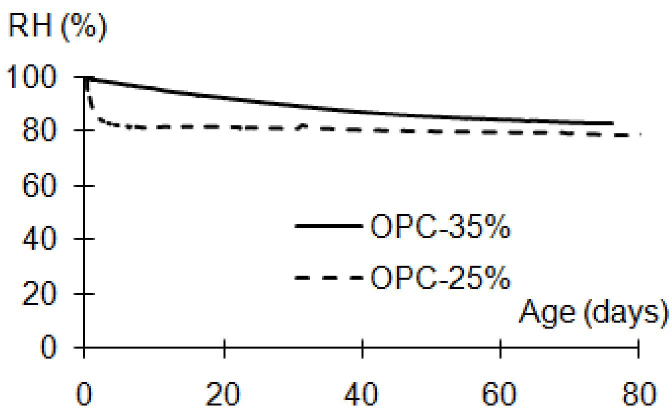

Figure 3. Internal RH comparison for OPC specimen

The pores were more saturated at the start of the experiment in specimen with W/C ratio of 35% than that with W/C ratio of 25%. Internal RH of sealed OPC mortar with W/C ratio of 25% decreases to 78% at 80 days while at W/C ratio of 35% it only decreases to 82%. It indicates that more internal moisture decreased by self-desiccation as a decrease of the water to cement ratio, especially at early ages due to denser pore structure. Fig 4 illustrates the same trend when the mortars containing BFS. The lower W/C ratio induces higher self-desiccation to impact decreasing of internal RH of mortars.

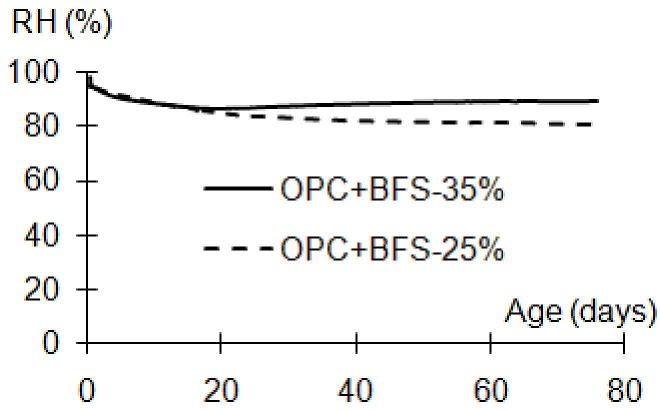

Figure 4. Internal RH of OPC mortar containing BFS.

The analytical results of RH distribution obtained from experimental results for specimens with W/C ratio of 35% using OPC specimens were then compared by the analytical results by using DuCOM. It is an integrated computational system designed based on physical and thermodynamics theories to evaluate durability performances since cement comes into contact with water. DuCOM is a versatile program for cementitious material and applicable to application of fly ash, BFS concretes, and, etc. in mixtures. Experiments verified that this computational system can accurately predict hydration processes and relative humidity for a different mix proportions under various temperatures. The input data used in the analytical program such as the geometric conditions, mix proportions, and the atmospheric condition is the same as those used in the experiment. According to the comparison shown in Fig 5, the experiment result agrees with the analytical result.

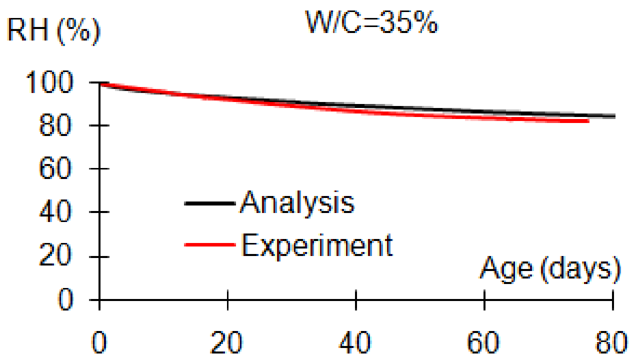

Figure 5. Internal RH comparison of analytical and experimental results

The Effect of Blast Furnace Slag (BFS). In Fig 6, at the same W/C ratio given, internal RH decrement of OPC specimen incorporated with 40% BFS is higher than that of pure OPC specimen at the same ages. Higher chemical shrinkage of cement containing BFS might lead to greater self desiccation, since there is no water supply under sealed curing. If the water supply is restricted, the pores empty and air-water menisci form. Here, moisture consumption in specimen containing BFS is faster than that in pure OPC specimen.

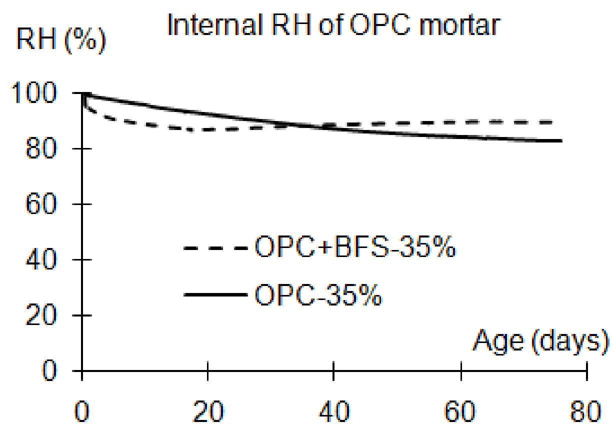

Figure 6. Internal RH of mortar with W/C ratio of 35%

According to some analytical studies proposed by Ishida et all [8], it was shown that cement replacement with BFS affected the degree of hydration and denser pore structure. Pore structure of specimens containing BFS is different from OPC due to its pore size distribution. At early age, pore size distribution of BFS mortars is denser than OPC mortars. However, low water to cement ratio has influence more in moisture loss if finer particles of BFS are applied in matrix. Moreover, moisture in capillary pores of the paste was consumed greatly. The early consumption of calcium hydroxide during hydration reaction may induce higher reactivity of slag [9].

Fineness of BFS is considered as mechanical accelerator [10,11]. As BFS has finer particles, which has larger surface area, it increases both the hydration reaction and the water consumption. It occurs faster when the ratio of w/c less than 40% which reduces pore sizes in cementitious matrix [12]. This finer structure which is the product of the dissolution of the calcium hydroxide crystals and the precipitation of CSH produced by the hydration reaction may cause the pores filled up. Those finer pores lead internal RH decrease rapidly and effects the self-desiccation on the chemical shrinkage [13].

Conclusions

1. IRH mainly decreased with time due to self-desiccation and moisture diffusion. In mortar with a low water-binder ratio, the IRH decrement depends not only on moisture diffusion but also on self-desiccation. The analytical result by DuCOM showed a good agreement with the experiment result when higher water to binder ratio was employed.
2. When partially replaced cement by blast furnace slag, the results showed lower internal relative humidity than that in Portland cement mortar. Physical and chemical properties of BFS are believed as the reason. Water consumed caused by finer particles and the chemical reaction at the early ages to start the hydration process may cause the moisture in the low W/C matrix is less than that in higher W/C.

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