Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Effects of slag fineness on durability of mortars

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Received Feb. 5, 2007; revision accepted July 5, 2007

Abstract: In recent years, the usages of by-products and wastes in industry have become more important. The importance of the sustainable development is also of increasing. The utilizations of wastes, as mineral admixture or fine aggregate, reduce the consumption of the natural resources and improve the durability of concrete. In this study, the effect of the fineness on the high temperature and sulphate resistances of concrete mortar specimens, produced with ground granulated blast-furnace slag (GBFS) replacing cement, is investigated. The compressive and flexural strength test results for all series related to durability effects, exposing temperature and solutions, exposure times for these durability effects, slag content and fineness are discussed. Consequently, the optimum slag contents are determined for producing the sulphate and high temperature resistant mortars.

Key words: Cement, Fineness, Ground slag, High temperature effect, Sulphate attack, Sustainable development

doi:10.1631/jzus.2007.A1725 **Document code:** A **CLC number:** TU31

INTRODUCTION

High consumption of natural sources, high production of industrial by-products and environmental pollution demand new solutions for the sustainable development. For example, carbon dioxide concentration has risen up to 50% during the 20th century and it is the major by-product of cement industry which is one of the two most deleterious industries (Mehta, 2001a). Besides, the concrete industry also increases the deleterious effects on economy and environment. For reducing these effects, the resource efficiency should be increased and the durability should be considered for concrete production (Mehta, 2001a). The resource efficiency is possibly improved by the reduction in use of energy and materials (Mehta, 2002). The durability is the main criterion for developing the sustainable concrete technologies and obtaining the structures with longer service lives (Mehta, 1997; 1999; 2001a; 2001b; 2002). Rehabilitation and maintenance costs of the concrete structures can be decreased by increased durability. The utilizations of by-products in concrete production such as fly ash, bottom ash, slag, silica fume, waste glass, etc. are the solutions to achieve the above objectives (Mehta, 1997; 1999; 2001a; 2001b; 2002; Yüksel *et al*., 2006; Ghafoori and Bulholc, 1996; Yüksel and Bilir, 2007; Topçu and Canbaz, 2004).

Durability is the ability to resist chemical and physical attacks that lead to the deterioration of concrete during its service life (Erdoğan, 2002). The environmental conditions such as temperature, humidity and the mechanism of chemical transports are the causes for the deteriorations (Baradan *et al*., 2002; Topçu, 2006a; 2006b; 2006c). For instance, sulphate or acid environment caused by industrial by-products, wastes or chemical residues in reclaimed ground is one of the most severe conditions to affect the durability of concrete (Binici and Aksoğan, 2006). The composition of cement is pointed out as the major factor in the sulphate resistance of concrete. Among the cement hydration products, alumina-bearing phases and calcium hydroxide are more susceptible to sulphate attack because of their reaction in sulphate environment that leads to the production of ettringite

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and gypsum. On hydration, 5%~8% C_3A-bearing cements will contain most of the alumina in the form of monosulphate hydrate. In cements with more than 8% C_3A, the hydration products may also contain hydrogarnet. In the presence of calcium hydroxide, both monosulphate and hydrogarnet react with sulphate ions and are converted to ettringite (Ramyar and İnan, 2007). Some researchers have reported that the use of low water/cement ratio and the use of admixtures, such as air entraining to protect the chemical attack of a rich mixture, additive, or ground granulated blast-furnace slag (GBFS), would be the most effective treatment for reducing the sulphate-inducing damage (Binici and Aksoğan, 2006). Besides, mineral admixtures have shown to improve the sulphate resistance of cementitious systems due to their pore refinement, grain refinement, C_3A dilution and removal of calcium hydroxide by pozzolanic reaction (Ramyar and İnan, 2007). Under the sulphate environment, cement paste undergoes deterioration resulting from expansion, spalling and softening. Therefore, cracks occur, the impermeability, durability and compressive strength of concrete decrease.

Additionally, the effect of high temperature on mortars or concrete is another one of durability problems. When concrete is heated, the free water in capillary pores of the concrete, the water in CSH gel and chemical bond, and the water in CSH and sulphoaluminate evaporate. Consequently, this causes shrinkage in concrete around 300 °C (Ünlüoğlu *et al*., 2007). The shrinkage caused by this water loss and the steam pressure formed in the concrete reduce the resistance of the concrete cover, and expose the reinforcement to hot gases during a fire. When it is heated above 400 °C, the pore system dries up completely and a series of reactions take place in cement paste. Subsequently, the hydration products are detached, and CSH gels decompose. Around 530 °C, $Ca(OH)_2$ transforms to the anhydrate lime. As a result, the concrete breaks into pieces and their surfaces become white (Ünlüoğlu *et al*., 2007; Topçu and Demir, 2005). Thus, the high temperature leads to cracking and decreases the compressive strength of concrete (Topçu and Demir, 2005).

As one of the materials used in cement manufacture, the slag's usage goes to as far back as 1880. Since then, its use has expanded because it has various advantages over other cementitious materials. Firstly, slag has a relatively constant chemical composition compared with fly ash, silica fume and natural pozzolan, etc. Moreover, it has the advantages like low heat of hydration, high sulphate and acid resistance, better workability, higher ultimate strength, etc. (Binici and Aksoğan, 2006). It is also known that GBFS improves high temperature resistance and shows good performance for this aim (Topçu and Demir, 2005). Besides, increase in fineness of GBFS improves compressive strength due to pozzolanic reaction causing reduction in permeability (Yüksel *et al*., 2006). It means that finer slag can provide higher resistance against deteriorations due to some chemical or physical attacks.

In this study, the effect of the fineness of GBFS as mineral admixture on concrete durability is investigated. Some tests, related to loss in compressive and flexural strengths due to sulphate and high temperature effects, were attempted to make this objective done. Efforts are made to determine the optimum replacement ratio of GBFS for producing the sulphate and high temperature resistant mortars. After all, this study can contribute to the sustainable development, the resource efficiency, the durability, the environment and the economy.

MATERIALS AND METHOD

Materials

The cement used was CEM-I type Portland cement corresponding TS EN 197-1 (Turkish Standards Institute, 2005). Standard natural sand was used as fine aggregate. The fineness modulus of the fine aggregate is 2.94. GBFS was provided from Ereğli Iron and Steel Works Company. Chemical composition of GBFS is presented in Table 1. Two different finenesses of 3500 and 4000 cm^2/g Blaine are chosen to investigate the effect of fineness on high temperature and sulphate resistances.

Table 1 Chemical composition of GBFS (%)

SiO_2	CaO	MgO	Al_2O_3	Na_2O	SO_3	MnO	TiO_2	Fe_2O_3	P_2O_5
35.09	37.79	5.50	17.54	0.30	0.66	0.83	0.68	0.70	0.37

Mixing water used in this study was the drinkable water from city waterworks of Eskişehir City. It has properties as pH of 7.6 and total hardness of 12.8.

Method

In the study, 32 series of mortar specimens were produced with GBFS replacing cement at the ratios of 0, 10%, 20% and 30% by weight for both 3500 and 4000 cm^2/g Blaines. Reference series are produced twice for both 3500 and 4000 cm^2/g Blaines in order to see the experimental errors. Each series contain three mortar specimens with the dimension of 40 mm×40 mm×160 mm. After 28 d standard cure, the weight loss, flexural and compressive strength tests are conducted on all series. Some mortar specimens are exposed to high temperature at 300, 600 and 900 °C for 3 h with an average temperature increasing rate of 6.7 °C/min. Then, the specimens are cooled air-slowly. The weight loss, flexural and compressive strength tests are also conducted on these specimens. Test results for all series related to temperature, slag fineness and replacement ratio (slag content) are evaluated.

Besides, 24 additional series of mortar specimens were produced with GBFS replacing cement similar to the specimens produced for determining the high temperature resistance. These series were used for the tests to determine sulphate resistance. Each series contains three of 40 mm×40 mm×160 mm mortar specimens. All specimens are exposed to standard cure conditions for 28 d. After then, 6 series of specimens are continued to be exposed to standard cure, 6 series are kept in 40000 mg/L $MgSO_4$ and last 6 series are kept in 40000 mg/L Na_2SO_4 for 90 d. The weight losses, flexural and compressive strengths of the specimens which were kept in sulphate solutions and curing water are determined.

The mix proportions of mortar specimens produced are given in Table 2. Reference series, for testing both high temperature and sulphate resistances, are named as GBFS0. Moreover, series having 10%, 20% and 30% slag replacements are coded as GBFS10, GBFS20 and GBFS30, respectively. Consequently, the effects of slag fineness, slag content, exposing temperature and solution type on high temperature and sulphate resistances, are discussed.

Table 2 Mix proportions of three mortar specimens (kg/m^3)

Code	Description	Cement	Water	Natural sand	GBFS
GBFS0	Reference	450	225	1350	0
GBFS10	10% GBFS	405	225	1350	45
GBFS20	20% GBFS	360	225	1350	90
GBFS30	30% GBFS	315	225	1350	135

RESULTS AND DISCUSSIONS

Effect of slag fineness on the high temperature resistance

Figs.1a~1c show the test results for high temperature effect on mortars. Table 3 shows the results for all tests. The residual strengths are presented in Figs.1a and 1b. The weight losses after exposure of temperatures are shown in Fig.1c by percentage. As it is seen from the results, the usage of GBFS improves the high temperature resistance of mortars. GBFS shows better performance with the increment in slag content. It is thought that the thermal and pozzolanic properties of GBFS are the main factors for obtaining high temperature resistance. As it is known previously, slag has pozzolanic activity and leads to lower per-

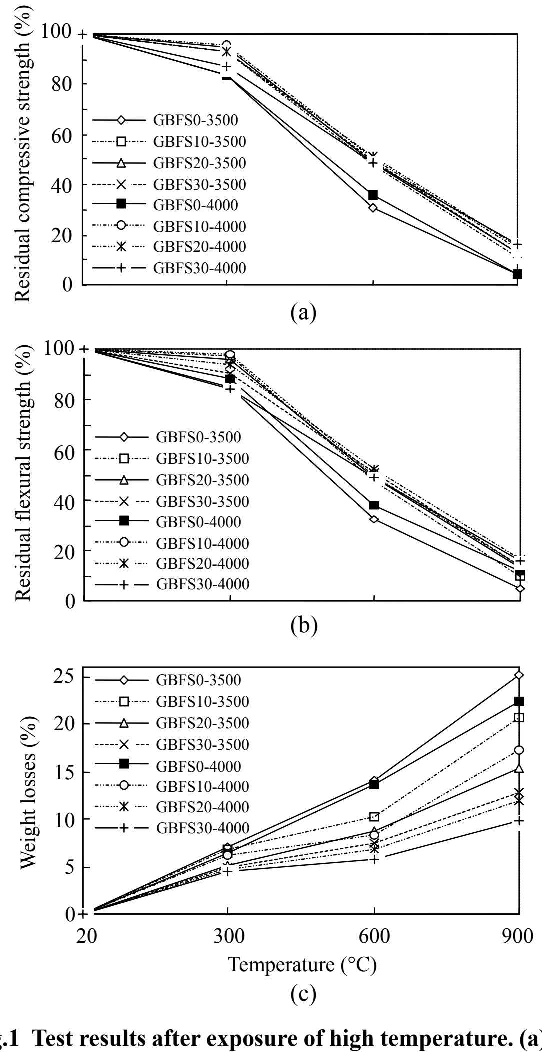

Fig.1 Test results after exposure of high temperature. (a) Residual compressive strengths; (b) Residual flexural strengths; (c) Weight losses

Table 3 Test results for high temperature effect

Series	Weight loss (%)				Flexural strength (MPa)				Compressive strength (MPa)			
	20 °C	300 °C	600 °C	900 °C	20 °C	300 °C	600 °C	900 °C	20 °C	300 °C	600 °C	900 °C
GBFS0-3500	0	7.0	14.1	25.2	4.0	3.4	1.3	0.2	39.4	32.9	12.2	1.6
GBFS10-3500	0	6.9	10.3	20.6	4.0	3.9	1.9	0.4	46.8	43.5	22.5	5.2
GBFS20-3500	0	5.2	8.8	15.4	4.5	4.3	2.2	0.6	55.1	52.4	27.0	7.0
GBFS30-3500	0	4.9	7.5	12.7	5.1	4.6	2.6	0.7	62.3	58.1	31.1	8.1
GBFS0-4000	0	6.5	13.7	22.4	4.2	3.7	1.6	0.5	42.3	35.6	15.1	1.9
GBFS10-4000	0	6.1	8.4	17.2	4.4	4.3	2.2	0.6	50.2	48.1	25.4	7.4
GBFS20-4000	0	4.7	6.9	12.0	4.8	4.5	2.5	0.8	58.9	54.9	30.1	9.2
GBFS30-4000	0	4.4	5.7	9.9	5.7	4.8	2.8	0.9	69.1	60.3	33.6	11.1

meability in mortar specimens compared with the reference mortar specimens. Thus, higher compressive strengths are obtained as slag content is increasing till 30%. However, increase in exposing temperature leads to decrease in compressive and flexural strengths of all mortar specimens. Eventually, the increase in slag content decreases the rate of deceleration of compressive and flexural strengths for the same temperatures. Besides, this deceleration with the increase in temperature is lower for GBFS30 series compared with GBFS0 (reference) series due to the pozzolanic and thermal properties of slag. Moreover, the behavior of the weight losses is similar to the behaviors of the strength results. This can also be seen easily in Table 3.

If the residual compressive strengths after exposure of high temperature are discussed, it is seen that the fineness and slag content increase the residual compressive strengths especially for the temperatures above 600 °C. The decrease in residual compressive strengths is regular and the tendency of decreasing is similar to each other for all series. The significant result is the clear observation for the effect of slag fineness and content. Below 600 °C, the residual strengths of the series containing 30% slag content are lower than those of the series incorporating 20% content having 3500 and 4000 cm^2/g specific surface areas. The residual strengths of the series containing 10% slag content are greater than those of the series including 0% content for both specific surface areas. Furthermore, GBFS0 series for both specific surfaces have almost the same experimental values except the residual compressive strengths obtained after exposure of 600 °C. Thus, it can be pointed out that the experimental errors are at the minimum level. In addition, there is only one experimental error for the series of GBFS30 having 4000 cm^2/g specific surface after exposure to 300 °C. The residual compressive strengths of other series containing the same slag content and having different specific surfaces are also very close to each other. When the residual flexural strengths are evaluated in Fig.1b, it can easily be seen that the tendency of the behavior of flexural strength after exposing temperatures is almost the same with the one for the residual compressive strengths. However, some experimental errors which do not generally affect the mentioned behavior of the strengths are also observed for different slag contents and finenesses exposed to different temperatures.

Finally, the weight losses verify the results obtained from compressive and flexural strength tests. The weight losses decrease with the increase in slag content and fineness even if the decreases in weight losses are occurred due to the increment of temperature. The tendency is contrary to the compressive strength tendency but the behavior is the same with the strength's. The maximum weight loss is obtained as 25% for the reference series produced for representing the slag content as 0% and the specific surface as 3500 cm^2/g. In other words, the maximum weight loss is observed for reference series about 24%. In the end, it can be said that 30% slag can be used as mineral admixture in order to produce high temperature resistant mortars.

Effect of slag fineness on the sulphate resistance

The behavior for compressive, flexural strengths and weight losses can be seen from Figs.2a~2c. Table 4 presents all test results for all series. As it is seen from the results, usage of a GBFS also improves sulphate resistance of mortars. Slag shows better performance by the increment in the slag replacement ratio like the performance for high temperature resistance. The reason is the pozzolanic activity of slag again. However, the same behavior is also valid for sulphate resistance and thus, exposing sulphate attack also leads to decrement in compressive strength and flexural strength for all mortar specimens but increase in slag replacement still causes increase in compressive and flexural strengths for exposure of the same conditions. Besides, deceleration of compressive and flexural strengths due to the sulphate attack is lower for GBFS30 series compared to GBFS0 (reference) series at the same time. In Fig.2, GBFS10-3500 represents the series produced by using slag having 3500 cm^2/g Blaine at 10% slag content. Increase in fineness of GBFS improves pozzolanic reactivity and compressive strength of concrete till 30% replacement ratio. Besides, it also improves sulphate resistance of mortars compared to the mortars produced with coarser GBFS. This situation is obtained because of the higher pozzolanic activity of finer slag and lower permeability of mortars occurred. However, the compressive strengths are very close to each other. Thus, the variations of compressive strengths are similar to each other for the series incorporating the same amount of slag. Furthermore, it is clear that increase in fineness improves sulphate resistance. $MgSO_4$ solution decreases compressive strength more than Na_2SO_4 solution. Besides, the decreases in compressive strength are about 85%~95% that of reference series. These are acceptable and appropriate values on account of sulphate effect.

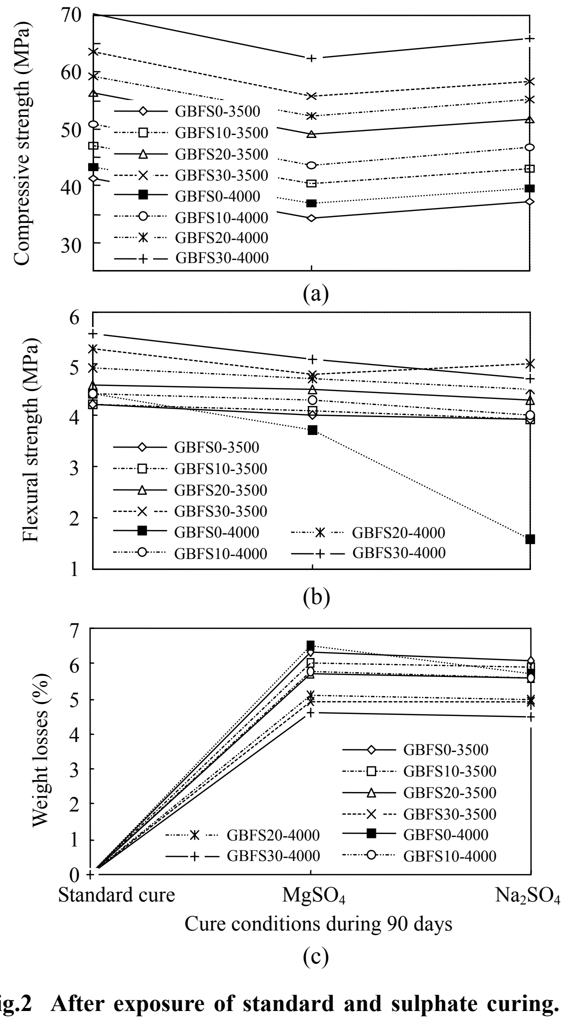

Fig.2 After exposure of standard and sulphate curing. (a) Compressive strengths; (b) Flexural strengths; (c) Weight losses

If the flexural strengths are considered in Fig.2b, it is easily seen that the tendency of the behavior of flexural strength after exposing sulphate solutions is similar to the one for the compressive strengths. On the other hand, $MgSO_4$ solution generally shows better performance than Na_2SO_4 solution and Na_2SO_4 solution decreases flexural strength more. However, some experimental errors which do not generally affect the mentioned behavior of the strengths are also observed for different slag contents and finenesses exposed to different temperatures. For example, the significant experimental error is observed for the

Table 4 Test results for sulphate attack

Series	Weight loss (%)			Flexural strength (MPa)			Compressive strength (MPa)		
	Standard cure	4×10^4 mg/L $MgSO_4$	4×10^4 mg/L Na_2SO_4	Standard cure	4×10^4 mg/L $MgSO_4$	4×10^4 mg/L Na_2SO_4	Standard cure	4×10^4 mg/L $MgSO_4$	4×10^4 mg/L Na_2SO_4
GBFS0-3500	0	6.3	6.1	4.2	4.0	3.9	41.2	35.8	37.9
GBFS10-3500	0	6.0	5.9	4.2	4.1	3.9	47.1	41.0	43.3
GBFS20-3500	0	5.7	5.6	4.6	4.5	4.3	56.4	49.1	51.9
GBFS30-3500	0	4.9	4.9	5.3	4.8	5.0	63.6	55.3	58.5
GBFS0-4000	0	6.5	5.7	4.2	3.7	1.6	43.4	37.8	39.9
GBFS10-4000	0	5.8	5.6	4.4	4.3	4.0	50.7	44.1	46.6
GBFS20-4000	0	5.1	5.0	4.8	4.7	4.5	59.4	51.7	54.6
GBFS30-4000	0	4.6	4.5	5.7	5.1	4.7	70.2	61.1	64.6

specimens produced for testing the series, containing 0% slag content and having 4000 cm^2/g specific surface exposed to Na_2SO_4 solution during 90 d.

Eventually, the weight losses verify the results obtained from compressive and flexural strength tests. The weight losses decrease with the increase in slag content and fineness even if the decreases in weight losses are occurred due to the solution type. The tendency is contrary to the compressive strength tendency but the behavior is the same with the strength's. By the way, the losses are very close for the series having the same slag content which are exposed to different solutions. Finally, it can also be said that 30% slag can be used as mineral admixture in order to produce durable mortars against sulphate attack.

CONCLUSION

In this study, it is concluded that GBFS, with a 30% of replacement, improves the high temperature and sulphate resistances of mortars due to its pozzolanic, chemical and thermal properties. Besides, all GBFS mortars are durable against the high temperature and sulphate impacts because of its lower or similar losses in compressive strengths comparing with the reference series. Occurrence of ettringite also improves sulphate resistance for 90 d but it is reported in literatures that after 6 months, this positive effect disappears due to the occurrence of cracks and increase in weight losses.

It is possible to produce durable mortars by using GBFS as mineral admixture at 30% replacement ratio. This means that GBFS can be used at its maximum amount and its disposal amount can be reduced. Thus, this study helps concrete industry to develop the technologies with technical, economical and ecological advantages beneficial to the resource efficiency and the sustainable development.

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