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The effects of elevated temperature on cement paste containing GGBFS

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Abstract

Fires can expose concrete to extreme temperatures. Thus, it is important to know the effect of elevated temperature on the concrete property. High performance concrete (HPC) often contains other supplemental cementitious materials besides cement, such as ground granulated blast furnace slag (GGBFS) and chemical admixtures such as superplasticizer (SP). GGBFS has been used successfully to improve concrete properties. This paper investigates the effects of GGBFS on concrete properties at elevated temperature. A total of 588 test specimens were prepared with three water-to-binder (W/B) ratios and six different GGBFS contents. The test specimens were cured for 28 days and then subjected to seven different elevated temperatures of up to 1050 °C for 4 h. It was found that at a temperature of 1050 °C, cracks appeared for all three W/B ratios when the GGBFS content was 10% or less. Cracking was significantly reduced as the GGBFS content was increased to 20% or above. It was also found that at elevated temperature (1050 °C), compressive strength greatly increased with increasing GGBFS content, especially for the W/B ratio of 0.23. Thus, the fire resistant properties of HPC are greatly improved by the addition of GGBFS. In contrast, GGBFS with a W/B ratio of 0.71 showed no significant increase in compressive strength. At a W/B ratio of 0.23, the clear trend was observed that the optimum GGBFS content for fire resistance is between 50% and 80%. The compressive strength of concrete is more susceptible than the elastic modulus to the effects of elevated temperature.
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Keywords: Elevated temperature; High performance concrete (HPC); Ground granulated blast furnace slag (GGBFS); Water-to-binder ratio (W/B); Compressive strength

1. Introduction

The disaster associated with the collapse of the Twin Towers of the World Trade Center stresses the importance of the performance of construction materials when exposed to extreme temperature [1]. The engineering properties of construction materials at elevated temperature are especially important for high rise buildings. Of all construction materials, concrete is one of the most resistant to heat and fire. Experience has shown that concrete structures are more likely to remain standing through a fire than are structures made of other materials. Unlike wood, concrete does not burn and unlike steel, it does not lose a substantial degree of its rigidity at moderately high temperatures [2]. As concrete is exposed to high temperature in the range of 400–500 °C, calcium hydroxide starts to decompose and concrete loses much of its load-bearing capacity at 600–700 °C [3]. In the construction of high rise buildings, high performance concrete (HPC) is often used, such as in the 85 Kaohsiung Tinged Tour and Taipei 101 projects. In general, HPC is a pozzolanic concrete which meets special performance requirements with regard to workability, strength, and durability that cannot always be obtained with techniques and materials typically used for producing conventional cement concrete. A HPC using only cement as a binder requires a high paste volume, which often leads to excessive shrinkage and a large amount of hydration heat, besides the increased cost. A partial replacement of cement with ground granulated blast furnace slag (GGBFS) has been proven to overcome these problems and improved the durability of concrete [4]. GGBFS, an industrial by-product from the iron and steel industry, serves as a supplementary cementitious material by

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forming additional low-density calcium silicate hydrate (C–S–H) gel and thereby increases the density of the matrix through a pore-filling effect. There are additional benefits in terms of cost, energy savings, ecological balance, and conservation of natural resources.

Fire is one of the most destructive powers to which a building structure can be subjected, often exposing concrete elements to extreme temperature. In a typical fire, Nassif et al. [5] reported that the temperature reaches 500 °C in about 10 min and 950 °C in 1 h. During a fire, temperatures commonly reach as high as 900 °C, and the outer layer of concrete member can be drastically hot while as the inner layer is not. The fire therefore creates a steep temperature gradient. The most common way to measure resistance to fire is described in ASTM E119, "Fire Tests of Building Construction and Materials". Standard test method also measures the ability of the materials (or assembly) to prevent the spread of fire. Test results are expressed in hourly ratings. If the building construction and materials maintain their structural integrity, they receive a rating equal to the length of time they were subjected to the flames. However, if the building construction and materials fail structurally, i.e. collapse during the heating, they receive a fire resistance rating instead, indicating that the building construction and materials might prevent fire from spreading for the length of time they stayed below the temperature limits, but that they may change composition or deform [2].

Therefore, it is very important to understand the effects of extreme temperature on the properties of concrete for high rise buildings. The HPC with varying amount of GGBFS and water-to-binder (W/B) ratio is tested to determine the residual strength and stiffness at different elevated temperatures (up to 1050 °C for 4 h).

2. Background

HPC is a modern construction material that has been widely used recently. The American Concrete Institute defines HPC as a concrete that meets special performance and uniformity requirements that cannot always be achieved by using only conventional materials and normal mixing, placing, and curing practices. The requirements may involve enhancements in placement and self-compaction, reduction of segregation, long-term mechanical properties, early-age strength, volume stability, or service life in severe environments. The enhanced performance characteristics of HPC are usually obtained by adding various cementitious materials and water reducing admixtures to conventional concrete mixture, and by modifying curing method. The addition of GGBFS or fly ash to concrete reduces the porosity of the concrete and increases its durability. Rajamane et al. [4] reported that the addition of GGBFS as a partial replacement of cement causes a reduction in the compressive strength of HPCs at early times due to an increase in effective W/C even though maintaining the same W/B ratio. This also can be attributed to a delay in the hydration of GGBFS [4]. At early ages (up to 7 days), GGBFS acts more as a filler material and nucleus for precipitation of cement hydration products than as a cementitious material. However after about 90 days, HPC with GGBFS have similar strength as those without GGBFS. The hardened matrix of HPC that containing GGBFS is more dense and impermeable than that without GGBFS [4].

According to Wang and Hwang [6], under high temperature the property of cement paste is predominantly affected by variations in moisture content and the decomposition of paste. At 105 °C, the capillary water and free water vaporize. At 250–700 °C, the cement hydration product decomposes [3]. As the temperature rises above 650 °C, small part of the decomposed paste is re-sintered into clinker and recovers little binding capability [3]. In addition, the cement paste also tends to expand rather than shrink [3,7] at elevated temperatures. In such cases, GGBFS slowly reacts with $Ca(OH)_2$ and water. The dissolution ratio of hydroxide increases with an increase in temperature and GGBFS reacts faster at high temperatures, which causes an increase in the early-age compressive strength [7]. Aggregates are different in their composition as well as in their heat endurance properties. The crystal transition temperature of silica aggregate (Quartz) is around 575 °C. The strength of concrete is reduced as the volume of aggregate expands with temperature. In addition, cement paste starts to shrink when heated above 200 °C. Due to different rates of expansion, cracks may occur on the surface of the concrete.

3. Test program

The safety and serviceability of concrete structures cannot be fully realized without a comprehensive knowledge of fundamental properties of the material. Concerns have been raised about the behavior of HPC under severe environmental conditions. In this study, an extensive laboratory investigation was performed to determine the extent of degradation of the HPC at seven elevated temperatures (25, 105, 200, 440, 580, 800 and 1050 °C).

3.1. Test materials

Ordinary type I cement and GGBFS manufactured locally were used in this study. The chemical composition and physical properties of the type I cement and GGBFS are shown in Table 1. Rapid water-cooling during granulation prevents the crystallization of the slag minerals, imparting GGBFS with the most valuable characteristic of a good cementitious material.

As indicated in Table 1, the surface area of GGBFS is 4420 cm^2/g, which is much finer than the type I cement surface area of 3150 cm^2/g. When GGBFS is used in concrete, it improves workability, increases strength, and improves durability. In this study, three different water-to-binder ratios (W/B = 0.23, 0.47, 0.71) were used to produce differ-

Table 1
Chemical composition and physical properties of the type I cement and granulated blast furnace slag (GGBFS)

	Test material		
	Type I cement		GGBFS
	Specification	Taiwan Cement, Co. Ltd.	Chung Lien Slag, Co. Ltd.
Chemical analysis (%)			
SiO_2	–	22.01	34.65
Al_2O_3	–	5.51	13.76
Fe_2O_3	–	3.38	1.43
CaO	–	63.8	41.42
MgO	MAX: 6.0	2.59	7.51
Na_2O	–	0.01	0.13
K_2O	–	0.01	0.37
SO_3	MAX: 3.5	2.09	–
f-CaO	–	0.72	–
Loss on ignition	MAX: 3.0	0.59	Trace
Insoluble residue	MAX: 0.75	0.32	–
Bogue potential compound (%)			
C_3S	50	51.2	–
C_2S	25	26.4	–
C_3A	12	8.2	–
C_4AF	8	10.2	–
CSH_2	5	4.21	–
Physical properties			
Fineness (cm^2/g)	MAX: 2800	3150	4420
Air content	–	–	5.6
Specific gravity (25 °C)	–	3.15	2.88
Pozzolanic activity index			
With lime 7 days (kg/cm^2)	–	–	78.0
With cement 28 days (%)	–	–	114

ent types of cement pastes. B is defined as binder, or cementitious materials, that include cement, GGBFS, fly ash, and silica fume. Six different percentages (5%, 10%, 20%, 50%, 80% and 100%) GGBFS were utilized to replace type I cement of cement paste as shown in Tables 2–4.

3.2. Sample preparation and testing

After mixing, the cement paste was compacted in a 20 mm-$\phi \times 40$ mm-length cylinder mold and cured in a environmentally controlled room with a constant temperature and humidity (23 ± 1.7 °C, over 70% RH) for one day. A total of 588 specimens were prepared, with duplicates prepared for each test. After curing for one day, the specimens were remolded and placed in a constant temperature (23 °C) water basin for 28 days. The specimens were then surface dried and placed in a high temperature furnace. The drying process is necessary to minimize the risk of explosion of the concrete specimens when they are directly subjected to high temperatures within the furnace. The initial furnace temperature was set at 25 °C. The test specimens were then heated to a specific temperature (25, 105, 200, 440, 580, 800, and 1050 °C) with a temperature increase from 25 to 105 °C within the first two hours. The heating duration at 200 and 440 °C was 6 h, and the duration for 580, 800 and 1050 °C was 4 h. Once the desired temperature was reached, that temperature was maintained until the specimens were removed.

At the end of the heating process, the specimens were cooled to room temperature, photographed and weighed. Weight loss resulting from heat-induced cracking and spalling was recorded. The compressive strength and the

Table 2
Weight loss of pastes with various GGBFS contents and water to binder ratios under elevated temperatures

W/B	T (°C)	OPC	GGBFS (%)					
			5	10	20	50	80	100
0.23	25	−2.2	−2.4	−2.3	−2.1	−1.7	−1.2	−1.7
	105	−12.2	−12.2	−12.3	−21.1	−11.3	−1.3	−1.4
	200	−14.1	−13.7	−14.3	−14.8	−14.3	−15.5	−2.9
	440	−18.0	−18.1	−18.4	−19.8	−18.3	−1.8	−4.1
	580	−19.7	−19.5	−19.9	−19.6	−19.8	−1.8	−6.2
	800	−21.8	−21.5	−22.1	−22.0	−20.5	−19.2	−6.2
	1050	−22.4	−22.9	−22.9	−23.2	−21.2	−20.5	−5.8
0.47	25	−9.5	−9.0	−8.5	−7.5	−5.1	−5.5	−3.41
	105	−22.5	−22.5	−22.2	−22.2	−23.2	−25.6	−15.2
	200	−24.3	−24.5	−24.9	−25.0	−25.8	−27.6	−13.9
	440	−29.0	−29.1	−29.4	−29.8	−30.6	−30.8	−11.7
	580	−30.5	−30.8	−31.1	−31.0	−31.9	−31.5	11.8
	800	−33.1	−33.5	−33.8	−34.1	−33.6	−33.8	−10.6
	1050	−34.6	−35.1	−35.1	−34.8	−33.5	−32.8	−9.4
0.71	25	−15.9	−15.3	−17.0	−15.6	−10.6	−18.0	−2.9
	105	−28.1	−28.7	−28.4	−29.6	−29.1	−30.1	−16.1
	200	−30.8	−30.9	−30.6	−32.8	−31.8	−32.8	−19.9
	440	−34.3	−34.8	−35.7	−36.0	−36.3	−36.1	−13.0
	580	−36.3	−36.2	−36.0	−38.5	−37.9	−36.6	−12.4
	800	−39.3	−39.1	−39.5	−40.5	−38.7	−38.0	−12.2
	1050	−40.7	−41.2	−40.8	−42.1	−38.8	−38.1	−11.6

Table 3
Compressive strengths (MPa) of paste with various GGBFS contents and W/B ratios under elevated temperatures

W/B	T (°C)	OPC	GGBFS (%)					
			5	10	20	50	80	100
0.23	25	64.9	53.1	36.9	67.9	65.6	61.8	*
	105	67.9	61.7	25.0	52.3	47.3	48.4	6.1
	200	31.9	35.4	17.2	34.8	58.7	60.9	6.7
	440	32.7	37.8	28.7	55.1	64.6	81.2	5.2
	580	15.1	13.2	31.1	49.5	50.1	67.5	6.9
	800	*	11.1	11.1	27.8	35	34.5	13.1
	1050	*	*	*	12.7	32	15.9	18.7
0.47	25	42.2	48.6	37.8	19.3	27.4	30.95	4.2
	105	32.5	33.0	28.2	19.2	14.7	18.0	1.1
	200	28.2	23.7	26.4	16.3	22.8	19.7	1.1
	440	34.0	24.2	11.6	28.7	19.7	15.9	2.8
	580	4.7	7.5	5.8	10.9	5.6	16.0	2.9
	800	4.5	12.7	15.5	12.9	14.5	16.6	7.7
	1050	*	*	*	5.2	5.6	5.6	11.7
0.71	25	15.6	14	16.9	11.6	5.2	3.9	2.6
	105	13.9	17.7	15.0	10.3	6.7	5.4	*
	200	9.8	7.1	13.7	9.3	8.2	4.4	1.6
	440	14.8	9.2	4.2	7.5	3.4	9.2	1.4
	580	*	*	*	*	2.9	11.6	4.0
	800	*	13.7	4.8	3.7	9.2	6.6	12.1
	1050	*	*	*	2.6	2.9	4.0	*

*Means the specimens was damaged and test results were not available.

Table 4
Comparisons of elastic Modulus (MPa) under elevated temperatures at various GGBFS contents and water to binder ratios

W/B	T (°C)	OPC	GGBFS (%)					
			5	10	20	50	80	100
0.23	25	*	0.5	1.0	2.0	4.9	7.8	9.8
	105	8.5	8.4	7.1	7.3	6.8	6.2	0.0
	200	13.3	11.5	8.2	6.6	5.9	4.8	2.2
	440	5.3	8.4	8.3	6.5	7.4	4.9	5.0
	580	4.2	5.1	5.0	5.3	5.4	8.4	7.1
	800	*	*	5.7	5.7	5.9	6.4	6.6
	1050	*	*	*	*	*	4.4	6.6
0.47	25	8.0	7.0	6.4	6.3	5.9	5.4	3.0
	105	4.1	5.1	6.7	5.8	5.5	6.0	4.4
	200	5.4	6.2	5.3	5.2	4.6	4.4	3.2
	440	2.8	2.7	3.5	3.8	3.7	3.0	1.9
	580	*	*	*	*	4.4	3.5	2.2
	800	*	*	2.9	3.1	3.5	3.8	4.6
	1050	*	*	*	2.4	3.4	4.4	4.2
0.71	25	5.2	5.0	5.0	4.6	4.1	4.0	2.4
	105	4.5	3.8	3.7	3.5	3.5	2.1	1.7
	200	3.0	3.1	3.0	2.2	2.0	1.8	1.2
	440	2.5	2.2	1.9	2.0	2.1	1.9	1.3
	580	*	*	*	*	1.7	1.8	3.4
	800	*	*	*	*	*	*	*
	1050	*	*	*	3.4	3.0	2.5	3.7

*Means the specimens was damaged and test results were not available.

elastic modulus of the heated specimens were measured by using a 5 ton testing machine with an LVDT attachment. Crushes the specimen and measures the absorption capacity according to ASTM C127.

4. Results and discussion

4.1. Appearance

Various levels of surface cracking and spalling were observed upon heating the test specimens to elevated temperature. Fig. 1a shows the photo of typical specimen at 1050 °C. In general, severe cracks caused specimens to break down with 10% and less GGBFS contents for all three W/B ratios (0.23, 0.47, 0.71), where B is the total amount of cementitious materials. Fig. 1b shows specimens at different temperatures at a W/B ratio of 0.47. The results for 0% and 100% GGBFS contents are given in Fig. 1b. No cracks were observed on specimens with 100% GGBFS at any temperature. The control specimens, which contained 0% GGBFS, started to crack at 580 °C and continued to crack severely as the temperature increased.

4.2. Weight loss due to heating

Table 2 and Fig. 2 summarize the weight losses for specimens with different W/B ratios and slag content after being subjected to different elevated temperatures. Higher W/B ratios and higher temperature are correlated with more weight loss for specimens with 80% slag content or less. This result clearly indicates that higher water content in the cement leads to more weight loss due to heating. This behavior is the same as that of pure cement paste (designated as OPC in Table 2). It is also observed from Table 2 that the GGBFS content has little impact on weight loss.

4.3. Compressive strength

The compressive strength at different water-to-binder ratios, GGBFS contents, and elevated temperatures is shown in Fig. 3 and Table 3. OPC containing 0% GGBFS, as listed in Table 3, is used as the reference. It was observed that, for the paste with a W/B ratio of 0.23, a higher GGBFS content result in higher compressive strength after exposure to a temperature of 1050 °C. It is concluded that the fire resistance of HPC would be greatly improved with the addition of GGBFS. After exposure to a temperature of 580 °C, the compressive strength of paste with 20% of GGBFS is 49.5 MPa; this value is more than three times the control specimen's compressive strength of 15.1 MPa. When the GGBFS content was less than 10%, specimens cracked upon heating to 1050 °C regardless of the W/B. However, cracking can be reduced with an increase in GGBFS content, implying that the addition of GGBFS improves the fire resistance of concrete. At a W/B ratio of 0.47, the compressive strength of GGBFS-containing paste increases as the exposure temperature exceeds 580 °C (refer to Table 3). This reconfirms the results reported by Swamy [8] and Hooton and Emery [9] that heating accelerates the hydration process for specimens containing GGBFS. It is noted that the hydration of paste

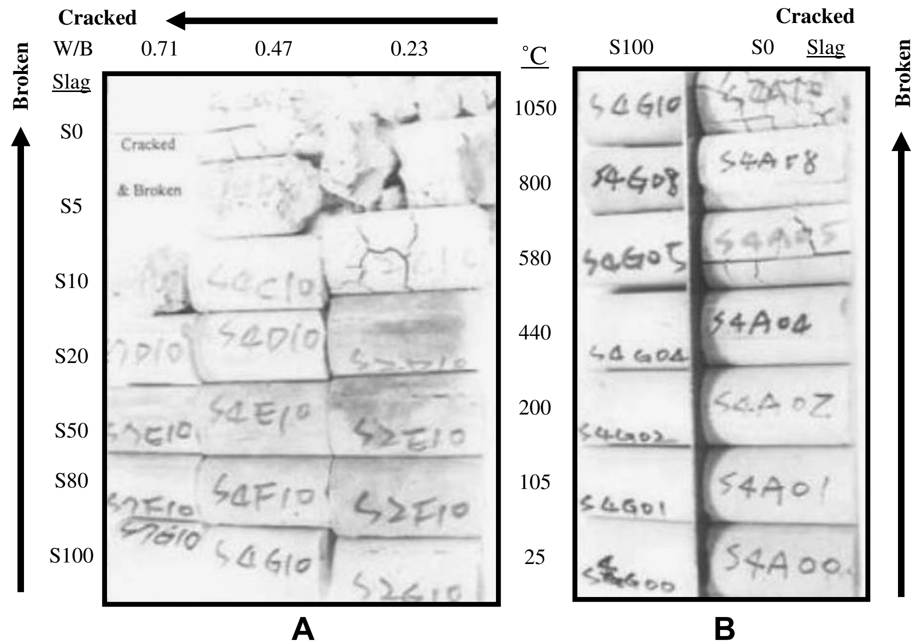

Fig. 1. Specimen appearances: (a) temperature at 1050 °C and (b) W/B = 0.47.

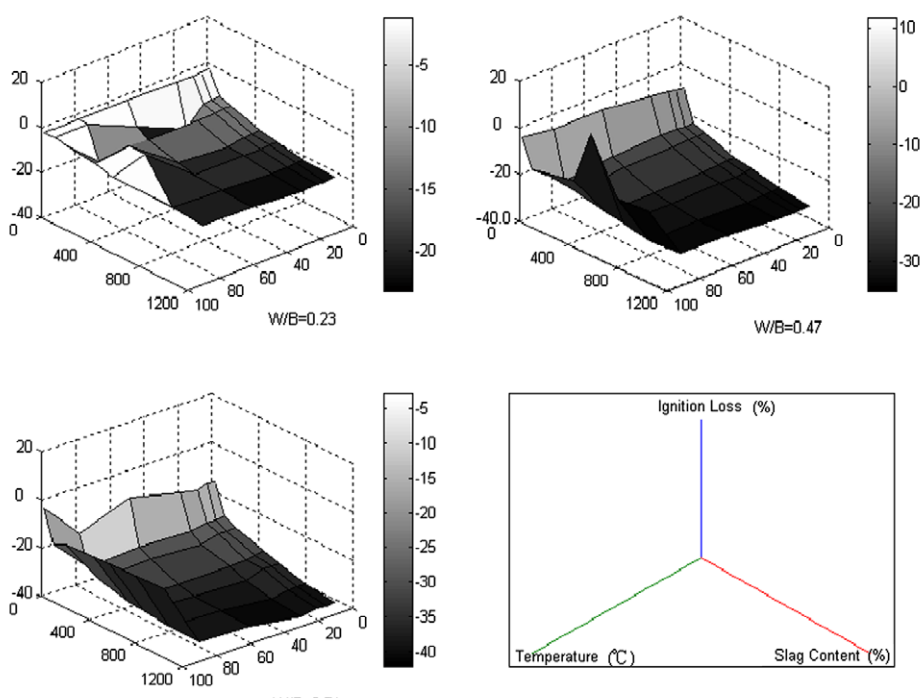

Fig. 2. Weight loss of paste with various GGBFS (slag) contents and water to binder ratios under elevated temperatures.

with GGBFS depends on the activation of the glassy phase and the hydroxyl and soluble alkali ions available during cement hydration. The reaction of the glass is relatively slow, exhibiting delayed hydration that leads to longer setting time and lower early strength development than those of the control. It is observed from Table 3 and Fig. 3 that the compressive strength decreases with increasing W/B ratio. It is interesting to note that at a W/B ratio higher than 0.71, the compressive strength of paste only increases when the GGBFS content is less than 10%.

An effort was made to find the optimal GGBFS content at different W/B ratios. The influence of elevated temperature on compressive strengths with different GGBFS content is shown in Fig. 3. At W/B ratio of 0.23, the optimum GGBFS content is between 50% and 80%. However, there were no clear trends for W/B ratios of 0.47 and 0.71.

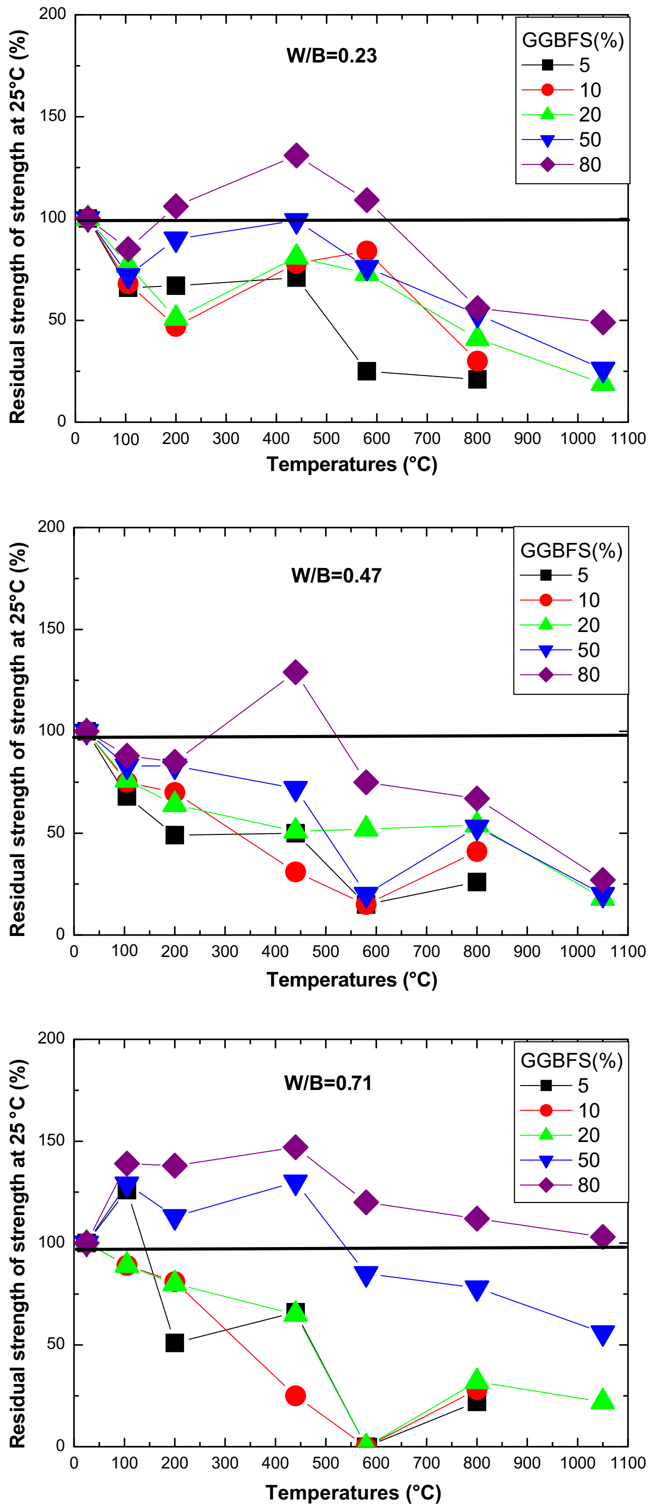

Fig. 3. Effects of GGBFS content and elevated temperature on compressive strengths.

4.4. Elastic modulus

Elastic modulus is an important engineering property related to the concrete deformation. The influencing factors for the elastic modulus include the properties and ingredients of the cement paste and aggregate, concrete density, compressive strength, capillary voids, humidity, test conditions, and loading conditions, among others [10]. Fig. 4 and Table 4 show the 2D relation of various W/B ratios, cement paste with GGBFS, temperature and elastic modulus. For W/B ratios of 0.23 and 0.47, the addition of GGBFS increases the elastic modulus at elevated temperature. However, at a W/B of 0.71, there is no improvement in elastic modulus for paste containing GGBFS. No paste specimens survived a temperature larger than 580 °C when the GGBFS content was less than 20%. Hence, the elastic modulus is not available under these exposure conditions.

From Figs. 3 and 4, it is seen that compressive strength is more susceptible than the elastic modulus of concrete to the effects of elevated temperature.

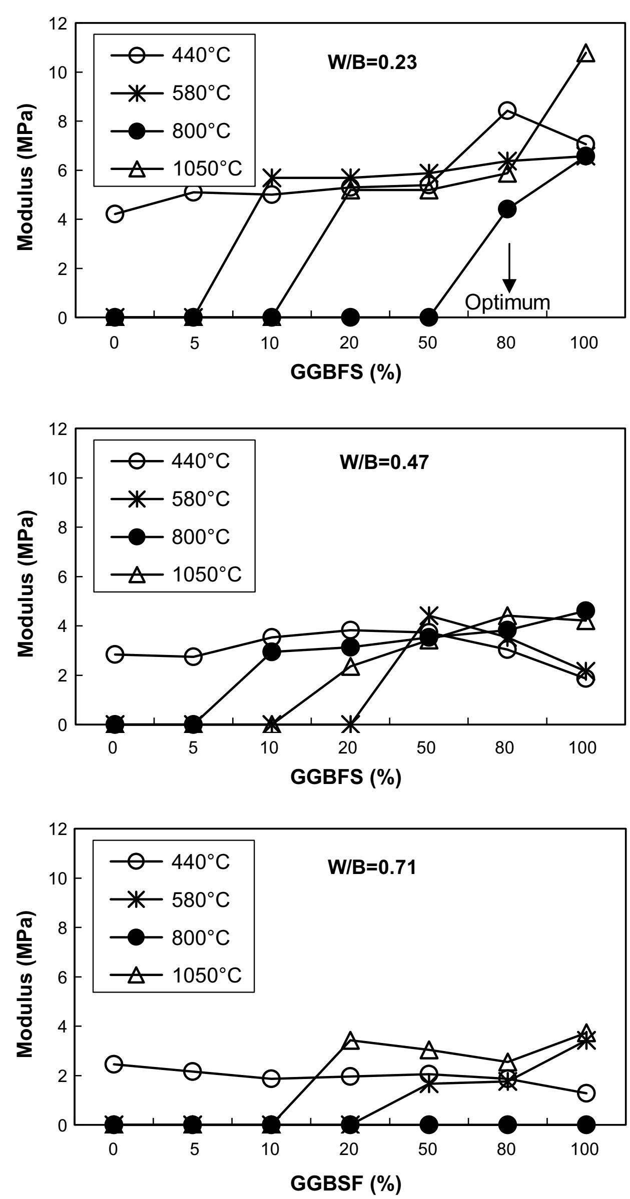

Fig. 4. Effects of GGBFS content and elevated temperature on elastic modulus.

4.5. Variations of absorption capacity

Fig. 5a shows that the absorption capacity (AC) increases with increasing temperature for different amounts of GGBFS at a W/B ratio of 0.23. It is seen by comparing Fig. 5b and c that the paste with less than 10% GGBFS and a W/B ratio of 0.71 has a higher AC than the paste with a W/B ratio of 0.47 at the same temperature and GGBFS content. At temperatures above 580 °C, the AC decreases with increasing GGBFS content. This effect occurs because high temperature accelerates the rate of hydration, and this process requires a significant amount of water [10] that decreases the AC of a specimen. This indicates that the pozzolanic reaction can consume the $Ca(OH)_2$ formed by cement hydration and alkali (N, K, C) content in the cement, converting them into low-density C–S–H gel and some small voids. This process increases the overall density of the cement paste.

4.6. Economics and practical implications of furnace slag

For years, engineers have recognized that the performance of concrete can be optimized by adding GGBFS. Thus, most of the GGBFS has been recycled even though GGBFS is a by-product from the iron and steel industry. The Federal Highway Administration (FHWA) reported that 90% GGBFS has been recycled in the US [11], and similarly, in European countries (e.g. Netherlands, Denmark, Germany) 100% GGBFS has been recycled. In Taiwan, it was estimated that 100% GGBFS, 4 million tons annually, is recycled.

Based on the current unit price in Taiwan, the costs for cement and GGBFS are $71 and $34.8 per ton, respectively. It is found that 10% of the concrete cost can be reduced through 20% replacement with GGBFS, based on 300 kg of cement per cubic meter of concrete. Similarly, 40% of costs can be saved with an 80% addition of

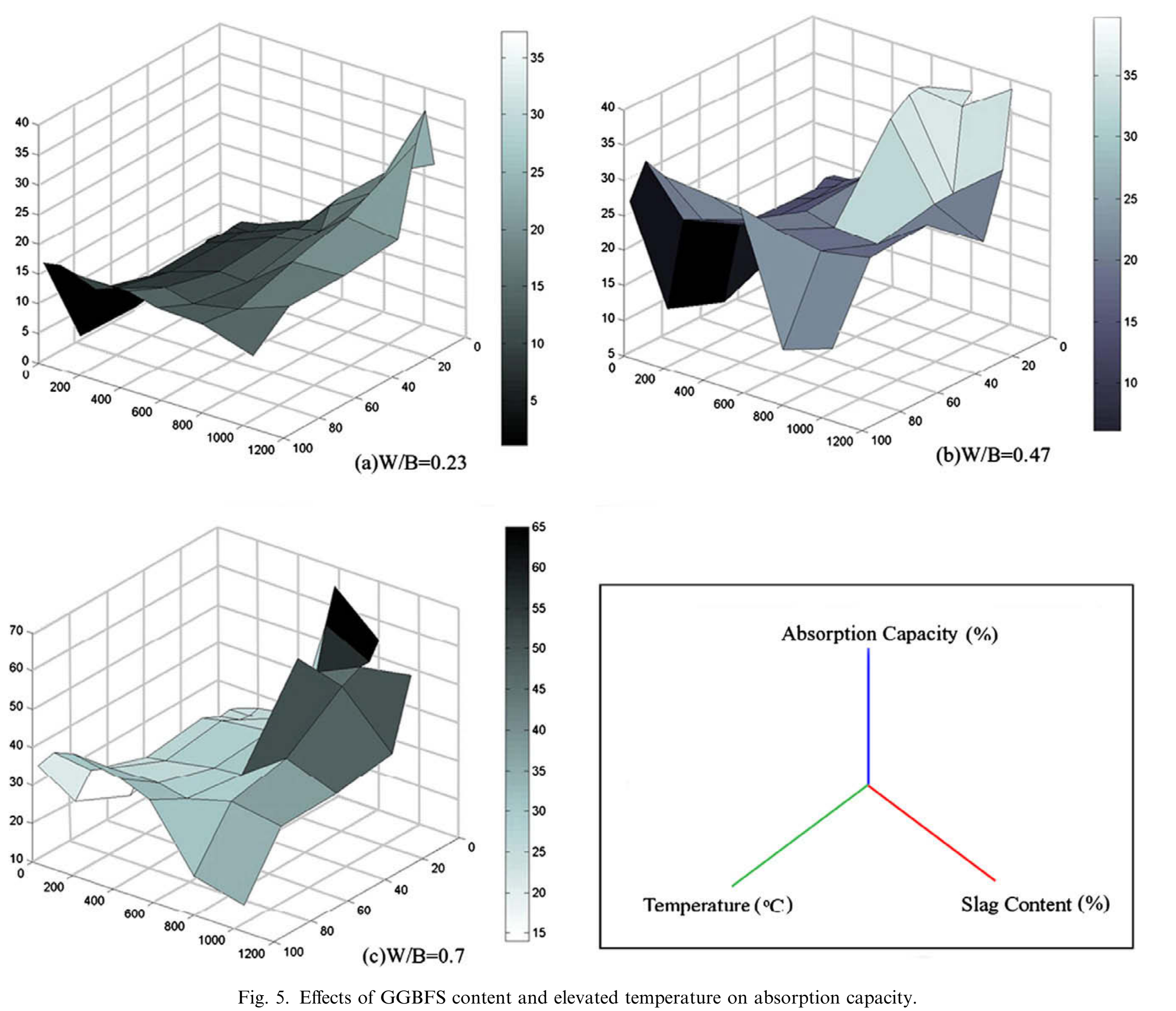

Fig. 5. Effects of GGBFS content and elevated temperature on absorption capacity.

GGBFS. In producing cement, about 45% of the cost represents electricity requirements whereas the rest is the material cost. It is estimated that the cement industry consumes about 8% of the electricity of a city [12]. With the addition of GGBFS, electricity consumption can be reduced.

Based on the aforementioned point, there are clear benefits to partially replacing cement with GGBFS, such as improvements in compressive strength and reduction of cracking at elevated temperature. At a W/B ratio of 0.23, the optimum GGBFS content was found to be 80%. With 80% addition of GGBFS, the material cost can be reduced by 40%. In view of the 28-day results (25 °C) in Table 3, there is a 5% reduction (from 64.9 to 61.8 MPa) in compressive strength corresponding to a 80% addition of GGBFS. This indicates that the 28-day compressive strength was compatible to the control that contained no GGBFS.

5. Conclusion

Based on the effects of elevated temperature treatments on the properties of the cement paste with 3 W/B ratios and 6 GGBFS contents, the following conclusions are drawn:

(1) Under an elevated temperature of 1050 °C, cracking occurs when the GGBFS content is 10% or less for all three W/B ratios. An increase of GGBFS content to 20% or above significantly reduces cracking.
(2) At a W/B ratio of 0.23, an increasing GGBFS content greatly increases the HPC compressive strength under elevated temperatures (1050 °C). Thus, the fire resistance of HPC is greatly improved when cement is replaced with GGBFS. However, at a high W/B ratio of 0.71, the addition of GGBFS does not significantly improve compressive strength.
(3) The W/B ratio of 0.23 shows a clear trend that the optimum GGBFS content for fire resistance is 50–80%.
(4) The study found that an elevated temperature treatment can increase the absorption capacity for the low W/B ratio (0.23) specimen with a proper GGBFS percent replacement; however, further increase of GGBFS content decreases the absorption capacity when the temperature is greater than 580 °C. This implies that adding GGBFS increases the density of the cement paste.
(5) The compressive strength of concrete is more susceptible than the elastic modulus to the effects of elevated temperature. For W/B ratios of 0.23 and 0.47, the inclusion of GGBFS increases the elastic modulus at elevated temperature.

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