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Early-Age Structural and Thermal Performance of GGBS Concrete

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***Abstract*—**A large amount of blast furnace slag is generated in China. Most ground granulated blast furnace slag (GGBS) however ends up in low-grade applications. Blast furnace slag, ground to an appropriate fineness, can be used as a partial replacement of cementitious material in concrete. The potential for using GGBS in structural concrete, e.g. concrete beams and columns is investigated at Xi'an Jiaotong-Liverpool University (XJTLU). With 50% of CEM I cement replaced with GGBS, peak hydration temperatures determined in a suspended concrete slab reduced by 20%. This beneficiary effect has not been further improved with 70% of CEM I replaced with GGBS. Partial replacement of CEM I with GGBS has a retardation effect on the early-age strength of concrete. More GGBS concrete mixes will be conducted to identify an 'optimum' replacement level which will lead to a reduced thermal loading, without significantly compromising the early-age strength of concrete.

***Keywords*—**GGBS, thermal effect, sustainable construction, CEM I.

I. INTRODUCTION

CHINA is going through a remarkable economic growth in the past 20 years. According to [1], the Gross Domestic Product (GDP) per capita in China increased from $963 in 1990 to $11,907 in 2013. It should be noted that the economic growth in China still largely depends on the investment, especially construction investment [2]. There will be a continuous increase in construction investment if this development trajectory is to be continued. There is however some problems associated with the development of construction industries. For instance, more than 80 million tonnes of blast furnace slag is generated annually as a waste material or a by-product of the steel industry. Approximately 80% of blast furnace slag is recycled [3]. Landfilling the remaining 20% still requires an equivalent volume of 10m deep and roughly 1 square km in surface area.

The majority of recycled blast furnace slag is used as an additive in low grade blended cement, i.e. Blastfurnace Cement P.S 32.5 (equivalent to the UK CEM III 32,5). The cost of grinding blast furnace slag into GGBS is similar to the gate price of CEM I cement in China. The cost of using GGBS in low-grade applications may not be reimbursed if the nearest steel company producing GGBS is further away from the construction site and this was found to be true in many major cities in China[4]. There is therefore a growing risk that more blast furnace slag may be disposed of in landfills.

Blast furnace slag, ground to an appropriate fineness, can be directly used as a cementitious material in concrete. GB/T 18046-2008 [5], Chinese standard for GGBS used in concrete, recognises that three classes of GGBS, according to its density and specific surface (TABLEI), can be used in concrete. It is a common concern that partial replacement of cement with GGBS may have a retardation effect on the strength of concrete, especially at an early age. In Shanghai, the maximum replacement ratio of CEM I with GGBS cannot go beyond the values given in TABLE II. In structural concrete slabs and beams, only up to 45% of CEM I can be replaced with GGBS. Tan [6] reported that with 50% CEM I replaced with GGBS, there is no detrimental effect on the strength of concrete at the age of 3, 7 and 28 days. The presence of GGBS can also improve the durability of concrete such as a reduced permeability. This beneficiary effect however may not become effective if the content of GGBS is less than 50% of the total binder [7]. There is scope to develop an 'optimum' GGBS mix proportion which could yield the best structural and durability performance in structural concrete.

The heat development from early-age cement hydration in concrete mixes containing GGBS as a partial cement replacement is slower than that of the CEM I only mixes. As a result, the peak temperature in fresh GGBS concrete is lower than that in CEM I only concrete. There is a beneficiary effect of using GGBS in structural concrete such as beams and slabs for crack mitigation purposes. Paine et al. [8] and Zheng et al. [9] reported that the heat development from cement hydration during early-age setting and curing in concrete mixes containing GGBS was slower than that of the CEM I mixes. Bamforth [10] and Dhir et al. [11] quantified this effect by introducing a short-term temperature difference factor T1 (°C) to define the difference between the peak temperature during the early age exothermic cement hydration reaction and the ambient temperature at the time of casting. The magnitude of T1 was found to be dependent upon the composition of the concrete mix, formwork materials and the ambient temperature. TABLE III gives T1 values determined from three different concrete mixes with and without using GGBS. These results were determined based on a 300mm thick ground bearing slab and the concrete placing temperature was at 20°C. With 70% of CEM I cement replaced with GGBS, thermal loading or the T1 value reduced from 17°C to 11.5°C. It should be noted that an increased concrete placing temperature will accelerate the hydration of both cement and GGBS which might result in a higher T1 value [12].

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TABLEI
REQUIREMENTS FOR GGBS USED IN CONCRETE[5]

	Classes		
	S105	S95	S75
Density (g/cm^3)		≥2.8	
Specific surface (m^2/kg)	≥500	≥400	≥300
Water content (%)		≤1	
SO_3 (%)		≤4	
Cl (%)		≤0.06	

TABLE II
MAXIMUM % OF CEM I CAN BE REPLACED IN CONCRETE[13]

	Maximum replacement ratio (%)
Concrete superstructure	45
Mass concrete, e.g. gravity foundation	70
Concrete drainage	45
Tunnel lining concrete	45
Bridge and road concrete	45

TABLE III
T1 VALUES[10]

	Total binder content (kg/m^3)	T1 (°C)
100%CEM I	380	17
50%CEM I + 50%GGBS	395	12
30%CEM I + 70% GGBS	480	11.5

Many experimental approaches have been developed to measure the temperature development in structural concrete slabs and beams. These helped to determine the temperature variations and associated thermal stresses. Da Silva et al. [14] reported that a semi-adiabatic test was a cost effective approach to investigate the heat development in mass concrete. Thermocouples were placed in the centre of a well-insulated concrete specimen to record the hydration temperature. Da Silva et al. [14] successfully predicted the hydration temperature in a 1050m^3 volume concrete foundation based on the experimental results obtained from a 1m^3 concrete cube specimen under a semi-adiabatic curing condition.

II. EXPERIMENTAL PROCEDURES

This paper reports an on-going project which investigates the potential of using high percentage of GGBS in structural concrete, which can be taken as a high-value application in China. The GGBS used for this project was Class S93 according to GB/T 18046-2008 [5]. The specific surface of GGBS was 425m^2/kg (Table IV). In comparison, CEM I 42, 5 cement used in this project only has a specific surface of 350m^2/kg. Image analysis was conducted on both CEM I and GGBS samples using a Hitachi TM3000 scanning electron microscope. The particle size of GGBS was observed to be smaller but more uniform compared with that of CEM I (Fig. 1). This indicates that a better grinding quality might have been achieved during the fabrication process.

The coarse aggregate used for this project was 40-5mm graded crushed gravel from a local quarry. The fine aggregate was well-graded medium sand. The particle density of the gravel and sand was 2680 and 2450kg/m^3 respectively. Three concrete mixes, as presented in TABLE V, were developed to investigate the effect of partial replacement of CEM I with GGBS on the heat and strength development in concrete. The target of Mix 1 was to make C35/40 concrete with a suitable workability for floor slab casting. BS 8500-1 [15] gives a slump range between 100mm and 150mm for slab casting. All three mix proportions have been finalized by casting and testing several trial mixes to satisfy this workability requirement.

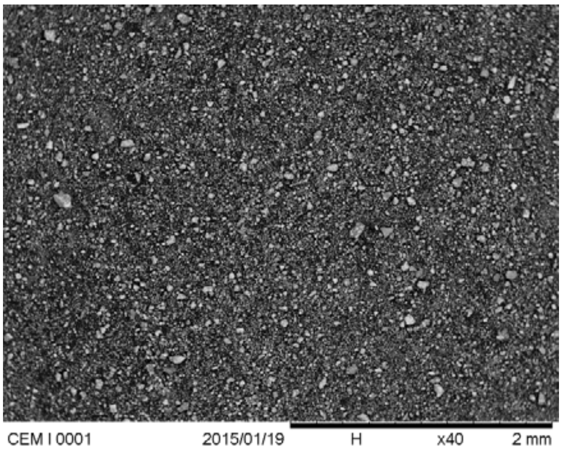
Concrete slab specimens, 350x250x300mm, were cast in an insulated plywood box to simulate the continuous curing conditions of a suspended concrete slab, as shown in Fig. 2. Four sides of the specimen were insulated with 2cm thick expanded polystyrene sheets. The bottom of the specimen was in contact with a plywood sheet and the top surface was exposed to air. These represented the expected thermal conditions of a continuous floor slab cast upon plywood formwork. Concrete slab specimens, inside the insulated plywood box, were placed in an environmental chamber immediately after casting. The environmental chamber was set at 20°C. Thermocouples were positioned in the centre of concrete slab specimens to record the temperature for 3 days after casting. Standard concrete cube specimens, 150x150x150mm, were cast alongside and cured at 20°C. The testing ages for the cube specimens were 3 and 28 days.

TABLE IV
GGBS USED IN THIS PROJECT

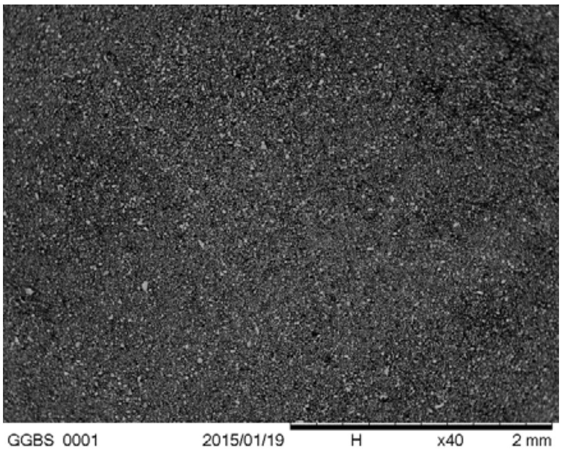
Specific surface area (m^2/kg)	Particle density (g/cm^3)	SO_3 (%)	Cl (%)
425	2.9	0.14	≤0.06

TABLE V
MIX PROPORTIONS

	Total binder content (kg/m^3)	Free W/C	Total aggregate content (kg/m^3)
Mix 1: 100% CEM I	398	0.49	1782
Mix 2: 50% GGBS	398	0.51	1782
Mix 3: 70% GGBS	398	0.51	1782



(a) CEM I particles



(b) GGBS particles

Fig. 1 Scanning Electron Micrographs (40 times of magnification)

Fig. 2 Insulated Plywood Box inside an Environmental Chamber

III. RESULTS AND DISCUSSIONS

Fig. 3 indicates that partial replacement of CEM I with GGBS have a detrimental effect on the early-age strength of concrete, especially with 70% CEM I replaced with GGBS, i.e. Mix 3. The average 3-day compressive strength of Mix 3 was 9.3N/mm^2, which was only 38% of that measured in Mix 1, 24.6N/mm^2. Fig. 4 shows the heat development in the centre of the slab specimens. With 50% of CEM I replaced with GGBS, the rate of hydration decreased alongside a reduced peak hydration temperature from 30°C to 24°C. This indicates the beneficiary effect of using GGBS to replace CEM I. This beneficiary effect however was not improved with 70% of CEM I replaced with GGBS, as shown in Fig. 4. In this project, the bottom of concrete was in contact with the plywood formwork directly and this contributed to a partial heat loss from the underneath. As a result, the T1 values were found to be lower compared to the T1 values reported for the ground bearing slabs, as presented in TABLE III.

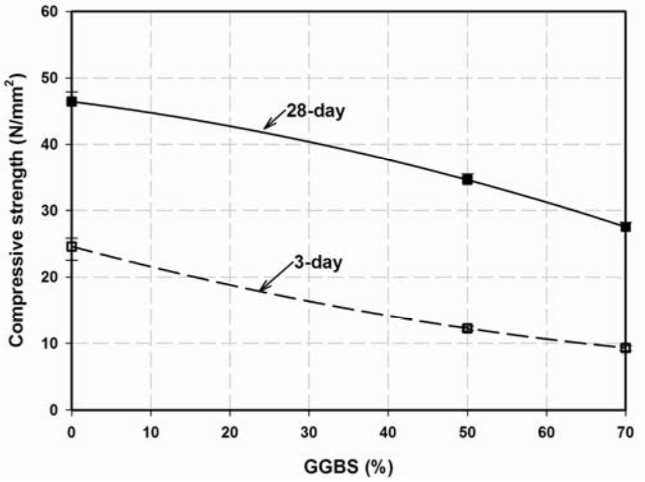


Fig. 3 Compressive strengths at 3 and 28 days

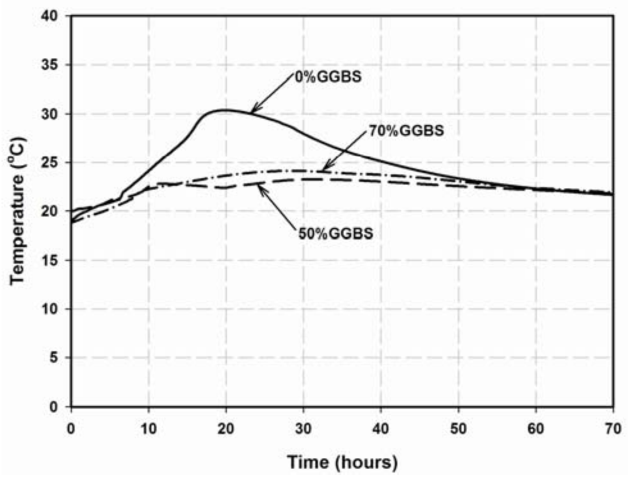


Fig. 4 Temperature history in the centre of concrete slab specimen

IV. CONCLUSIONS

Partial replacement of CEM I with GGBS has a retardation effect on the strength of concrete, especially at an early age. This is a common concern of the construction industry which might prevent its application in structural concrete. The presence of GGBS however has a beneficiary effect on a reduced peak hydration temperature. With 50% of CEM I replaced with GGBS, peak hydration temperatures determined in a 300mm thick concrete slab reduced from 30°C to 24°C. More GGBS concrete mixes will be conducted to identify an 'optimum' replacement level which will lead to a reduced thermal loading, without significantly compromising the early-age strength of concrete.

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