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High Value Applications of GGBS in China

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ABSTRACT

China accounts for approximately half of the global steel production and more than 80 million tonnes of blast furnace slag is generated every year as a by-product. About 80% of blast furnace slag is recycled in China and the majority of this is used as an additive in low grade Blastfurnace cement, i.e. P.S 32.5 (equivalent to CEM III 32,5). The Chinese State Council recently called to stop producing P.S 32.5 to make the way for high grade cement. Thus, there is a growing risk that more blast furnace slag may ultimately be disposed of in landfills. This paper discusses the technical feasibility of using ground granulated blast furnace slag (GGBS) in high performance concrete. The influence of partial replacement of CEM I with GGBS on the peak hydration temperature in long-span concrete structures has been investigated under a semi-adiabatic curing condition. Partial replacement of CEM I with GGBS contributed to the reduction of the peak hydration temperature and this has a beneficial effect in hot weather concreting.

1. INTRODUCTION

China accounts for nearly 50% of the global steel production. As a waste material or by-product in the manufacture process, over 80 million tonnes of blast furnace slag is generated annually, of which 80% is recycled (Zhang et al., 2001). 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 CEM III 32,5). In October 2013, the Chinese State Council called to stop producing P.S 32.5 to make the way for high grade cement (Chinese State Council, 2013). Blast furnace slag, ground to an appropriate fineness, can be used as a cementitious material in concrete. The GB/T 18046-2008 (GB, 2008) Chinese standard for GGBS used in concrete, recognises that three classes of GGBS, according to its density and specific surface, can be used in concrete (**Table 1**). It should be noted that the cost of grinding blast furnace slag into GGBS is similar to the gate price of CEM I cement in China. This makes the transportation cost a determining factor. The cost of using GGBS in low-grade applications may not be reimbursed if the nearest steel company producing GGBS is

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further away from the construction site compared to the nearest cement distributors and this is found to be true in most Chinese cities (Tang et al., 2013). Thus there is a growing risk that more blast furnace slag may ultimately be disposed of in landfills.

Table 1: Requirements for GGBS used in concrete (GB, 2008)

	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		

Fluctuations in ambient temperature due to the changing environmental conditions will cause the structural elements to expand or contract. Linear expansion and subsequent contraction will take place in concrete at early ages due to the thermal hydration process. Contraction can also be caused by autogenous shrinkage. Significant internal stresses will build up in long span concrete beams and slabs if these movements are externally restrained by supporting columns or shear walls. Expansion in these long span concrete elements against external restraints leads to compressive stresses and contraction leads to tensile stresses. It is the latter which is of more concern and may cause deleterious tensile cracking in concrete. The heat development from cement hydration during early-age setting and curing in concrete mixes containing GGBS as a partial cement replacement is slower than that of the ordinary CEM I mixes. As a result, the peak temperature in fresh GGBS concrete is lower and this will result in a reduced thermal contraction. There is therefore scope to use GGBS in long-span concrete structures for crack mitigation purposes. Paine et al (Paine et al., 2005) and Zheng et al (Zheng et al., 2005) 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 (Bamforth, 2007) and Dhir et al (Dhir et al., 2006) 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 2** gives T1 values obtained from three concrete mixes with and without using GGBS. These results were based on a 300mm thick ground bearing slab and the concrete placing temperature was at 20°C and 35°C respectively. A higher T1 value was noted when the concrete casting temperature was increased from 20°C to 35°C. This indicates that an increase in placing temperature will accelerate the hydration of cement and GGBS and this finding agrees with Bougara (Bougara et al., 2009).

Partial replacement of cement with GGBS may have a detrimental effect on the early-age strength of concrete. This may result in the failure of concrete in tension under early-age thermal contraction. It is therefore useful to justify the use of GGBS in long-span concrete structures by verifying if this detrimental effect can be contradicted by the beneficial effect of the reduced thermal contraction effect. Based on a review of literature, this has not been sufficiently investigated.

A high curing temperature has a detrimental effect on the long-term strength of concrete. Wang et al (Wang et al., 2012) reported that this detrimental effect might become less significant when part of the cement was replaced with GGBS. This was attributed to the enhanced micro-structures of the C-S-H gels from GGBS.

Table 2: T1 values (Bamforth, 2007)

	Total binder (kg/m^3)	T1 (°C)	
		20°C placing temperature	35°C placing temperature
Mix 1: 100% CEM I	380	17	19.4
Mix 2: 50% GGBS	395	12	14.4
Mix 3: 70% GGBS	480	11.5	13.9

It is important to determine the temperature development from cement hydration, especially large volume concrete pours. Many experimental approaches have been developed to measure temperature in and around concrete. These helped to determine the temperature variations and associated thermal stresses. Da Silva et al (da Silva et al., 2013) reported that a semi-adiabatic test was a cost effective approach to investigate the heat development in mass concrete. Kim et al (Kim et al., 2011) investigated the influence of GGBS on the early-age hydration temperature and autogenous shrinkage under a semi-adiabatic condition. A typical semi-adiabatic curing incubator, **Figure 1**, insulates the concrete specimen entirely. Thermocouples were located in the centre of the specimen to record the hydration temperature. This test was carefully set up to simulate the insulation effect of mass concrete. For instance, Da Silva et al (da Silva et al., 2013) 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. The actual curing condition in the centre of long-span concrete slabs may be different from that of the mass concrete because the heat losses from the top and bottom of the slab are still possible. The peak hydration temperature determined under this curing condition may therefore be an overestimate.

Figure 1: Semi-adiabatic curing incubator (Koenders et al., 2014)

2. EXPERIMENTAL PROCEDURES

This paper reports a project conducted at Xi'an Jiaotong-Liverpool University (XJTLU) which investigated the potential of using GGBS in long-span concrete structures by avoiding/reducing the use of more expensive crack control reinforcement. The objective was to determine an 'optimum' GGBS mix proportion which could result in a lower T1 value and associated saving in crack control reinforcement. Concrete slab specimens were cast in an improved semi-adiabatic condition to simulate in-situ continuous concrete floor slabs.

The GGBS used for this project, **Table 3**, was Class S93 according to GB/T 18046-2008 (GB, 2008), **Table 1**. The specific surface of GGBS was 425m^2/kg. In comparison, CEM I 42,5 cement used in this project only has a specific surface of 350m^2/kg. The coarse aggregate used for this project was 40-5mm graded crushed gravel from a local quarry with a water absorption value of 0.88%. The fine aggregate was well-graded medium sand with a water absorption value of 2.62%. The particle density of the gravel and sand was 2680 and 2450kg/m^3 respectively. Three concrete mixes, **Table 4**, have been developed to investigate the effect of partial replacement of CEM I with GGBS on the heat development in long-span concrete slabs. The target of Mix 1 was to make C35/40 concrete with a suitable workability for floor slab casting. BS 8500-1 (BSI, 2006) recommends 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. The total binder content has been increased in Mix 2 and 3 to maintain the early-age strength despite the replacement of CEM I cement with GGBS.

Concrete slab specimens, 350X250X300mm, were cast inside an insulated plywood box, **Figure 2**. Four sides of the specimen were insulated with 2cm thick expanded polystyrene sheets. The bottom of the specimen was in contact with a 17mm plywood sheet and the top surface was exposed to air. This allows the heat losses from both the top and the bottom of concrete, similar to the expected thermal conditions of a continuous floor slab cast upon plywood formwork.

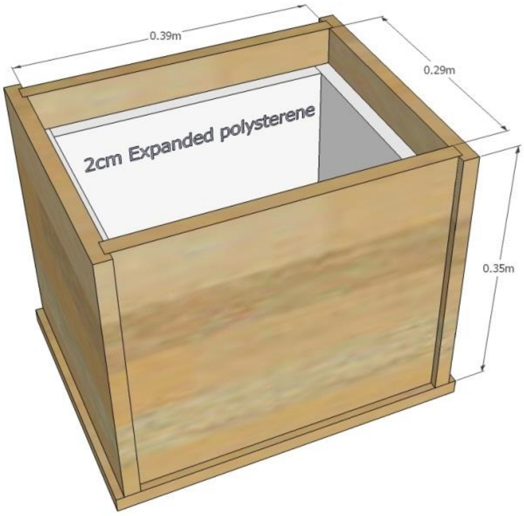
The American concrete code, ACI 305R (ACI Committee 305, 1999), recommends that the optimum concrete placing temperature is between 28°C and 38°C. The maximum allowable placing temperature recommended by ACI 305R, i.e. 38°C, is assumed to be appropriate in China. All concrete slab specimens, inside the insulated plywood box, were placed in an environmental chamber immediately after casting. The environmental chamber was set at 20°C and 38°C respectively. The latter represents the highest placing temperature in summer. Thermocouples were positioned in the centre of concrete slab specimens to monitor the temperature for up to 70 hours after casting. Standard concrete cube specimens, 150X150X150mm, were cast alongside and cured under room temperature, i.e. approximately 20°C. Within 24 hours after casting, the cube specimens were demoulded and placed inside a water curing tank which was set at the same temperature as the environmental chamber. The testing ages for the cube specimens were 3 and 28 days.

Table 3: 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 4: 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	438	0.51	1782
Mix 3: 70% GGBS	478	0.51	1782



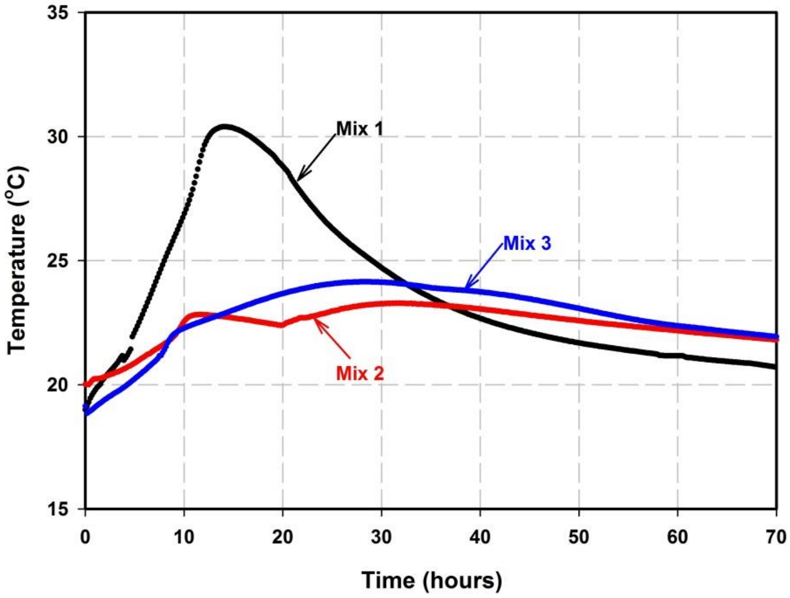
(a) Plywood box (indicative drawing) (b) Environmental chamber

Figure 2: Insulated plywood box and environmental chamber

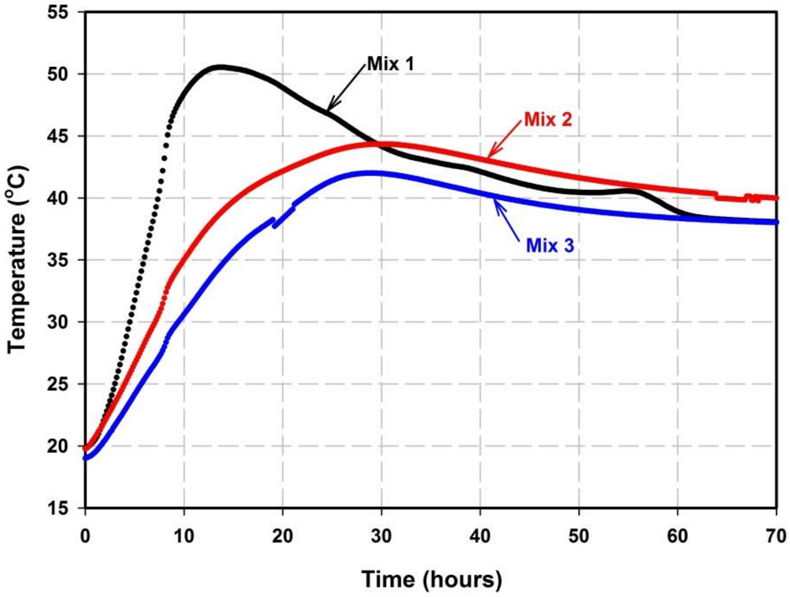
3. RESULTS AND DISCUSSIONS

Figure 3 (a) shows the heat development in the centre of the slab specimens under a curing temperature of 20°C. As the GGBS content increased, the rate of hydration decreased, even if the specific surface of GGBS is higher than CEM I. The shape of GGBS concrete hydration temperature history demonstrated 'S' shape peaks which might be caused by the hydration of CEM I and GGBS at a time interval. These agree with the findings by Bougara (Bougara et al., 2009).

At 38°C, the rate of heat development was greater than that at 20°C, **Figure 3 (b)**. This indicates that a higher curing temperature accelerated the hydration of both CEM I and GGBS mixes. T1 values obtained from all three mixes are summarized in **Table 5**. As the GGBS content increased, the T1 values decreased. This indicates the beneficial effect of using GGBS to replace CEM I. 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 those reported for the ground bearing slabs, **Table 2**.



(a) 20°C curing temperature



(b) 38°C curing temperature

Figure 3: Temperature in the centre of slab specimens

Table 5: T1 values in the core of 300mm slab specimens

	T1 (°C)	
	20°C curing temperature	38°C curing temperature
Mix 1: 100% CEM I	10.4	12.5
Mix 2: 50% GGBS	3.3	6.3
Mix 3: 70% GGBS	4.1	4.0

Partial replacement of CEM I with GGBS has a detrimental effect on the early-age strength of concrete under a standard curing temperature of 20°C. The 3-day compressive strengths of GGBS concrete mixes, i.e. Mix 2 and 3, were lower than that of Concrete Mix 1, **Figure 4**. This detrimental effect was found to be less significant at a higher curing temperature. The average 3-day compressive strength of Mix 2 was 24.0N/mm^2 which was very similar to that of Mix 1, 24.9N/mm^2, at 38°C curing temperature.

A high curing temperature however has a detrimental effect on the 28-day strength of concrete. The average 28-day compressive strengths of Mix 1 reduced from 46.4N/mm^2 to 42.2N/mm^2 when the curing temperature was increased from 20°C to 38°C, **Figure 4**. This detrimental effect however became less significant when 50% CEM I was replaced with GGBS. This indicates the strength of GGBS concrete was less adversely affected by the high temperature curing compared to CEM I mixes and this finding agrees with Barnett (Barnett et al., 2006) and Wang (Wang et al., 2012).

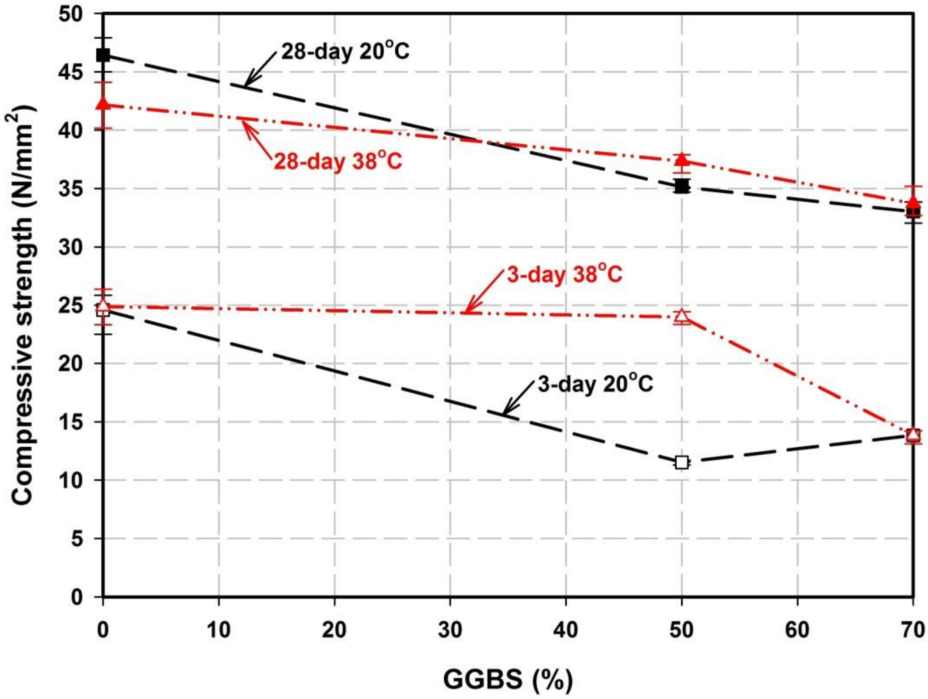


Figure 4: Compressive strengths at 3 and 28 days

4. CONCLUSIONS

Partial replacement of CEM I with GGBS contributes to a reduction in the peak hydration temperature. This has a beneficial effect on hot weather concreting. GGBS concrete has a lower early-age strength compared to CEM I concrete and this may cause a premature tension failure in long-span concrete structures. On the other hand, early-age strength of GGBS concrete is improved by high curing temperatures. More GGBS concrete mixes will be conducted to identify an 'optimum' replacement level which will balance these factors. A case study investigation will also be conducted to investigate the potential economic benefit through using GGBS in high value markets such as the replacement of cement in long-span concrete structures to reduce the requirement for thermal crack control reinforcement.

REFERENCES

ACI Committee 305 (1999). *Hot weather concreting.* ACI.
Bamforth, P. B. (2007). *CIRIA C660 Early-age Thermal Crack Control in Concrete.* London: CIRIA
Barnett, S. J., M. N. Soutsos, S. G. Millard & J. H. Bungey (2006). Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies. *Cement and Concrete Research* 36**:** 434-40.
Bougara, A., J. Khatib & H. Khellafi (2009). Some parameters affecting the heat of hydration of blast-furnace slag cement. *1st International Conference on Sustainable Built Environment Infrastructures in Developing Countries.* ENSET Oran, Algeria.
BSI (2006). *BS 8500-1: 2006 Complementary British Standard to BS EN 206-1. Method of specifying and guidance for the specifier* British Standards Institution (BSI) London.
Chinese State Council (2013). *The guidance on the overcapacity of industries.*
da Silva, W. R. L., V. milauer & P. temberk (2013). Upscaling semi-adiabatic measurements for simulating temperature evolution of mass concrete structures. 1-11.
Dhir, R. K., K. A. Paine & L. Zheng (2006). *Design data for use where low heat cements are used DTI Research Contract No. 39/680, CC2257. Report No CTU 2704.* University of Dundee.
GB (2008). *GB/T 18046-2008 Ground granulated blast furnace slag used for cement concrete.* General administration of quality supervision, inspection and quarantine of the People's Repulic of China.
Kim, G.-Y., E.-B. Lee, J.-S. Nam & K.-M. Koo (2011). Analysis of hydration heat and autogenous shrinkage of high-strength mass concrete. *Magazine of Concrete Research* 63**:** 377-89.
Koenders, E. A. B., M. Pepe & E. Martinelli (2014). Compressive strength and hydration processes of concrete with recycled aggregates. *Cement and Concrete Research* 56**:** 203-12.
Paine, K. A., L. Zheng & R. K. Dhir (2005). Early-Age Temperature Rises in GGBS Concrete - Part 2: T1 Values for Low Heat and Very Low Heat Cements. In Dhir, R. K., T. A. Harrison & M. D. Newlands (eds.) *International Congress - Global Construction: Ultimate Concrete Opportunities.* London, Thomas Telford. 183-94.

Tang, K., S. Millard & G. Beattie (2013). Technical and economic aspects of using GGBFS for crack control mitigation in long span reinforced concrete structures. *Construction and Building Materials* 39**:** 65-70.

Wang, Q., M. Miao, J. Feng & P. Yan (2012). The influence of hightemperature curing on the hydration characteristics of a cement-GGBS binder. *Advances in Cement Research* 24**:** 33-40.

Zhang, J., H. Liu & X. Hu (2001). High-grade compound cement production with large amount of fly ash. *Cement* 3**:** 46.

Zheng, L., K. A. Paine & R. K. Dhir (2005). Early-Age Temperature Rises in GGBS Concrete: Part 1: Determination of T1 Values. In Dhir, R. K., T. A. Harrison & M. D. Newlands (eds.) *International Congress - Global Construction: Ultimate Concrete Opportunities.* London, Thomas Telford. 173-82.