- Technical Paper -

THERMAL CRACKING SENSITIVITY OF SLAG AND FLY ASH CONCRETES BY THE UNIAXIAL RESTRAINT TEST

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ABSTRACT

This paper presents the thermal cracking sensitivity evaluation of blast furnace slag and fly ash concretes by a temperature-stress testing machine (TSTM) under full restraint, moderate and high temperature rise, and sealed curing conditions. Common mix proportions of additive admixture were experimented and compared with OPC conventional concrete for the sake of real application. Slag in high temperature rise case had a negative effect. Fly ash concrete was found to possess a better cracking resistance than the case of slag concrete.

Keywords: restraint stress, restraint degree, stress relaxation, thermal deformation

1. INTRODUCTION

Industrial by-product, such as blast furnace slag and fly ash, is an important material in concrete production for cost reduction, durability, and environmental preservation. Base on these merits and the mechanical properties particularly low heat of hydration generation, these additive admixtures have been used for cracking mitigation in massive concrete structures. However, it was reported that slag concrete exhibited thermal cracking in mass concrete [1], while fly ash concrete did not.

Extensive efforts have been made to evaluate the cracking sensitivity of slag and fly ash concrete, but a clear conclusion has not been drawn and a realistic cracking mechanism remains uncertain due to two main reasons. First, the causes of thermal cracking were investigated separately without considering interaction among the different causes. In general, thermal cracking in concrete is induced where the tensile stress exceeds the tensile strength. This restrained stress is further determined by potential volume changes, the restraint degree, Young's modulus, creep, and stress relaxation. The volumetric shrinkage is dominated by thermal deformation which is directly controlled by the hydration heat, plastic shrinkage, drying shrinkage, autogenous shrinkage, and so on. When the hydration heat changes, autogenous shrinkage, one of the non-thermal deformations, varies accordingly along with the thermal deformation [2]. In short, almost all of the properties of concrete are affected by temperature [3]. Second, the existing evaluated data on thermal cracking sensitivity were quite different from one another due to different chemical composition, dependent on the manufacturer and country, and testing methods [4-8].

The main objective of this paper is therefore to evaluate the cracking sensitivity of slag and fly ash concretes. Restrained stress essentially which is determined by restraint degree and temperature history, was measured by utilizing a Temperature-Stress Testing Machine (TSTM). Cracking sensitivity under effects of several influencing factors could be evaluated quantitatively. In order to obtain the realistic result in regards to massive concrete, the temperature setting condition was primarily discussed. Then the main cause of cracking sensitivity such as hydration heat, Young's modulus, and restrained stress, a most important in thermal cracking sensitivity evaluation, were discussed. Finally, the thermal cracking sensitivity could be evaluated.

2. TEST PROGRAMS

2.1 Equipment

A laboratory testing device, a TSTM (Fig. 1) made by Dr. LIN at the University of Tokyo [9], was used to measure the restrained stress and free deformation of a 120x120x1200-mm specimen. By means of preventing heat lose of specimen by a temperature control chamber in which 3cm-heat isolation was applied and of simulating the temperature surrounding the specimen 0.1°C lower in medium temperature rise case and 1°C higher in high temperature rise case, the temperature rise of the specimen could be controlled in semi-adiabatic conditions. The temperature inside the specimen was recorded continually by two temperatures sensors, placed in the middle and near the end of specimen. The deformation was measured by two linear variable

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Fig.1 Temperature-stress testing machine (TSTM)

displacement transducers (LVDT) with a precision of 0.1μm between the two cross heads. The restrained stress was regularly measured and recorded by a load cell. A program can monitor the restraint of the concrete beam in the range of 0% or 100%. The measurement began with the casting of concrete in the TSTM mold.

2.2 Test conditions

Full restraint condition was achieved by limiting the axial length of the specimen to ±0.5μm in order to measure the restrained stress.

In regards to temperature condition, two temperature rise conditions were adopted in this study. First was medium temperature rise that could be achieved by keeping a chamber temperature lower than the specimen temperature 0.1°C until temperature of specimen return to the room temperature. Second was high temperature rise condition that was achieved by keeping the chamber temperature higher than the temperature inside the specimen 1°C until specimen temperature drop 0.2°C from the maximum temperature then lowering the chamber temperature to 0.1°C lower than the specimen temperature until temperature of specimen return to the room temperature and finally, artificial cooling at the rate of 0.3°C/h was adopted until specimen cracked to simulate the most severe condition on it.

2.3 Test procedure

Before mixing, all concrete constituent were placed in the mixing room for at least one day so that the materials' temperatures were the same as room temperature which is about 20°C.

After mixing, the fresh concrete was placed and compacted in the horizontal mold of TSTM. Two hours afterward, the surface of the specimen was covered with a slightly wet cloth and wrapped with two layers of plastic sheet to prevent the moisture loss due to both drying and water absorption of the specimen from cloth. Twenty fours hours later, the lateral and bottom molds were separated from the beam allowing it to deform freely over three-roller supports without friction disturbance.

2.4 Materials

Four concrete mixes were prepared with OPC as a reference, cement blended with fly ash at 30% replacement ratio, and slags at 50% and 45% replacement ratio which are very common ratios as recommended by the manufacturer and commonly used in the construction site. All concretes were mixed with the same water-cement ratio (45%), binder amount (400Kg/m^3), water content (180L/m^3), aggregate ratio (47%), and air entrained agent to achieve a slump of 10 to 17 cm and air content of 1% to 4%. Detailed concrete mix proportions are given in Table 1.

Table 1 Concrete mix proportions

Mix No.	C	FA	BFS	S	G	AE
	(kg/m^3)					
CM(H)	400	0	0	844	942	2
FA30CM(H)	280	120	0	823	919	2
BFS50CM	200	0	200	838	935	2
BFS45CH	220	0	180	838	936	2

C: Ordinary Portland cement, FA: Fly ash, BFS: Blast furnace slag, S: Sand, G: Gravel, AE: Air entrained agent, M: Moderate temperature rise, H: High temperature rise

2.5 Young's modulus measurement method

Young's modulus plays a crucial role in thermal cracking investigation of concrete. However, it is difficult to measure it with high accuracy. Therefore,

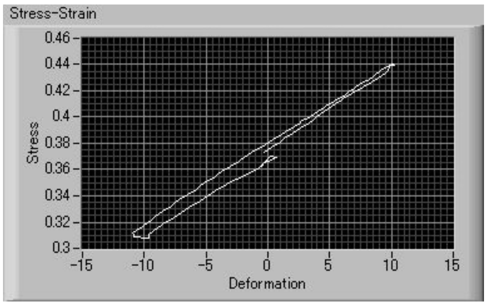


Fig.2 (a) Example of a Young's modulus testing procedure

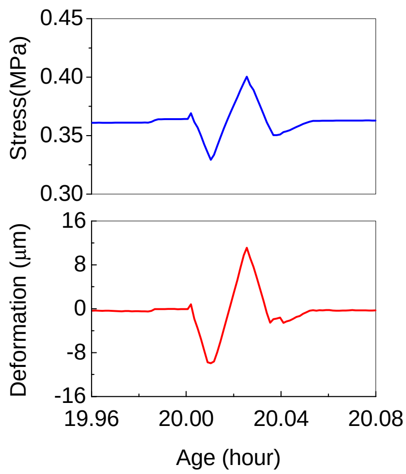


Fig.2 (b) Variational deformation and stress the measurement method must be taken into consideration. In the literature, the measurement of such modulus could be adopted in hardened concrete only by the means of compressing cylinder cured in room temperature without taking into account the temperature history and humidity condition, therefore, a realistic Young's modulus at the very early age could not be obtained. According to the advance technology adopting in TSTM, Young's modulus can be measured directly, under realistic, simulated condition from the beginning. However, measurement technique depends on the device capacity. The proposed method of Springenschimid [10] to measure the Young's modulus by relation between the recovered displacement and corresponding stress variance was previously adopted in this TSTM, but the error of tested value was too large, sometimes reaching several hundred percents due to the small threshold value, 0.5μm, which was set close to the displacement precision, 0.1μm, and the disturbance of displacement control mechanism. Therefore, a new special method was adopted by applying artificial compression or tension once per hour to the specimen to generate a displacement about 20μm (fig.2). On the basis of stress-strain relation, the Young's modulus could be calculated tangentially [11].

3. TEST RESULTS

3.1 Tensile strength

Tensile strengths of concrete in moderate temperature rise case were obtained by direct tension of specimen after its temperature had returned to the room temperature. Nonetheless, in high temperature rise case, the tensile strength was assumed to be equivalent to the stress at which concrete had cracked under induced restrained stress.

The tensile strength result is given in Figure 3.

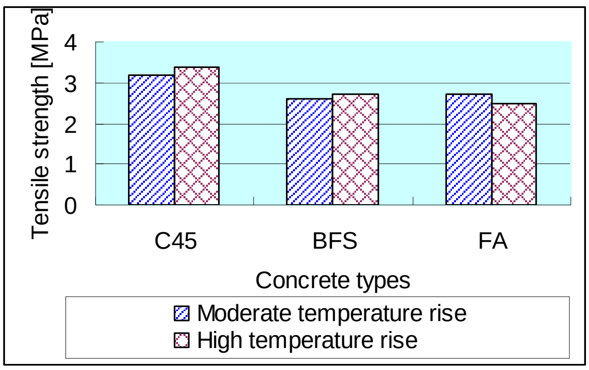
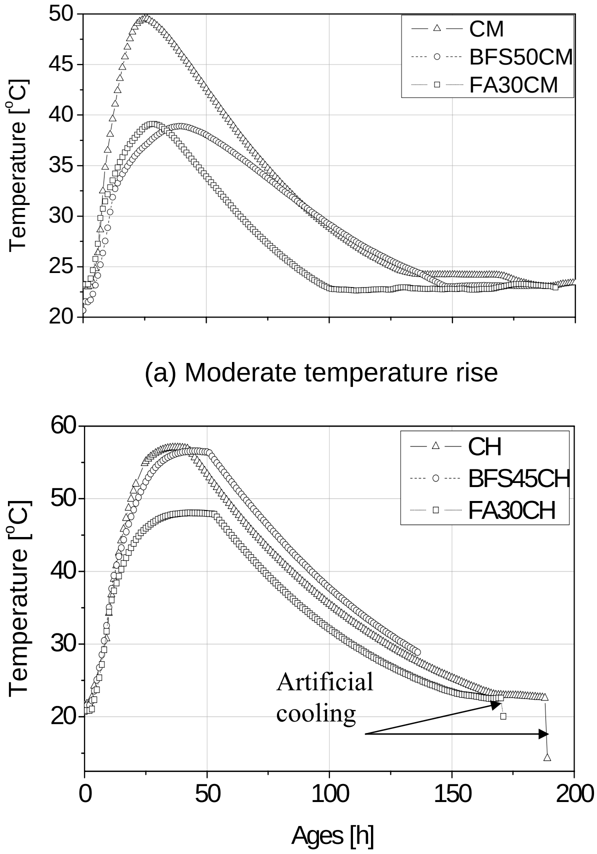


Fig.3 Tensile strength of concrete

3.2 Temperature rise

In moderate temperature rise case, temperature rise of concrete is shown in Figure 4(a). It was observed that temperature rise of slag and fly ash concretes were similar and about 10°C lower than the case of OPC concrete. However, the rate of temperature drop of slag concrete was the lowest.

In high temperature rise case, Figure 4(b), the temperature rise of slag concrete increased as high as



(a) Moderate temperature rise

(b) High temperature rise

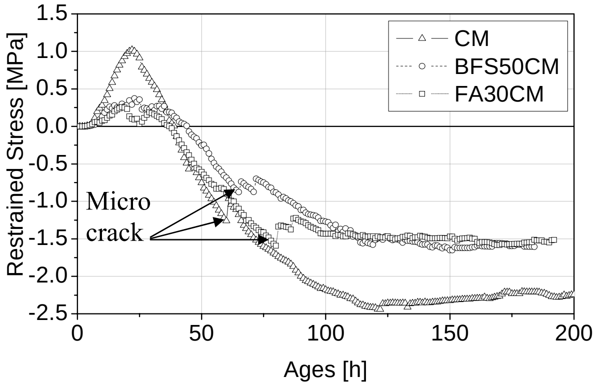
Fig.4 Temperature rise of concrete

the case of OPC concrete, and 10°C higher than the case of fly ash concrete.

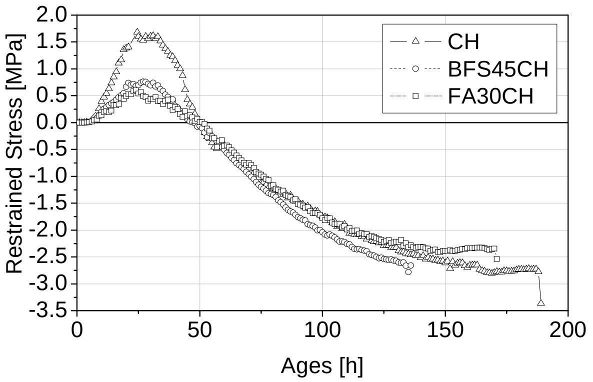
3.3 Restrained stress

In moderate temperature rise case, Figure 5(a), in addition to the similar temperature rise of slag and fly ash concrete, compressive stress of slag and fly ash concretes were almost the same and 0.7MPa smaller than that of OPC concrete. However, the tensile stress development rate in case of slag concrete was found lower than in case of fly ash and OPC concrete. Despite this fact, micro crack occurred in slag concrete almost at the same time as in OPC concrete, but earlier than in fly ash concrete. Finally, the tensile stress of slag and fly ash were same and about 0.75MPa lower than that of OPC concrete.

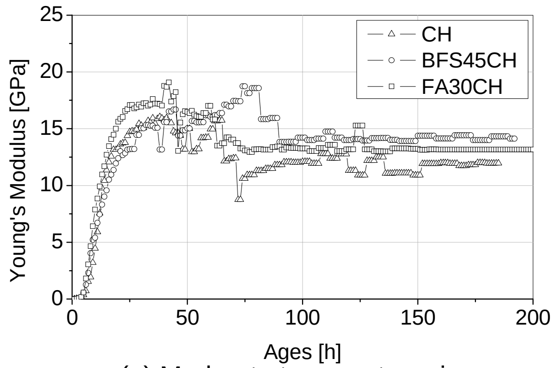
In high temperature rise case, Figure 5(b), even though the temperature rises of slag and OPC concretes were same, the compressive stress in slag concrete was still lower than in OPC concrete and similar to the case of fly ash concrete. However, its tensile stress development rate was higher than that of fly ash and OPC concrete. Finally, slag concrete cracked at a high temperature of 29°C before reaching the room temperature, but fly ash and OPC concrete did not crack yet until an artificial cooling was conducted to lower the concrete temperature to 20°C and 14°C respectively.



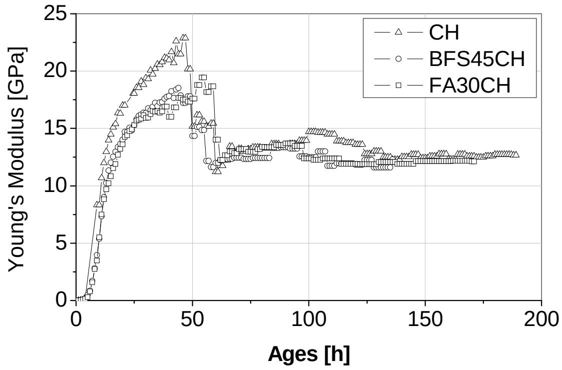
(a) Moderate temperature rise



(b) High temperature rise
Fig.5 Restrained stress of concrete



(a) Moderate temperature rise



(b) High temperature rise
Fig.6 Young's modulus of concrete

3.4 Young's modulus

The result is given in Figure 6. It was observed that the Young's modulus of all concrete types developed quickly during the first day along with the hardening process and then the increase rate slowed down as concrete generated nearly its full hardening performance. At the second day, it suddenly decreased dramatically due to conversion from compressive stress to tensile stress.

Even though Young's modulus for all concrete followed a similar pattern, in all temperature conditions, the magnitude and increase rate of slag and fly ash concretes' modulus were similar, but smaller than that of OPC concrete. The difference between these two concrete types and OPC concrete became larger and larger from the first half day.

4. DISCUSSION

4.1 Temperature rise

The temperature rise of slag concrete was found significantly increased in high temperature rise case compared to moderate temperature rise case. In moderate temperature rise case, temperature rise was comparable to fly ash concrete which was about 65% of OPC concrete. It means only 15% of the hydration heat belonged to hydration of slag since the replacement ratio of slag was 50%. However, in high temperature rise case where heating is applied, the temperature rise of slag concrete increased up similarly to OPC concrete. Since the hydration heat of slag and OPC are similar [13], it was clear that the considerable boost in temperature rise of slag concrete in high temperature rise case was mainly attributed to fully intensified hydration of slag in addition to OPC.

4.2 Compressive stress

Based on the comparative data, Figure 5, slag concrete always showed low compressive stress compared to OPC concrete although the temperature rise of these two concrete types were same as shown in Figure 4(b). A possible explanation arises from the fact that the boost in temperature rise of slag concrete revealed the increase in hydration. When hydration is increased, the free water in the system was more consumed causing an increase in capillary tensions. Reduction in volume of water associated with an increase in capillary tension resulted in magnification of autogeneous shrinkage [15-16] which counteracted the thermal expansion that plays a crucial role in compressive stress generation. By the meantime, during the first twenty fourth hours the Young's modulus development of slag concrete was always lower than that of OPC in Figure 6. Since restrained stress was also determined by Young's modulus, the lower the Young's modulus in a very early-age, the lower compressive stress. Furthermore, low Young's modulus means low stiffness. The softer the concrete subjected to loading, the higher the creep can be generated [18]. The more the concrete creeps, the more compressive stress relaxes. Therefore, large compressive stress could not be generated.

4.3 Tensile stress

Restrained tensile stress evolution of slag and fly ash concretes were found strongly accelerated in high temperature rise cases. It could be explained that the high temperature rise in concrete is followed by a large thermal contraction and also autogeneous shrinkage as above mentioned [15-16]. In other words, the volumetric shrinkage was intensified. Since shrinkage determines tensile stress, an increase in shrinkage resulted in an enlargement of tensile stress. On the other hand, the augmentation of temperature results in an increase in creep development [18]; however, strength is also amplified accordingly. Since the tensile strength developed faster than the tensile stress (this will be explained below), the stress-strength ratio decrease and finally resulted in a decrease in creep/relaxation that was confirmed by LIN test result [17]. Nevertheless, an other factor that determine the restrained stress is Young's modulus, but between moderate and high temperature rise the modulus were similar so it can be inferred that Young's modulus did not involve in tensile stress magnification in high temperature rise case. Therefore, the high tensile stress in high temperature rise condition was mainly due to an increase in volumetric shrinkage preceded by an increase in thermal contraction and autogeneous shrinkage and to stress relaxation reduction.

4.4 Micro crack

Micro crack was recognized when a sudden release of tensile stress occurs. Theoretically, occurrence of micro crack is postulated when the stress-strain relation deviate from linearity [18]. It means the strain rate is higher than stress rate. In the other words, stress is higher than elastic strength. Analogously, when strain rate is higher than stress rate in TSTM, concrete extents immediately larger than the threshold, ±0.5μm, then load cell applies compressive force to drive the specimen to its original position. Since the corresponded compressive force is high enough to reduce the tensile stress, the abrupt release of tensile stress could be observed. On the other hand, this crack can not be actually seen so its position is still obscured. However, it is supposed to be near the cross head because the strength of concrete there may be lower than in the core of the specimen where the maturity is higher because of higher temperature.

Micro crack was found disappeared from the restrained stress in high temperature rise case. Based on the maturity concept [19], it can be seen from table 2 that all concrete type in high temperature rise cases always showed the longer time and the larger maturity which correspond to a tensile stress where micro crack was supposed to occur in moderate temperature rise cases. It means that in high temperature rise, tensile stress development was delayed and the tensile strength progressed faster than the tensile stress. Nonetheless, the tensile stress development is preceded by the compressive stress reduction which mainly depends on the temperature history. Since the temperature of concrete maintained in high temperature rise cases longer than in moderate temperature rise cases, it can be deduced that the maintenance and augmentation of temperature of concrete in high temperature rise case delayed the tensile stress generation and inversely enhance the tensile stress development. When tensile stress was lower than the tensile strength, the micro crack could not appear.

Table 2 Relation of release stress and maturity

Mix No.	σ_{cr}	Moderate		High	
		t_{cr}	M	t_{cr}	M
	[MPa]	[h]	[^{o}C-h]	[h]	[^{o}C-h]
CM(H)	-1.26	60	3120	82	4682
FA30CM(H)	-1.59	80	3435	93	4752
BFS50CM	-0.87	65	2914	-	-
BFS45CH	-	-	-	68	3962

σ_{cr}: Tensile stress where micro crack occurs, t_{cr}: Time corresponding to σ_{cr}, M: Maturity of concrete corresponding to σ_{cr}

4.5 Temperature setting

In the moderate temperatures rise condition, three important points were observed from the data comparison. First, the temperature rise in slag concrete was similar to fly ash concrete, but much lower than that in OPC concrete, which contrasts with the adiabatic temperature rise test [12]. Second, tensile stress and strength of both slag and fly ash concretes were the same, pointing out that there is no clear different cracking tendency between these two concrete types. Third, the slag concrete did not crack when it reached the room temperature which contradicts the fact that slag concrete cracks in massive concrete structure. Therefore, this condition is not a criterion for describing the property of slag and fly ash in real massive structure.

In the high temperature case, the most striking observation to emerge from the data is that the temperature rise of slag and OPC concrete were almost exactly the same. Moreover, slag concrete indeed cracked suddenly before reaching the room temperature. Therefore, this condition should be good enough to describe the real slag and fly ash concretes' property in massive concrete structure.

4.6 Thermal cracking evaluation

In general, concrete that possesses high cracking resistance in extreme condition including temperature and restraint degree always shows high cracking resistance in less extreme condition as well. Since the temperature condition in the high temperature rise case was severer than in moderate temperature rise and the restraint condition was the same, it was considered as the most extreme condition. Therefore, the result from this case will be used to evaluate the cracking sensitivity of the concrete. Nonetheless, the OPC concrete is very common used in construction field and well known possessing high cracking sensitivity. Thus, in order to assess how strong slag and fly ash can resist the thermal cracking, OPC is used as reference.

In regards to slag concrete, the temperature rise was comparable to OPC concrete. However, tensile stress development rate was higher. In addition, it cracked at high temperature of 29°C before its temperature return to the room temperature while OPC concrete did not. Therefore, it can be concluded that slag concrete possess higher cracking sensitivity than the case of OPC concrete.

In case of fly ash concrete, even though the temperature rise was very low, tensile stress development rate was as high as the case of OPC concrete. On the other hand, when concrete temperature returned to the room temperature, the final tensile stress, 2.3MPa, was similar to the tensile strength, 2.5MPa. The difference between tensile stress and strength indicated that crack almost took place. Furthermore, the cracking temperature, 20°C, was higher than the case of OPC, 15°C.Therefore it can be deduced that the cracking resistance of fly ash concrete is comparable to the case of OPC concrete.

5. CONCLUSIONS

(1) Non-appearance of micro crack in high temperature rise is attributable to the acceleration of tensile strength improvement.
(2) The high tensile stress in high temperature rise condition was mainly due to an increase in volumetric shrinkage preceded by an increase in thermal contraction and autogeneous shrinkage and relaxation reduction
(3) Slag and fly ash reduce the stiffness of concrete
(4) Slag possesses a highest thermal cracking sensitivity while fly ash cracking resistance is similar to that of OPC concrete.

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