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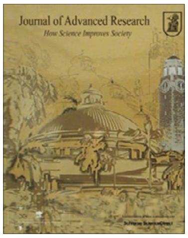

ORIGINAL ARTICLE

Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures

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Abstract Normal strength (NSC) and high-performance concretes (HPC) are being used extensively in the construction of structures that might be subjected to elevated temperatures. The behaviour of concrete structures at elevated temperatures is of significant importance in predicting the safety of structures in response to certain accidents or particular service conditions. This paper deals with the mechanical properties of concrete made with ground granulated blast furnace slag (GGBFS) subjected to temperatures up to 350 °C. For this purpose, normal concrete having compressive strength of 34 MPa was designed using GGBFS as partial replacement of cement. Cylindrical specimens (150 × 300 mm) were made and subjected to temperatures of 100, 200 and 350 °C. Measurements were taken for mass loss, compressive strength, splitting tensile strength, and modulus of elasticity. This investigation developed some important data on the properties of concrete exposed to elevated temperatures up to 350 °C.

Introduction

The most important effects of elevated temperature on concrete are: dehydration of cement paste, porosity increase, modification in moisture content, thermal expansion, alteration of pore pressure, strength loss, thermal cracking due to incompatibility, thermal creep and thermal spalling due to excessive pore pressure [1,2]. Water distribution and transport, whether in gaseous or liquid form, play important roles in the local damage of concrete structures [3,4]. During heating, the endothermal nature of vaporisation creates locally high thermal gradients and high vapour pressure, which can lead to tensile stresses exceeding the concrete's strength [5]. The escape of chemically bounded water in the Calcium Silicate Hydrates (CSH) leads to the failure of concrete at temperatures over 450 °C. Aggregate type strongly influences the behaviour of

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concrete at elevated temperatures. The aggregate's thermal expansion is partly opposed to the drying of the cement paste. This phenomenon makes it possible to think that limestone aggregate, whose thermal coefficient of expansion is lower than that of siliceous aggregate, is more favourable to the behaviour of concrete at elevated temperatures [6]. Recent studies showed a weak influence of the kinetics and durations of heat treatment on the residual properties of the concrete [3,4,7].

Literature review

Elevated temperatures affect concrete's microstructure, strength properties, and permeability, and may result in loss of strength and/or mass and increased porosity and/or permeability.

The thermo-physical properties of concrete decreased with the increase in temperature except for the specific heat, and particularly the conductivity and the diffusivity are a 50% lower at 900 °C as compared with the values at room temperature [8]. Castillo and Durrani [9] observed a loss of about 15–20% in strength at temperatures of 100–200 °C. Diederichs et al. reported that the residual strength of concrete was below the initial strength at elevated temperatures [10]. According to Ghosh and Nasser [11], there was gradual deterioration of strength and static modulus of elasticity with a rise in temperature (21–232 °C) at all pressures (5.2–13.8 MPa). Felicetti and Gambarova [12] reported dramatic reduction in residual compressive strength, splitting tensile strength and elastic modulus at elevated temperatures up to 500 °C. Janotka and Bágel [13] revealed that there were no significant changes at temperatures up to 400 °C. Noumowe [14] concluded that after initial heating to 200 °C, and subsequent cooling, the residual compressive strength was 18–38% lower than the non-heated concrete and PP fibres did not improve the initial compressive or the residual compressive strength of the concrete.

There was significant reduction in the weight of the specimen and the relative strength of the concrete at elevated temperatures (200–1200 °C) [15]. There was no obvious explosive spalling found in high-performance concrete (HPC) with blast furnace slag (BFS) at temperatures of 20–800 °C [16]. Xiao and Falkner [17] implied that BFS may contribute somewhat to the residual compressive strength of HPCs at elevated temperatures. Xiao and König [18] mentioned that strength, elastic modulus and peak strain, etc., degraded with increases in temperature, and the mechanical behaviour of concrete under high temperature was better than that after high temperature.

Concretes containing slag as a partial replacement of cement (up to 40%) had higher compressive and flexural strengths casting and curing at +42°C than those of concretes made with Portland cement alone [19]. Wang and Chen [20] observed that (i) the 7-day compressive strengths of mortars with a water-to-cementitious material ratio of 0.44 were almost proportional to the proportions of Portland cement; (ii) the contribution of GGBFS to the strength gain over 7–28 days, and also over 28–56 days, were the largest. Mahdy et al. [21] observed that, as the temperature increased to 100 °C, the strength of heavy weight high strength concrete decreased compared to the room temperature strength. At the temperatures of 500 and 700 °C, the strength in each case dropped sharply. Phan et al. [22] indicated that HPCs with higher original strength (lower w/cm) and with silica fume retained more residual strength after elevated temperature exposure than those with lower original strength (higher w/cm) and without silica fume. Janotka and Nürnbergerová [23] concluded that the strength, elasticity modulus and deformation of concrete were irreversibly influenced by temperature elevation, mainly to 100 and 200 °C.

Research significance

Investigation of mechanical properties of concrete subjected to elevated temperatures is very useful in the design of nuclear structures. Type of cement and supplementary cementing materials such as GGBFS play an important role in mechanical behaviour of concrete. Ground granulated blast furnace slag (GGBFS) has become an important constituent material for the design of normal strength and high-performance concrete. Existing literature does not provide the detailed investigation of the residual mechanical properties at high temperatures of concrete made with GGBFS. The findings of this investigation will help in predicting the behaviour of concrete made with GGBFS aggregates intended for nuclear or similar applications.

Experimental

Materials

Ordinary Portland (53 grade) cement was used and its properties are given in Table 1. It met the requirements of Indian Standard Specifications IS: 8112-1989 [24]. Natural sand with a 4.75-mm maximum size was used as a fine aggregate. Coarse aggregates used in this study were of 10 mm nominal size. They were tested as per Indian Standard Specifications IS: 383-1970 [25] and their physical properties are given in Table 2. Ground granulated blast furnace slag (GGBFS) was obtained from Nippon Denro Ispat Ltd., India. Its properties are given in Table 3. Sikament 170, a concrete superplasticizer based on Sulphonated Naphthalene Polymer, was used as a water-reducing admixture. The dosage of superplasticizer taken was 1.1% by weight of cement.

Mixture proportions

One control mixture (M-0) was designed per Indian Standard Specifications IS: 10262-1982 [26] to have 28-day compressive

Table 1 Properties of cement.

Physical test	Results obtained	IS: 8112-1989 Specifications
Normal consistency (%)	34	–
Initial setting time (minutes)	48	> 30
Final setting time (minutes)	240	< 600
Fineness (%)	3.0	< 10
Specific gravity	3.10	–
Compressive strength (MPa)		
7-day	21.9	
28-day	34.5	

Table 2 Properties of aggregates.

Property	Fine aggregate	Coarse aggregate
Type	Uncrushed	Crushed
Maximum size (mm)	4.75	10
Specific gravity	2.19	2.6
Total water absorption (%)	4.88	2.32
Fineness modulus	1.75	6.17

strength of 34.8 MPa. The other concrete mixtures, viz. M-1 to M-3, were made with replacement levels of 20%, 40%, and 60% of GGBFS by weight of cement. In doing so, the water-to-cementitious materials ratio was kept the same in order to investigate the effects of replacing cement with GGBFS when other parameters were unchanged. The mixture, designation and quantities of the various materials for each designed concrete mixture are given in Table 4.

Preparation and casting of specimens

Cylindrical moulds of size 150 × 300 mm were used to prepare the concrete specimens for the determination of compressive strength, splitting tensile strength and modulus of elasticity of concrete. All specimens were prepared in accordance with Indian Standard Specifications IS: 516-1959 [27]. Moulds were cleaned and oiled properly. They were securely tightened to correct dimensions before casting. Care was taken that there were no gaps, so as to avoid the possibility of leakage from the slurry. The specimens were allowed to remain in the steel mould for the first 24 h at ambient conditions. They were then demoulded with care so that no edges were broken and placed in the curing tank at the ambient temperature. The ambient temperature for curing was 27 ± 2 °C.

Table 3 Properties of GGBFS.

Properties	GGBFS Specification	Requirements as per BS: 6699
Fineness (m^2/kg)	340	275 (min.)
Soundness Le-Chatelier expansion (mm)	1.5	10.0 (max.)
Insoluble residue (%)	1.5	1.5 (max.)
Magnesia content (%)	12.0	14.0 (max.)
Sulfide sulfur (%)	1.7	2.00 (max.)
Sulfite content (%)	2.5	2.50 (max.)
Loss on Ignition (%)	1.0	3.00 (max.)
Manganese content (%)	1.0	2.00 (max.)
Chloride content	0.05	0.10 (max.)
Moisture content	1.0	1.0 (max.)
Glass content (%)	90	67 (min.)
Compressive strength (MPa)		
7 days	25	12.0 (min.)
28 days	40	32.5 (min.)
Chemical moduli		
(a) $CaO + MgO + SiO_2$	70	66.66 (min.)
(b) $CaO + MgO/SiO_2$	> 1.0	> 1.0
(c) CaO/SiO_2	< 1.4	< 1.4

Heating and cooling regimes

After curing for 28 and 56 days, the specimens were taken out of the tank and air-dried. Then the specimens were heated in an electric oven up to 100, 200, and 350 °C. The heating rate was set at 8 °C/min. The temperature was maintained at the respective temperature for 1 h to achieve a thermally steady state. Then the furnace door was opened and the specimens were allowed to cool naturally to room temperature.

Testing procedures

Concrete cylinders, 150 × 300 mm, were tested for the determinations of compressive strength, split tensile strength and modulus of elasticity of concrete as per Indian Standard Specifications IS: 516-1959 [27] in a fully computerised servo-controlled universal testing machine of maximum compression capacity 1000 KN. A uniaxial compressive load was applied at a rate of 0.5 MPa/s or with a load speed of 235.62 KN/min, in the direction of the central axis of the specimen.

Results and discussion

Mass loss

Mass loss measurements were recorded between 27 and 350 °C, and the results are given in Table 5. Mass loss increased with the increase in temperature. Below 100 °C, generally little mass loss is observed, since abundant free water is not left in the hardened and dried concrete specimens. When temperature is raised from 100 to 350 °C, the mass loss is little

Table 5 Mass loss of GGBFS concrete.

Testing age (days)	Temperature exposure	GGBFS content (%)			
		0	20	40	60
28	100 °C	0.5	1.0	1.5	2.5
	200 °C	1.5	2.5	3.0	3.0
	350 °C	3.0	3.0	4.0	5.0
56	100 °C	0.5	1.5	1.5	2.5
	200 °C	1.5	2.5	3.0	4.0
	350 °C	2.5	3.0	4.5	6.0

Table 4 Mixture proportions.

Mixture	Cement (kg/m^3)	GGBFS (kg/m^3)	Fine agg. (kg/m^3)	Course agg. (kg/m^3)	Water (l/m^3)	Plasticizer (l/m^3)	Slump (mm)
M-0	450	0	482	1040	203	4.95	100
M-1	360	90	482	1040	203	4.95	90
M-2	270	180	482	1040	203	4.95	85
M-3	180	270	482	1040	203	4.95	75

more owing to the release of both capillary water and gel water. When the heating is continued beyond 200 °C, then a portion of water in hydrated products escapes. It was noticed that the water loss for the specimens heated at 100 °C was three times lower than that measured in the specimens heated at 200 and 350 °C. This confirms the small proportion of free water in this concrete compared to the hydrated concrete's water content.

Compressive strength

Compressive strength test results are shown in Figs. 1 and 2.

Effect of replacement of cement with GGBFS

It is evident from these results that the compressive strength of concrete mixtures decreased with the increase in GGBFS content at normal temperature (27 °C) and 350 °C. At room temperature (27 °C), 28-day compressive strength of concrete containing 20%, 40% and 60% GGBFS was respectively 16.8%, 23.9% and 28.5% lower than the control mixture (34.8 MPa). Similar findings were reported by Ujhelyi and Ibrahim [19] and Dehuai and Zhaoyuan [20]. Ujhelyi and Ibrahim [19] reported 14.9%, 17.0% and 42.5% loss in 28-day compressive strength as compared to the control (47 MPa) at 10%, 20% and 40% GGBFS contents, respectively. A similar trend was also observed by Dehuai and Zhaoyuan [20] wherein they reported 21.2%, 25.8% and 36% loss in 28-day compressive strength as compared to the strength of the control (51.9 MPa) at 35%, 50% and 70% GGBFS content, respectively. But at 100 and 200 °C and at both the ages, the compressive strength increased at 20% GGBFS content and then decreased afterwards.

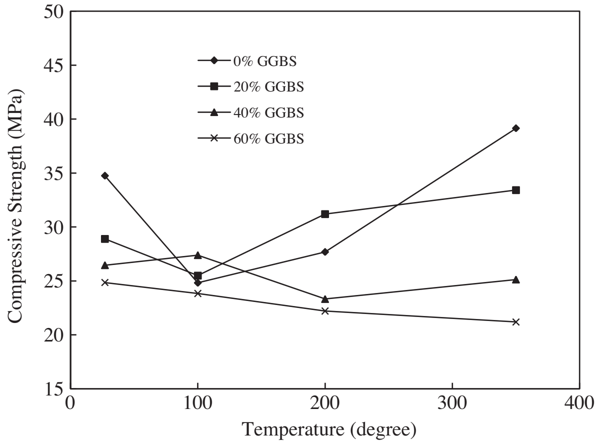

Fig. 1 Effect of temperature on the compressive strength of concrete at the age of 28 days.

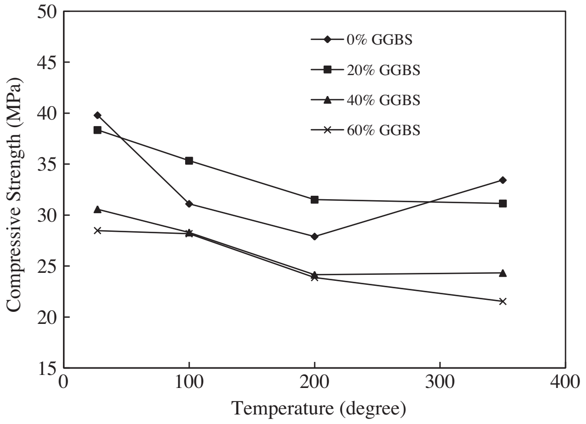

Fig. 2 Effect of temperature on the compressive strength of concrete at the age of 56 days.

Effect of temperature on 28-day compressive strength

Fig. 1 shows that at 28-days, with 0% GGBFS, the residual compressive strength of concrete at 100 °C dropped by 28.6% as compared to room temperature strength (34.8 MPa). The reduction could be due to the stresses generated at the interface between the aggregate and the hardened cement paste on heating. The difference between the thermal expansion of the cement paste and the aggregate could result in micro-cracking and disruption of the cement-aggregate bond with a consequent reduction in strength. As the temperature increased beyond 100 °C, the compressive strength increased a little but was still lower than that of room temperature strength and it increased further, by 12.6%, at 350 °C. This increase was considered to be mainly due to rapid drying of the concrete, which increased its strength. Xiao and König [18], Mahdy et al. [21] and Phan et al. [22] reported similar findings. Xiao and König [18] had explained in one graph this trend through the work of four researchers (Li and Guo [28]; Lu [29]; Niu et al. [30]; and Yao [31]), each showing the same type of trend, i.e. decrease in strength at 100 °C, then some increase at 200 °C and further increase at 300 °C. According to Mahdy's [21] investigations, the compressive strength decreased at 100 °C by 28% as compared to room temperature strength (99.72 MPa). With a further increase in temperature to 300 °C, the specimens recovered the strength loss and reached peak strength of 18% above room temperature strength.

A similar trend was observed with 20% replacement of cement by GGBFS at 28-days, i.e. a decrease in compressive strength by 11.8% at 100°C and then an increase by 8% at 200°C and another increase, by 15.6%, at 350°C, as compared to room temperature strength (28.9 MPa). But at 40% and 60% replacements of cement with GGBFS at 28-days, the relative residual compressive strength did not change significantly with rises in temperature, and thus maintained their original compressive strengths. This implies that GGBFS may contribute to some extent to the residual compressive strength of concrete at elevated temperatures. Similar findings were reported by Xiao and Falkner [17]. Therefore, from these investigations we can conclude that at 20% GGBFS content, the rate of strength loss of concrete is less as compared to the concrete containing no GGBFS and at 40% and 60% GGBFS content there is no strength loss.

Effect of temperature on 56-day compressive strength

Fig. 2 shows that at 56-days, the residual compressive strength decreased with the increase in temperature at all percentages of GGBFS. At 0% replacement, the residual compressive strength decreased by 21.9%, 29.9% and 16% at 100, 200 and 350 °C, respectively when compared to normal temperature strength (39.8 MPa). Similarly, the residual compressive strength decreased at all other percentages of GGBFS with increases in temperature. But the decrease was comparatively less than in the concrete containing no GGBFS. Degradation of mechanical properties of this concrete between room temperature and 100 °C was very limited. But at 200 and 350 °C, there was a significant reduction in compressive strength, ranging between 16–30% at 20%, 40% and 60% replacement of cement by GGBFS. This is probably because when the temperature was raised to 200 and 350 °C, the water loss was very significant. The modification of hydrates generated a degradation of the concrete microstructure.

Splitting tensile strength

Splitting tensile strength test results are shown in Figs. 3 and 4.

Effect of replacement of cement with GGBFS

It is evident from these results that the 28-day splitting tensile strength of concrete at room temperature (27 °C) decreased with increases in GGBFS content. The splitting tensile strength of concrete containing 20%, 40% and 60% GGBFS was respectively 17.4%, 8.2%, and 15.6% lower than the control (3.2 MPa) at room temperature.

Effect of temperature on splitting tensile strength

The splitting tensile strength of concrete decreased with the increase in temperature (Figs. 3 and 4). At 28 days (Fig. 3), the splitting tensile strength of concrete containing 20% GGBFS content at 100, 200 and 350 °C was respectively 17.68%, 21.0%, and 28.9% lower than the concrete at room temperature (2.94 MPa). Similar trends were observed with concrete containing 40% and 60% GGBFS. It is evident from Fig. 4 that a similar trend was found at 56 days. The loss in split tensile strength is very pronounced, which is different from the more gradual loss of compressive strength. This is because the tensile strength is more sensitive to cracks either on a macro- or micro-scale, which are caused by concrete becoming subject to high temperatures.

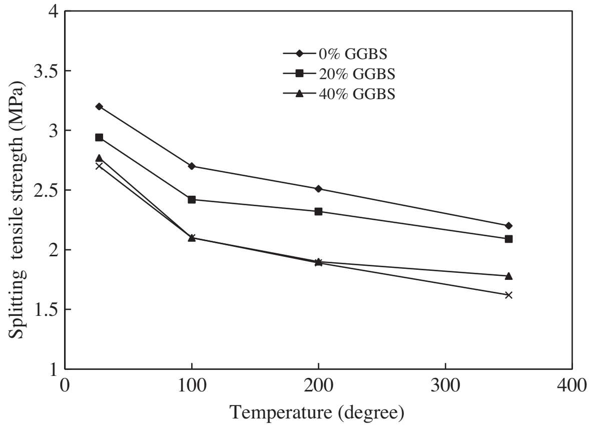

Fig. 3 Effect of temperature on the splitting tensile strength of concrete at the age of 28 days.

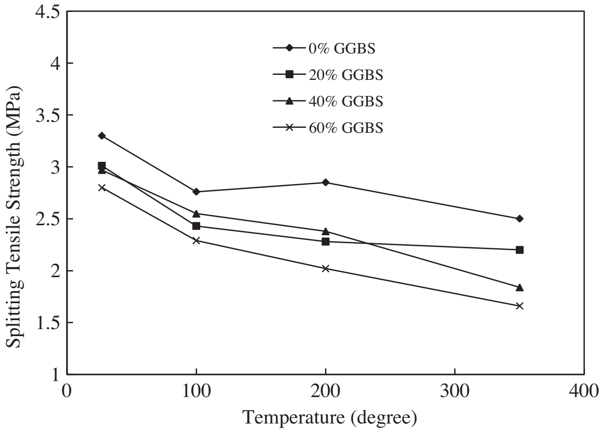

Fig. 4 Effect of temperature on the splitting tensile strength of concrete at the age of 56 days.

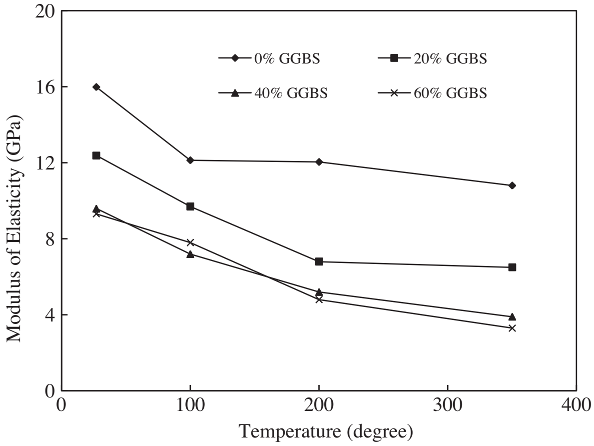

Fig. 5 Effect of temperature on the modulus of elasticity of concrete at the age of 28 days.

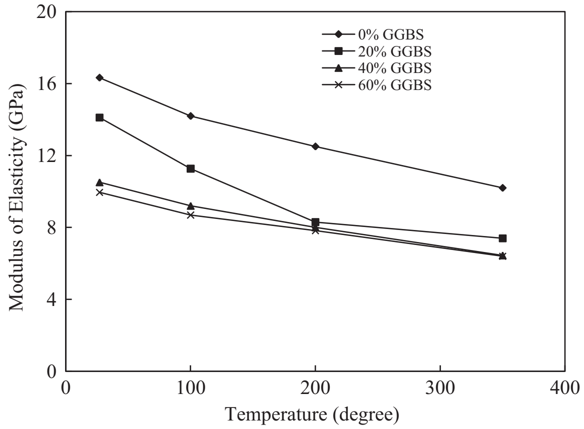

Fig. 6 Effect of temperature on the modulus of elasticity of concrete at the age of 56 days.

Modulus of elasticity

In this investigation, the modulus of elasticity, which is also called the secant modulus, is taken as the slope of the chord from the origin to some arbitrary point on the stress–strain curve. The secant modulus calculated in this study is at 33% of the maximum stress. The modulus of elasticity of concrete mixtures was determined at the ages of 28 and 56 days. The results are shown in Figs. 5 and 6.

Effect of replacement of cement with GGBFS

It is evident from these results that the 28-day modulus of elasticity of concrete at room temperature (27 °C) decreased with increases in GGBFS content. The modulus of elasticity of concrete containing 20%, 40% and 60% GGBFS was respectively 22.5%, 39.98% and 41.7% lower than the control (15.98 GPa) at room temperature.

Effect of temperature on modulus of elasticity

Fig. 5 shows the variation of modulus of elasticity with temperature at 28-days. The modulus of elasticity of concrete decreased with increases in temperature. At 0% GGBFS content, the modulus of elasticity of concrete at 100, 200 and 350 °C was respectively 24.1%, 24.6% and 32.5% lower than the control (15.98 GPa). Similar tends were observed with concrete made with 20%, 40%, and 60% GGBFS.

Fig. 6 shows the variation of modulus of elasticity with temperature at 56 days. The modulus of elasticity of concrete decreased with increases in temperature at 56 days at all percentages of GGBFS content. At 0% GGBFS content, the modulus of elasticity of concrete at 100, 200 and 350 °C was respectively 13.1%, 23.4% and 37.5% lower than the control (16.32 GPa). At 20% GGBFS content, the modulus of elasticity of concrete at 100, 200 and 350 °C was respectively 20.13%, 41.2% and 47.6% lower than the concrete at room temperature (14.11 GPa). At 40% GGBFS content, the modulus of elasticity of concrete at 100, 200 and 350 °C was respectively 12.5%, 23.9% and 38.7% lower than the concrete at room temperature (10.51 GPa), and at 60% GGBFS content, the modulus of elasticity of concrete at 100, 200 and 350 °C was respectively 12.7%, 21.4% and 35.7% lower than the concrete at room temperature (9.95 GPa).

Conclusions

Based on the results obtained, the following conclusions can be drawn:

Concrete containing GGBFS could possibly be used in applications involving elevated temperatures. There was no very significant deterioration of the mechanical properties of the concrete between 27 and 100 °C. Reduction in the values of compressive strength, splitting tensile strength and modulus of elasticity remained lower than 40% of the initial value even after a temperature of 350 °C was applied. At temperatures between 200 and 350 °C, the mass loss is not very significant. The modification of the hydrates generates a degradation of the concrete microstructure. From the results it can be easily concluded that up to 20% GGBFS could be suitably used in concrete designed for nuclear structures. However, more investigations are needed on other parameters such as thermal behaviour, porosity, and permeability aspects. These results could be useful in further investigating the behaviour of concrete made with GGBFS at elevated temperatures.

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