LOAD INDUCED THERMAL STRAINS IN ULTRA HIGH PERFORMANCE CONCRETE AT ELEVATED TEMPERATURE

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Abstract

This study reports the results of an investigation of a steel fibre-PVA hybrid UHPFRC mix under elevated temperature. A specially designed furnace loading frame was assembled, facilitating simultaneous heating and loading of the specimens. The specimens consisted of 100 mm diameter by 200 mm high cylinders. The cylinders were first loaded in compression to their specified load of zero or 14 per cent or 28 per cent of their strength measured under ambient conditions and then gradually heated to 600^{o}C. The changes in strain were measured; the free thermal strains were found to be similar to that of a siliceous aggregate concrete and the ‘transitional thermal creep’ are significant when the temperature increases above 250^{o}C.

Résumé

Cet article présente les résultats de l'étude d'une formule de BFUP hybride comportant des fibres en acier et PVA. Une presse couplée à un four a été spécialement conçue pour faciliter le chargement simultanément thermique et mécanique des échantillons, consistant en des cylindres de diamètre 100 mm et hauteur 200 mm. D'abord chargés en compression jusqu'à une charge spécifiée de 0, 14 ou 28 % de leur résistance à température ambiante, ils ont ensuite été chauffés progressivement jusqu'à 600 °C. La déformation a été mesurée. Les déformations thermiques libres se sont avérées similaires à celles d'un béton de granulats siliceux, et le fluage thermique transitoire est apparu important lorsque la température dépasse 250°C.

1. INTRODUCTION

Concrete is generally regarded as a material that performs well in high temperature environments, as compared to materials such as steel and timber. However, some concretes, high-strength concretes (HSC), show explosive spalling during heating, which can significantly affect the performance of structural elements fabricated with these materials. This spalling is caused mainly by the build-up of pore pressures and thermal stresses [1]. Limited experiments, however, are reported in the literature on the behaviour of UHPFRC under elevated temperatures [2-4]. Pimienta *et al.* [4] summarise the results of a number of commercial UHPFRC mix under high temperature and conclude that the thermal and mechanical properties at high temperatures vary disparately.

Explosive spalling in normal strength concrete is unlikely to occur if the free moisture content is below 3 or 4 % [5]. While studies on the micro-structure of UHPFRC show an absence of capillary porosity [6], the volume of free water, which leads to explosive spalling in HSC, is low. However, Hertz, [7] reported that high strength and ultra-high strength concretes, which are achieved by tight particle packing, can suffer explosive spalling even in their dry state.

In a study by Sanchayan et al. [8], it was demonstrated that at temperatures above 400^{o}C, steel fibre (SF) UHPFRC is prone to explosive spalling of a violent nature. They showed that at temperatures of about 400^{o}C, unloaded 200 mm high by 100 mm diameter SF-UHPFRC cylinders, both with and without pre-conditioning through oven drying, exploded violently (Figure 1a and 1b); it was concluded that this is due to release of chemically bound water, combined with the low porosity of the matrix.

Sanchayan et al. [8] also observed that steel fibres in UHPFRC oxidized at temperature of 500^{o}C and above. At these temperatures, the fibres became brittle and were less effective in maintaining the integrity of the cylinders.

(a) (b)

Figure 1: Exploded cylinders of SF UHPFRC mix after heated to approximately 400^{o}C (a) not oven dried prior to testing and (b) oven dried at 105^{o}C prior to testing

When a portion of the SF was replaced with polyvinyl acetate (PVA) fibres, Sanchayan et al. [8] found that explosive spalling could be controlled. At temperatures of 500^{o}C and above, the SF-PVA UHPFRC specimens showed some cracking; however, the cylinders remained relatively intact (Figure 2). While on one hand, the addition of some PVA fibres, with a melting point below 300^{o}C, helped to lessen the problem, on the other, at temperatures above 400^{o}C SF-PVA UHPFRC suffers considerable damage to its micro-structure leading to a significant loss in stiffness.

Figure 2: Cracked cylinder of SF-PVA UHPFRC (oven dried) and heated to 500^{o}C

While generic material observations, such as those described by the tests reported above, are valuable in determining qualitative performance criteria for structures and structural elements (such as; beams, slabs, columns, walls, etc.) under fire, more detail is needed on thermal, geometric and structural aspects for design. In this study thermal strain properties are determined for an UHPFRC mix that was found to perform better under heating, with a lower propensity for explosive spalling. Thus, an objective of the study is to investigate the behaviour of a hybrid UHPFRC mix containing both steel and PVA fibres and with a compressive strength exceeding 150 MPa.

‘Load inducted thermal strains’ (LITS) have been studied for many years and consists of various components that go to describe the non-linear, creep, strain behaviour of concrete under stress at elevated temperatures. The most important of these are the ‘transitional thermal creep’ (TTC) and the ‘drying creep’ (DC), with the sum of these two components referred to as the ‘transient creep’ (TC) [9].

Dehydration is defined by to the mass loss of chemically bound water, and is separated from the drying, or vaporisation, component, which is conventionally attained for temperatures of less than 105^{o}C [10]. Beyond 105^{o}C the chemically bound water starts to be released by dehydration. Mindeguia et al. [11] made similar conclusions for high performance concrete demonstrating removal of some, or all, of the drying component for samples that were pre-heated to 80^{o}C for a period of 60 hours.

Khoury et al. [12] found that oven-dry specimens of conventional strength concrete experienced the highest total expansion for temperatures above 150^{o}C; this was said to be due to the absence of drying shrinkage. When the results of tests on specimens with different initial moisture conditions were adjusted for their initial condition, Khoury et al. [12] found that the results were similar and that the free thermal strains, at higher temperatures, develop independently of the initial moisture state. That is, the free thermal strains can be combined with drying, thermal and elastic strains to determine the total strain.

TTC may be determined by testing to establish the TC and the DC components, separately, for specimens under controlled or non-controlled initial states, or directly by the testing of specimens pre-conditioned to first remove the DC component. In this study, to ensure a consist initial state, and eliminate shrinkage strains induced through drying creep, all cylinders used in this test series were pre dried at 105^{o}C in an oven until a constant mass was attained. Thus, the resulting strains are induced by heating and loading alone and the TTC strains obtained directly. Details of the experimental programme and the results obtained are presented herein.

2. EXPERIMENTAL PROGRAMME

2.1 Materials and mix design

The materials used to make the UHPFRC mix were Type 1 general purpose cement complying with Australian Standard AS3972-2010 [13], undensified silica fume manufactured by SIMCOA, Western Australia, Sydney sand with maximum particle size of 600 µm and dried at 105^{o}C and Glenium 51 superplasticizer. The mix contained equal volumes of 13 mm long by 0.2 mm diameter steel fibres and 12 mm long by 0.2 mm diameter PVA fibres. The fibres occupied a total volume fraction of 2% (that is, 1% steel fibres and 1% PVA fibres). The steel fibres were manufactured by Dramix, Belgium, and had a reported minimum strength of 1800 MPa and an elastic modulus of 200 GPa. The PVA fibres were manufactured by Kuraray, Japan, and had a reported minimum strength of 1000 MPa, an elastic modulus of 29 GPa and a melting point of 220^{o}C.

The detailed mix data is presented in Table 1 with the quantities expressed as mass ratios relative to the mass of cement. Table 2 presents the chemical compositions of the binder materials as determined by X-ray Diffraction analysis.

Table 1: Mix design data (mass ratios)

Component	Mass Ratio
Cement	1.0
Silica fume	0.25
Sydney sand	1.1
Superplasticizer	0.062
Steel fibres	0.087
PVA fibres	0.014
Water	0.17

Table 2: Chemical Composition of binders

Composition	Cement (%)	Silica fume (%)
SiO_2	19.8	91.6
CaO	63.7	0.11
AL_2O_3	4.29	0.11
FE_2O_3	3.10	0.03
SO_3	2.7	0.02
K_20	0.67	0.28
MgO	0.12	0.35
Na_2O	0.12	0.28
Loss on ignition	3.8	6.89

2.2 Mixing and fabrication

The materials were batched using an electronic balance and mixed using a horizontal pan type mixer. The dry constituents were mixed for 10 minutes and then the water and superplasticizer were added together. Mixing was continued until an even plastic consistency had been attained. The fibres were then sprinkled into the mix and mixing was continued for another 5 minutes.

Cylinders of 100 mm diameter and 200 mm high were cast in steel moulds and were stored in a controlled environment room at 50% relative humidity (RH) and 23^{o}C for a period of 24 hours. After 24 hours, the cylinders were de-moulded and cured for a further 72 hours at 85^{o}C in a hot water bath. At the end of the curing period, the cylinders were removed from the hot water bath and stored in the controlled environment room at 50% RH and 23^{o}C until the time of testing.

The mean compressive strength obtained for the batch was 158 MPa. The elastic modulus was 43 GPa.

2.3 Testing apparatus

The tests were conducted in a specially designed furnace-loading-frame to facilitate simultaneous heating and loading of the cylinders. The apparatus consisted of a vertical single zone split type furnace, which can be used to heat up to a maximum temperature of 1220^{o}C, and a stiff 1 MN Instron servo-hydraulic controlled testing frame (Figures 3 and 4). The load was transferred from the frame to the specimens using Nickel Alloy 625 loading rods and platens that can tolerate high temperatures. Ultra high strength concrete blocks were used between the loading rods and the frame to safeguard the frame from heat and the loading rods were also insulated using thermal blankets. A spherical seat was placed between the upper loading plate and the upper insulation block. A high temperature extensometer was used to measure the strain (Figures 3a) and the load and strain data were captured using a TMR 211 data logger.

Strains were measured using a furnace mounted extensometer manufactured by Epsilon model-3548, as shown in Figure 3a. Both thermal and mechanically induced strains are measured while the specimens are under load.

(a) (b)

Figure 3: Arrangement of the furnace: (a) open showing high temperature extensometer; (b) closed during testing.

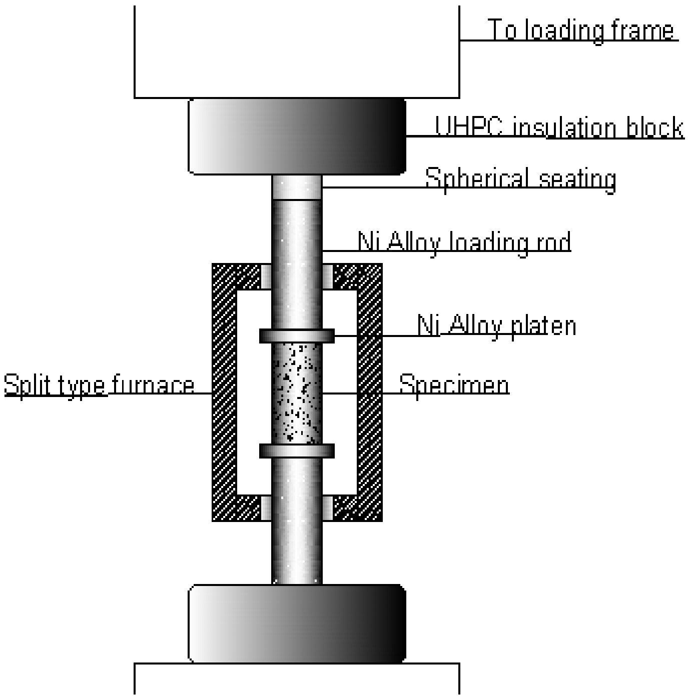

Figure 4: Schematic of the furnace and the loading frame

2.4 Testing procedure

The cylindrical specimens were loaded to their initial state under ambient laboratory conditions (approx. 20^{o}C). The loading levels adopted in this study were zero, 14.2 % (22.5 MPa) and 28.4 % (45.0 MPa) of the strength that was measured under ambient conditions and the loads, once applied, were maintained for the remainder of the test.

Once the initial load state was attained, the specimens were next heated at a rate of 2^{o}C/min under this constant load until the final temperature of the furnace was at 600^{o}C, noting that the temperature measured on the surface of the specimens is slightly less than that of the furnace itself. The on-specimen temperatures were measured using a thermocouple attached at the mid-height of the cylinder; the temperatures reported in the following results are the on-sample temperatures.

The strains reported in the following sections are the change in strain measured after the initial loading was applied at the room temperature. Two cylinders were tested for each loading level and the results reported below are the average of the two tests.

3. RESULTS AND DISCUSSION

Figure 5 shows the evolution of axial thermal strain of UHPFRC cylinders when subjected to heating to 600^{o}C under constant loading. The strains are presented as a function of the surface temperature of the cylinder. Positive strains indicate expansion; negative strains indicate contraction. As outlined, three constant loading levels were considered, 0 %, 14 % and 28 % of the mean compressive strength obtained at ambient conditions. The results show a very different behaviour depending on the level of the applied load. For the zero loading condition, the specimen expands freely due to heat, and the ‘free thermal strains’ (FTS) were measured.

When the specimens were heated while under load, initially they underwent thermal expansion; subsequently, after temperatures reach 200^{o}C to 250^{o}C, the cylinders contracted. This is as expected due to the changing strains under mechanical loading caused by the deterioration of the elastic modulus at high temperature and the effect of basic creep. However, the strain was found to be much greater than can be explained by those effects alone; this increased strain is due to the ‘transitional thermal creep’ (TTC) [12, 14]. It is reported that TTC occurs due to dehydration of CSH and CH phases in concrete and it is peculiar to cementitious materials during virgin heating [12].

The TTC is calculated as the difference between FTS, measured without load, and strains measured under the constant loading. The results, presented in Figure 6, show the dependence on stress level; higher applied stress resulting in higher transient creep. The behaviour of the TTC for UHPFRC determined from this study is similar to that reported for other cementitious materials by Khoury, et al. [12] and becomes significant above temperatures of 250^{o}C. The TTC continues to increase with increasing temperature and the average coefficient of thermal contraction due to TTC is calculated as 2.7×10^{-5} per ^{o}C for the 14 % load case and 4×10^{-5} per ^{o}C for the 28 % load case.

Figure 7 compares the FTS of UHPFRC with that of siliceous and calcareous aggregate concretes, as given in the model in BS EN 1992-1-2-2004 [15]. From the figure it is observed that the behaviour of UHPFRC is similar to that of siliceous aggregated concrete.

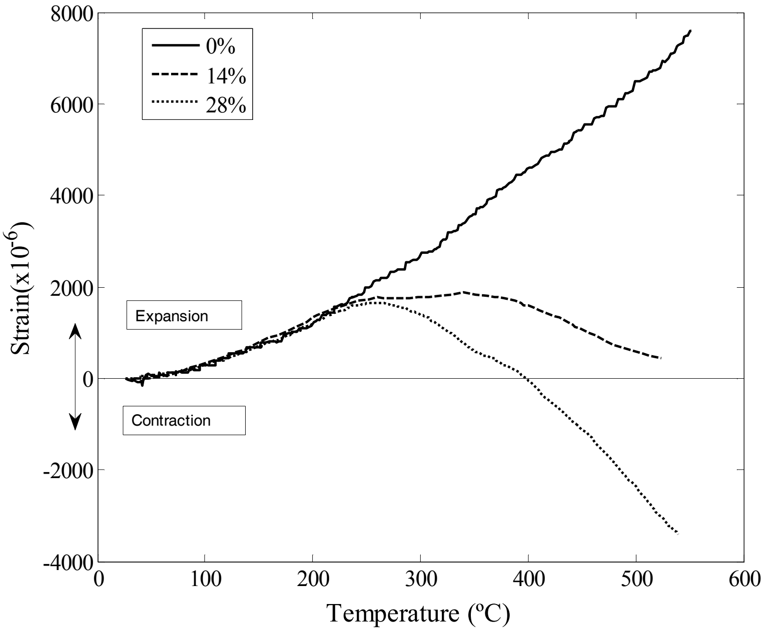

Figure 5: Thermal strains under heating with constant loading

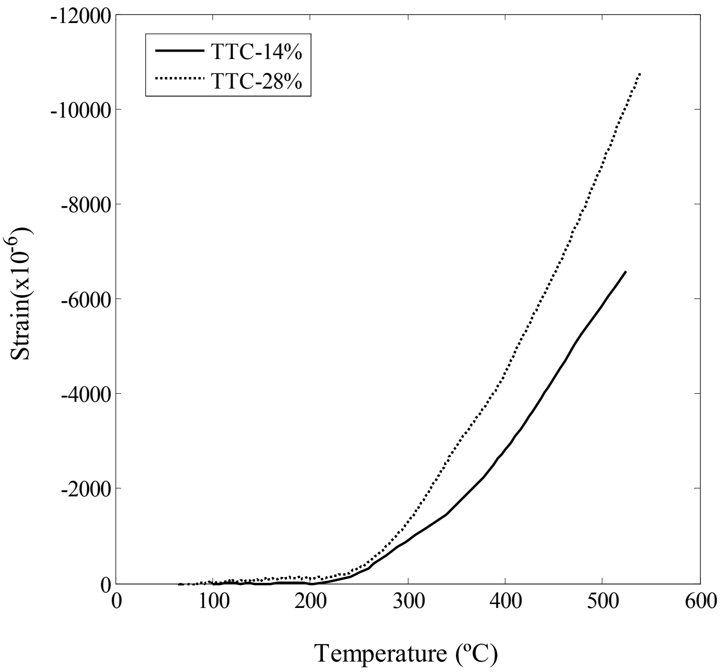

Figure 6: Transitional Thermal Creep (TTC)

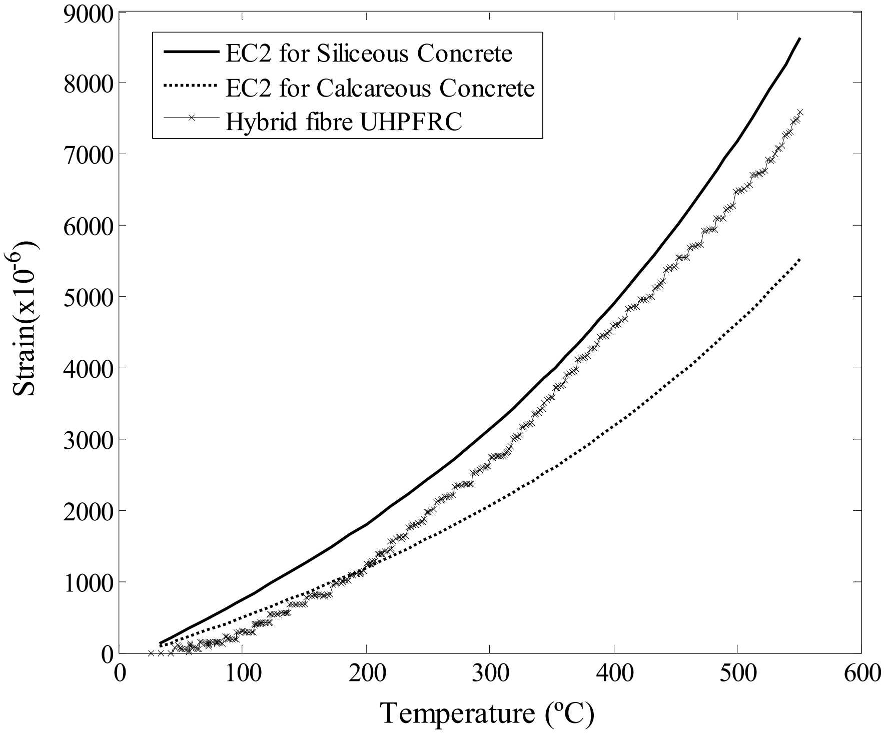

Figure 7: Comparison of thermal strains of hybrid fibre UHPFRC with given values for siliceous and calcareous aggregate concretes in BS EN 1992-1-2-2004 [15]

4. CONCLUSIONS

This research studied the transient thermal strain behaviour of PVA-steel fibre reinforced UHPFRC subjected to high temperatures. The thermal strains were measured for the UHPFRC cylinders with applied loads of zero, 14 % and 28 % of the strength measured at ambient conditions, while the temperature was increased from ambient to 600^{o}C at the rate of 2^{o}C/min. With the thermal strains measured for the different loading conditions, the 'load induced thermal strains' were then calculated for the 14 % and 28 % load cases.

The following observations are made and conclusions drawn:

- Free thermal strains of the hybrid steel-PVA fibre UHPFRC were found to be similar to that of a siliceous aggregate concrete; and
- Load induced thermal strains (TTC) are significant when the temperature rises above 250^{o}C.

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