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# High temperature material properties of calcium aluminate cement concrete

Wasim Khaliq *, Hammad Anis Khan

*National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan*

## HIGHLIGHTS

- High temperature properties of calcium aluminate cement concrete were evaluated.
- CACC exhibited better compressive and tensile strength in 20–800 °C range.
- Elastic modulus and stress–strain response indicate a better performance of CACC.
- Compressive toughness property showed improved response in CACC up to 800 °C.
- Visual and microscopic assessment helped understand microstructure of CACC.

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## ABSTRACT

In this study, material properties of calcium aluminate cement concrete (CACC) were investigated at various temperatures of 23, 200, 400, 600 and 800 °C. Material properties namely compressive strength, splitting tensile strength, elastic modulus, stress–strain response, mass loss and compressive toughness were measured using unstressed and residual test methods. High temperature performance of CACC was compared with conventional normal strength concrete (NSC). Data from high temperature tests of CACC revealed that the presence of alumina as a binding agent showed considerable enhancement in the mechanical performance compared to NSC. At elevated temperatures, reduction in the stress–strain response was observed in both CACC and NSC; however, increase in axial strain was more in case of CACC. Compressive toughness was higher in case of CACC as compared to NSC which increases up to 200 °C, but decreases beyond this temperature. Scanning electron microscope (SEM) was used to differentiate the microstructural changes in both types of concrete at temperatures up to 600 °C. Visual investigations after high temperature exposure revealed that CACC exhibits low cracking with less color changes as compared to NSC. Data generated from material property tests was utilized to develop simplified relations for expressing material properties of CACC as a function of temperature.


## 1. Introduction

Fire is one of the most severe hazards to which structures may be exposed. The exposure of concrete to elevated temperatures causes major physical and chemical transformations [1,2], resulting in disintegration and deterioration of concrete. This leads to loss of strength, cracking and spalling of concrete. Moreover, higher temperatures cause gradual destruction of bonds between aggregate and cement paste [2], resulting in inferior structural performance. Proper fire safety provisions as per building codes should be provided to ensure safe performance of structures against fire [3]. The high temperature properties of concrete are, therefore, of utmost importance to evaluate fire performance of different concrete structural systems. The high temperature material properties that are desired for fire resistance evaluation of concrete structures are thermal, mechanical, deformation, and material specific properties such fire induced spalling and mass loss [4]. The thermal properties consisting of specific heat, thermal conductivity, thermal diffusivity, and thermal expansion are important material properties that effect the development of thermal response of concrete structural members. The mechanical properties such as strength, deformation and elastic modulus are important material properties that significantly influence fire response of structural systems [5].

The performance of conventional concrete against elevated temperatures is extensively studied and its properties are well

* Corresponding author.
*E-mail addresses:* wasimkhaliq@nice.nust.edu.pk (W. Khaliq), hammadaniskhan@hotmail.com (H.A. Khan).

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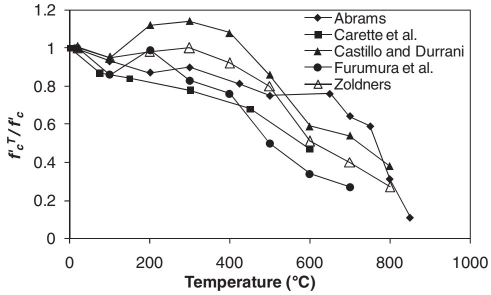


**Fig. 1.** Variation of relative compressive strength of NSC as a function of temperature [6–8,13].

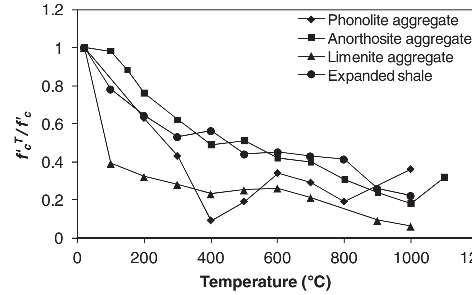


**Fig. 2.** Strength variation of CACC with different aggregate as a function of temperature [26].

established [6–12]. The high temperature material properties of concrete depend on mix design, type of aggregate, water-cement ratio, curing conditions and loading conditions [11]. Fig. 1 shows the ratio of compressive strength at elevated temperature to that at room temperature ($f'^T_c/f'_c$) for traditional normal strength concrete (NSC) having limestone based coarse aggregate [6–8,13,14]. The loss of strength of NSC is linked to the physical and chemical changes within microstructure of concrete which results in deterioration of hydrated products. At temperatures up to 300 °C, minor cracks in the microstructure were observed with the increase in the size of the pores. Above 400 °C, calcium hydroxide $Ca(OH)_2$ which forms a major portion in the hydrated products of concrete starts to disintegrate [15]. Further, at 600 °C the calcium silicate hydrate (C–S–H) gel, which binds the ingredients of concrete as cement paste and gives the strength to the concrete, starts to crumble [2,16,17]. This decomposition is aggravated around 800 °C, causing complete deterioration of microstructure and major loss to the material properties of the concrete [8,18].

Owing to the research and advancements in concrete technology, different types of high performance concrete (HPC) have emerged having excellent performance in terms of strength and durability, surpassing average performance of conventional NSC. Calcium aluminate cement concrete (CACC) is a type of HPC having calcium aluminate cement (CAC) as a main binder instead of ordinary Portland cement (OPC). It has applications not only in infrastructural works like sewerage networks but also in hydraulic dams, where resistance to abrasion is essential. Experimental data obtained after exposing the CAC pastes and mortars to chemically aggressive environment and biogenic corrosion confirmed its efficiency and its ability to provide long term service in these conditions [19]. Moreover, its performance in terms of rapid hardening and strength development is also recognized due to which CAC is also preferred as a repair material. Compared to OPC, CAC can give 28 days strength equivalent of OPC just in 5–6 h [20]. It is also a preferred choice as a refractory material i.e. in the lining of the kilns and steel industry [21].The mineralogy of CAC shows that calcium oxide (CaO) and alumina ($Al_2O_3$) are the principal oxides. Depending upon their percentage within CAC, they combine to give monocalcium aluminate (CA) as major active phase. This active phase reacts with water to give calcium aluminate hydrates. However, unlike portland cement, the formation of CAC hydrates depends upon the availability of moisture and environmental temperature [22]. Calcium aluminate decahydrate ($CAH_{10}$) is usually formed below 15 °C, which convert to dicalcium aluminate octahydrate ($C_2AH_8$) and gibbsite ($AH_3$) with the increase in temperature. However, $CAH_{10}$ and $C_2AH_8$ are metastable in nature and convert to stable tricalcium aluminate hexahydrate ($C_3AH_6$) and $AH_3$ with the liberation of water at temperatures above 27 °C. This process is known as conversion reaction and is described in Eqs. (1) and (2) below. This reaction is inevitable and its rate depends upon temperature and availability of moisture [19].

$$2CAH_{10} \rightarrow C_2AH_8 + AH_3 + 9H \quad (1)$$

$$3C_2AH_8 \rightarrow 2C_3AH_6 + AH_3 + 9H \quad (2)$$

Though CAC is not a new material, but the confidence on its use is limited because of ambiguity in terms of its performance against severe loading and environmental conditions, as well as the instability of its microstructure. This instability is related to the reactions causing the conversion of the metastable hydrates $CAH_{10}$, $C_2AH_8$ into stable, permanent and dense $C_3AH_6$, $AH_3$ hydrates. This conversion reaction causes an increase in porosity and decrease in the compressive strength of CACC [19,22,23]. Many researchers have tried to identify this chemical reaction and the effect of this reaction on the performance of CACC [19,20,22,24].

Three test procedures are mainly adopted to evaluate the material properties of concrete at elevated temperatures namely, stressed, unstressed and unstressed residual test procedures [10]. The difference between the unstressed and residual test procedures is the temperature and stress scenario to which the specimens are exposed without prestress. In case of unstressed test procedure, the behaviour of concrete is observed in a heated specimen at elevated temperatures, while a residual test simulates the post fire scenario of a concrete specimen cooled down to room temperature after exposure to elevated temperatures. Further, both the unstressed and residual test procedures are carried out without any prior stress conditions, unlike stressed test procedure [10,25].

The compressive strength is considered most important property of CACC observed by different researchers. Although, residual strength of CACC is somewhat studied, but it does not reveal its true behaviour at elevated temperatures. The performance of CACC has been studied [26] within the temperature range of 23–1100 °C using different types of refractory aggregate such as limenite as shown in Fig. 2. Zoldner et al. [26] observed sudden drop in strength up to 400 °C which is linked to the conversion reaction within the microstructure of CACC. However, the loss of strength reduced and remained gradual from 400 °C till 800 °C. Further, a slight gain in strength was observed at 1000 °C and 1100 °C for phonolite and anorthosite aggregate concrete respectively, due to development of ceramic bonds [26].

The main objective of this study was to evaluate the performance of CACC made of traditional limestone aggregate in terms of its material properties at elevated temperatures. The high temperature material properties included compressive and tensile strength, elastic modulus, stress–strain response, energy absorption capacity in compression (toughness), and mass loss. All the properties were measured at 23, 200, 400, 600 and 800 °C temperatures. Further, these properties have not only been evaluated at elevated temperatures (unstressed) but are also compared with the conventional NSC having similar mix parameters. In addition, the performance of CACC is also compared in terms of different test scenarios i.e. unstressed and residual test conditions. Scanning