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The influence of water absorption and porosity on the deterioration of cement paste and concrete exposed to elevated temperatures, as in a fire event

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ABSTRACT

This study investigates why CaO rehydration causes total strength loss of OPC paste compared to only 65% loss of OPC concrete after 800 °C exposure. Subsequent water sorptivity tests revealed paste reacted instantaneously with water, completely disintegrating within minutes. This was attributed to an accelerated rehydration of CaO into $CaOH_2$. This was not observed in concrete. Sorptivity tests using acetone eliminated the disintegration due to CaO reaction with water. Porosity tests indicated a higher porosity and coarser capillary pore size distribution (PSD) in paste compared to paste in concrete. This has an influence on the rate of water absorption. The rate of water absorption determines the CaO rehydration rate and ultimately the growth rate of $CaOH_2$ crystals and type of $CaOH_2$ crystals formed. Different types of $CaOH_2$ crystals cause different levels of deterioration, not always leading to total disintegration. Therefore, the rate of water absorption is the determining factor controlling the extent of deterioration caused by CaO rehydration.

1. Introduction

The behaviour of cement paste and concrete after exposure to elevated temperatures, as in a fire event, has been of interest to many researchers for decades. One of the first studies was conducted by Lea [1] in 1920.

When concrete is subjected to high temperatures, physical and chemical transformations take place resulting in deterioration of its mechanical properties [2]. A common way of investigating those physical and chemical transformations is by dividing the investigation into two steps: (i) the cement paste and (ii) the concrete as a whole, i.e. paste, aggregates and the interface between paste and aggregate.

Investigating (i) the cement paste, Lea and Stradling [3] reported that one product of hydration of ordinary Portland cement (OPC) paste is calcium hydroxide ($CaOH_2$). This compound decomposes at about 400 °C into calcium oxide (CaO) and water. In addition, they proposed that the high loss of water that occurs between 300 and 500 °C is due to the dehydration-dissociation of $CaOH_2$.

Dias et al. [4] reported that although no initial signs of distress were visible on OPC pastes heated to 400 °C or above and cooled to room temperature, all specimens exhibited severe cracking to the point of disintegration after a few days. According to Petzold and Rohrs [5], the reason for this cracking is the expansive, and hence disruptive, rehydration (due to reaction with airborne water vapour) of previously dissociated $CaOH_2$ which is accompanied by a 44% volume increase.

Studies by the authors revealed similar findings [6,7]. The critical temperature of 400 °C for OPC pastes was confirmed. Above this temperature OPC pastes presented total strength loss due to dehydration of $CaOH_2$ and rehydration of CaO. However, dehydration of $CaOH_2$ and rehydration of CaO had no impact in pastes where OPC was partially replaced with ground granulated blast furnace slag (slag), a by-product of the iron blast furnace industry. This is illustrated in Fig. 1. During hydration slag consumes most of the available $CaOH_2$, consequently reducing or even eliminating the negative effects caused by $CaOH_2$ dehydration and subsequent CaO rehydration when cement paste is submitted to elevated temperatures. The compressive strength of OPC and 50% slag pastes after exposure to temperatures up to 800 °C is presented in Fig. 2.

Following the investigation of cement paste, Lea and Stradling [8] assessed the effects of elevated temperatures on (ii), concrete as a whole. Their work stated that specimens of OPC concrete made with Rowley Rag aggregate (volcanic dolerite stone) exposed to 700 °C crumbled to pieces 6 days after the heat treatment.

Khoury [9] stated that, following Lea and Stradling, it was recognised that the $CaOH_2$ problem could be the Achilles' heel of concrete in high temperature applications.

Moreover, other researchers reported strength loss of OPC concrete when submitted to temperatures as high as 1200 °C, but no significant disintegration or crumbling were reported [10–13]. In

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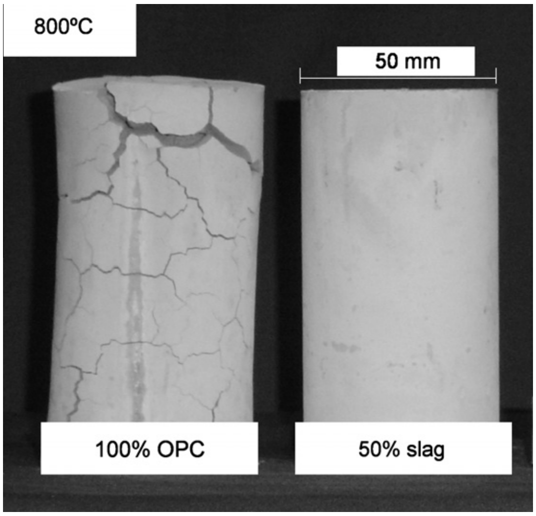

Fig. 1. OPC and 50% slag pastes after exposure to 800 °C.

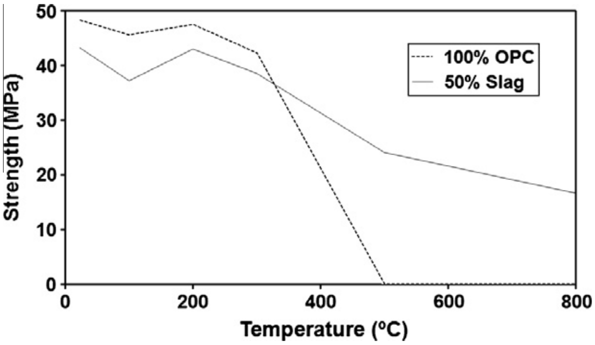

Fig. 2. Compressive strength of OPC and 50% slag pastes at different temperatures.

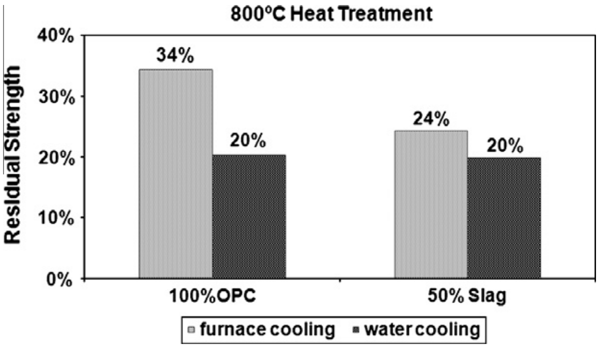

Fig. 3. Residual strength of OPC and OPC/slag concretes after exposure to 800 °C.

addition, Khoury [9] affirmed that there was scope for improvement within the temperature range of 300–600 °C. In 2000, Khoury [2] suggested that the deterioration of the mechanical properties of concrete can be reduced by judicious design of concrete mix, with the choice of aggregate possibly being the most important factor. Flint or Thames gravel is said to break up at relatively low temperatures (<350 °C), while granite is expected to exhibit thermal stability up to 600 °C. Basalt aggregate was reported not to undergo phase changes at temperatures up to 800 °C [2,14].

The authors have also performed tests on concrete [15]. The concrete specimens were made with the same OPC cement and slag blends as used in which OPC pastes disintegrated [15]. The coarse aggregate used was basalt, as described above as having high thermal stability. Fig. 3 presents the residual compressive strength for the OPC and 50% slag concretes after exposure to 800 °C followed by either furnace or water cooling. It was found that even though dehydration of $CaOH_2$ and rehydration of CaO occurred as determined by infrared spectroscopy (IR), the OPC concrete did not disintegrate or crumble, even months after the heat treatment.

The authors have also reported the long-term effects of the CaO rehydration on OPC pastes [7]. It was reported that 1 year after exposure to 800 °C, the OPC paste has been reduced to a powder. This was confirmed to be due to continuous rehydration of CaO via airborne water vapour throughout the year. Based on that, it is thus expected that the OPC cement paste in the concrete would disintegrate, even if over longer time periods, independently of the thermal stability of the aggregate. However, it is clear from the discussion above that after exposure to elevated temperatures, the OPC paste test results does not represent the same deterioration behaviour of the OPC paste present in concrete.

Therefore, the present work aims to identify why the dehydration of $CaOH_2$ and rehydration of CaO is not detrimental for the OPC paste in concrete as it is for an OPC paste specimen (Fig. 1). The study investigates differences in the dehydration/rehydration process of cement paste and concrete and focuses on distinguishing differences in how the water is absorbed by the cement paste and concrete subsequent to heating. Firstly, water sorptivity tests were conducted. Secondly, sorptivity tests using a solvent (acetone) instead of water were performed, which is supposed to cause no damage to the specimens due to reaction of water and CaO. Thirdly, an attempt to determine the porosity of the pastes and concretes using a solvent was made. Afterward, nitrogen adsorption was performed to provide information regarding the pore size distribution of the specimens. Discussion of each technique is presented in the relevant sections.

2. Materials and methods

2.1. Paste

Ordinary Portland cement (OPC) and ground granulated blast furnace slag (GGBFS or "slag") conforming to the requirements of Australian Standard AS 3972 were used as binder materials. The chemical composition and properties of the binders are presented in Table 1. The OPC used in this study has a low C_3A content of <5%. In this investigation OPC was partially replaced (i.e. 50% by weight) with slag. The term water/binder (*w*/*b*) ratio is used instead of the

Table 1
Chemical composition and properties of the binders.

Constituent/property (%)	OPC	Slag
SiO_2	19.90	32.5
Al_2O_3	4.70	13
Fe_2O_3T	3.38	0.22
MgO	1.30	5.47
CaO	63.93	42.1
Na_2O	0.17	0.21
TiO_2	0.245	1.08
K_2O	0.446	0.25
MnO	0.079	0.43
P_2O_5	0.063	bd[a]
SO_3	2.54	4.1
LOI	2.97	0.35
Fineness (m^2/kg)	360	435
Specific gravity	3.15	2.92

[a] Below detection.