



# An investigation on very high volume slag pastes subjected to elevated temperatures



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## HIGHLIGHTS

- HVS pastes exhibited lower compressive strength than neat PC paste at all ages.
- HVS pastes showed higher residual strength at 400 and 600 °C than their references.
- At 800 °C, HVS pastes kept 50–90% of their original strengths, whilst PC kept 27.5%.
- pH value of pastes decreased with increasing slag content and treatment temperature.

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## ABSTRACT

In this investigation, high volume slag (HVS) pastes were studied under heat treatment. Portland cement (PC) was replaced with ground granulated blast-furnace slag (shortened as slag) at levels of 0%, 85%, 90%, 95% and 100%, by weight. The pastes were exposed to elevated temperatures ranging from 200 °C to 800 °C with an increment of 200 °C for 2 h. Compressive strengths and pH values before and after firing were measured. The various decomposition phases formed were identified using X-ray diffraction (XRD) and thermogravimetric (TGA) analyses. The morphology of the formed hydrates was studied using scanning electron microscopy (SEM). Visual inspections were also conducted. The results showed an increase in the reference compressive strength of HVS pastes with heat treatment up to 600 °C, then a reduction at 800 °C was observed. The relative compressive strength of HVS pastes was higher than that of 100% PC paste. The optimum slag content was 85% which exhibited residual compressive strength comparable to that of 100% PC at 600 °C and 800 °C. The pH values of the pastes decreased with increasing heat treatment and slag content.

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## 1. Introduction

Portland cement (PC) is the leading binding material for manufacturing industrial concrete worldwide. However, its production requires the decomposition of limestone and burning of large quantities fossil fuel, both of which result in significant emissions of carbon dioxide (CO<sub>2</sub>). For every tonne of PC manufactured, nearly one tonne of CO<sub>2</sub> is produced and the exact quantity of this depends on the production process used [1]. Cement plants were reported to release up to 3.24 billion tonnes of CO<sub>2</sub> into the atmosphere annually [2]. The release of not only CO<sub>2</sub> from cement plants is a concern, but also SO<sub>2</sub> and NO<sub>x</sub> from the cement manufacturing process can contribute the greenhouse effect and acid rain [3]. The cement production not only contributes to the destruction of the environment but also consumes considerable quantities of natural

resources, for instance: to manufacture a tonne of PC about 1.5 tonnes of raw materials are needed [3]. Furthermore, the manufacture of PC clinker involves extensive energy [4]. Due to the consequential serious environmental impact, there is a need to find sustainable and environmentally friendly cementitious composites that would reduce the PC production. One of the efforts to produce more environmental friendly concrete is to replace the amount of PC in concrete with by-product materials such as slag.

The world production of slag from iron and steel industries is almost 50 million tonnes per year, of which approximately 12 million tonnes is produced in Europe [5]. The vast majority of this slag is still disposed of in landfills [6]. One option to dispose the slag in an ecologically sensitive manner is to reuse it in concrete production after suitable grinding. A significant part of slag is utilized for the production of aggregate. Another part is ground and blended with PC. For each tonne of the material, the energy required to grind slag is only about 10% of the total energy required for the production of PC [7]. The blending quantity of slag is

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normally 25–30% in composite cements [8]. Replacement levels of PC with slag varying from 30% up to 85% are also available, but 50% is usually used in most applications [9].

Overall, in composite cements, the use of a suitable replacement material can participate in the cementitious hydration products. Other advantages that accompany the use of these materials might include saving in consumption of energy and natural resources. However, the inclusion of slag in PC has many benefits, such as:

- (i) Improving workability, compressive strength and other mechanical properties [10].
- (ii) Decreasing pore size and cumulative pore volume [11], and permeability of the concrete [12].
- (iii) Improving the resistance to alkali aggregate reactivity, sulphate attack [13], chloride-ion penetration [14] and corrosion [15], thereby enhancing the service life of concrete structures [7].

Another characteristic of slag concrete that has been investigated is its resistance to high temperatures, such as that found in a fire. The effects of high temperature on mechanical properties of concrete have been investigated since the middle of the 20th century. The fire resistance capacity of concrete is complicated because it consists of different components that have different thermal properties, moisture content and porosity [16]. Researchers have tried to enhance the fire resistance of paste/mortar/concrete by adding slag [17–22] and such studies have indicated that the addition of slag improves fire resistance of paste/mortar/concrete. The heating regime and the PC replacement levels used in some of these studies have been summarized in Table 1.

Mendes et al. [17] demonstrated that the damage (destroyed specimens) due to elevated temperatures is reduced by blending PC with slag provided that the slag blended cement achieved a significant and beneficial reduction of the amount of  $\text{Ca}(\text{OH})_2$ . The DTG results showed that the decomposition peak of PC at 500 °C, which is related to  $\text{Ca}(\text{OH})_2$ , was four times greater than the 65% slag peak. It was also reported that an increase in the proportion of slag in the cement paste (up to 65% in their study), in general, led to an improvement in the residual compressive strength compared to 100% PC following the exposure to temperatures beyond 400 °C. Further investigations were carried out by Mendes et al. [18] to ascertain the short term and long term effects of exposing pastes manufactured with different proportions of slag (i.e. 35, 50 and 65 wt%) to temperatures up to 800 °C (Table 1). To study the short term effect, the pastes were exposed to 800 °C heat treatment at an age of one week before carrying out the compressive strength test. In the long term study, the pastes were exposed to 800 °C heat treatment at an age of one year and then the compressive strength

test was carried out. They concluded that the PC pastes presented no compressive strength after either short term or long term whilst the PC/slag pastes retained compressive strength in the range of 11–14 MPa in the short term and there was no significant change in compressive strength in the long term.

Aydın [19] studied the residual compressive strength of mortar specimens after being exposed to elevated temperature of 900 °C for 3 h. The results showed that the mortar containing 80% slag exhibited only 23% and 28% compressive strength loss when cooled in air and water, respectively, whilst mortars without slag lost almost 70% of their strength. The XRD pattern of the sample exposed to 900 °C showed a formation of gehlenite, quartz, feldspar and calcite. Seleem et al. [20] reported that concrete containing 10% and 20% slag exhibited higher residual compressive strength than 100% PC concrete after heat treatment up to 800 °C for 3 h. The XRD pattern of the sample exposed to 800 °C showed a formation of merwinite, alkermanite and the spinel magnesium. Li et al. [21] reported that after exposure to 500 °C, the relative compressive strength of concrete with 0%, 10%, 30% and 50% slag was 60%, 62%, 44% and 41%, respectively.

Generally, the research into the use of HVS content in concrete has not been as extensive as that of high volume fly ash (HVFA) content in concrete. Not surprisingly, the application of HVS concrete in structures is very limited. In line with this, there is an abundance of information in the literature related to the influence of different slag contents up to about 60% of the total cementitious content on the some properties of concrete such as workability, mechanical strength, microstructure, creep, shrinkage, chloride penetration, water absorption and corrosion resistance. However, very limited studies have been conducted on the use of the slag concrete at higher replacement levels (higher than 60%). In this paper the effects of elevated temperatures ranging from 200 °C to 800 °C with an increment of 200 °C on the residual strength and microstructure of PC and HVS pastes are reported where cement was replaced with slag at replacement levels of 0%, 85%, 90%, 95% and 100%, by weight. Visual observations after the heat treatment of the pastes as well as pH values of different hardened pastes before and after the exposure to different temperatures were noted. The results are intended to add valuable knowledge to the field of fire resistance of cementitious materials containing large volumes of slag as a replacement for cement.

## 2. Experimental details

### 2.1. Materials

Portland cement, CEMI Class 42.5R, with a Blaine surface area of 270 m<sup>2</sup>/kg (complies with EN 197-1: 2001) was used as a reference cementitious material. Slag that was supplied by UK Hanson Cement was used as the source material to

**Table 1**  
Summary of slag additions and heating regimes from the literature.

Reference	Slag levels	Heating regime
<i>Investigation using paste</i>		
Mendes et al. [17]	0%, 35%, 50% and 65% by weight of PC	Up to 800 °C with 100 °C intervals For 1 h
Mendes et al. [18]	0%, 35%, 50% and 65% by weight of PC	800 °C For 1 h
<i>Investigation using mortar</i>		
Aydın [19]	0%, 20%, 40%, 60% and 80% by weight of PC	900 °C with 300 °C intervals For 3 h
<i>Investigations using concrete</i>		
Seleem et al. [20]	0%, 10% and 20% by weight of PC	800 °C with 200 °C intervals For 3 h
Li et al. [21]	0%, 10%, 30% and 50% by weight of PC	150, 300, 400, 500, 600, 700 °C For 4–6 h
Xiao et al. [22]	50% by weight of PC	20 °C and 800 °C with 200 °C intervals For 3 h at 200 °C; 2.5 h at 400 °C and 2 h for other temperatures

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