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Performance of geopolymer high strength concrete wall panels and cylinders when exposed to a hydrocarbon fire

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HIGHLIGHTS

- Geopolymer concretes have no signs of spalling when exposed to a hydrocarbon fire.
- Residual strength of 60% was maintained after fire exposure.
- Geopolymers have excellent fire resistance due to low thermal incompatibility.

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ABSTRACT

This study presents an investigation of the effect of hydrocarbon fire exposure on the residual compressive strength properties of geopolymer concrete panels and cylinders. Gladstone flyash was utilized as the binder whilst the alkaline solution/fly-ash ratio and sodium silicate to sodium hydroxide (Na_2SiO_3/NaOH) ratio was 0.4 and 2.5 respectively. The compressive strength at the test date was 64 MPa. Two different cylindrical specimens' sizes (150 and 100 mm diameter × 300 and 200 mm high) were exposed on all sides to the hydrocarbon fire scenario for 120 min whilst panels of 1075 × 1075 × 200 mm were exposed on one side for the same time duration. Results showed that no significant spalling occurred in any of the specimens and the mass loss during heating was between 2.70 and 4.65% respectively which was attributed due to moisture loss. Low differential gradients and thermal incompatibility between the geopolymer paste and aggregates provides geopolymer concrete with superior spalling resistance than Ordinary Portland cement concrete. Residual compressive strength testing showed that the panels maintained approximately 60% of their initial compressive strength indicating that geopolymer concrete specimens can maintain sufficient load bearing capacity in the event of fire exposure. The residual strength profiles indicated that specimen size effect was also exhibited with the remaining strength of the cylinders being approximately 10 and 20% for the 100 mm and 150 mm dimeter specimens respectively. The dull red color exhibited in all specimens after fire testing indicated the presence of high iron content in the geopolymer matrix. Insitu temperature analysis showed that the geopolymer concrete had excellent heat resistance capabilities with temperatures at a depth of 100 mm from the exposed surface ranging between 39 °C and 45 °C after 30 min of fire exposure even though the temperature at exposed surface exceeds 1000 °C. This is reinforced by the fact that the geopolymer has a high heat storage capacity as indicated by the geopolymers lower thermal diffusivity than OPC concrete.

1. Introduction

Since geopolymers were first bought to attention in the 1970's [1], many advancements in the properties of geopolymeric materials have been made in the laboratory environment [2]. In addition, geopolymer concretes have been used in real life projects including the Brisbane West Wellcamp Airport [3] and Queensland's University GCI building whereby three suspended floors were made with structural geopolymer concrete [4]. These advances in research has provided confidence that geopolymers can offer similar if not better performance to conventional Ordinary Portland cement concrete (OPCC). These properties include high compressive strengths within 24 h of curing [5], ease of workability and controllable setting times [5], good abrasion resistance [6], superior resistance

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to alkali environments [7], low shrinkage and low thermal conductivity [8], ability to bond to steel, glass, ceramics and old concrete substrates [2] and high corrosion resistance of steel reinforcing [9]. Due to the number of high fire risk infrastructures built around the world, including concrete tunnels, petrochemical plants, nuclear reactors and oil refineries, the need for concrete structures to have superior fire resistance is in high demand. OPC concretes are generally considered to have adequate fire resistance, however at elevated temperatures OPC concretes suffer strength deterioration due to chemical and physical changes [10] and under rapid temperatures, spalling can occur, reducing the load bearing capacity [11–13]. It has been reported [14] that geopolymer composites is ideally suited for construction, transportation and infrastructure where fire endurance is part of the requirement. The performance of geopolymers exposed to fire and the potential for concrete spalling requires a detailed investigation before geopolymers can be used in engineering applications, particular for high risk fire infrastructures. Resistance to fire is also an important parameter for geopolymers that needs investigation in order to determine whether repair works are needed. The results presented in this study aimed to investigate and explain the effect of fire exposure to cured geopolymers and their effect on compressive strength and spalling.

1.1. Literature review

Türkmen et al. [15] investigated the residual compressive strength performance of two geopolymers (50 mm in dimensions and of approximately initial strengths of 35 and 32 MPa respectively) after exposed to temperatures (100, 200, 300, 400, 500, 600, and 700 °C) for a duration of 1 h after reaching the target temperatures. Samples were allowed to cool naturally to the room temperature (24 °C ± 1 °C) before they were tested for compressive strength. The average of three samples indicated that between 100 and 300 °C, the maximum compressive strength is reached which [15] attributed this to the promotion of polycondensation between chain-like geopolymer gels. Between 300 and 700 °C, the residual compressive strength of the geopolymer concretes deteriorated by approximately 46 and 47% respectively. This mechanical damage was attributed to the thermal incompatibility between the paste and aggregate and fracture cracking due to the buildup of insitu pore pressures.

Su et al. [16] carried out dynamic compression testing on geopolymer concretes and discovered that between room temperature and 200 °C, compressive strength increases whilst above 800 °C, a reduction in compressive strength is experienced. Sarker & Mcbeath [17] exposed geopolymer panels (500 × 500 mm) of different thickness (125, 150 and 175 mm) on one side to the standard fire curve for a period of 2 h. It was concluded that the geopolymer has a higher thermal conductivity, due to ceramic type nature of these materials which minimized the differential thermal gradients. This resulted in the geopolymer panels to have less spalling damage compared to OPC concrete panels and retained residual compressive strengths in the order of 65.6%. Sarker & Mcbeath [17] also reported the geopolymer panels turned a dull red after exposure to 800 °C which was attributed to the high iron content in the fly ash. Shaikh & Vimonsatit [18] evaluated the residual compressive performance of geopolymer concrete cylinders (100 mm in diameter and 200 mm in height) at 200, 400, 600 and 800 °C. The effect of different dosages of alkaline activators, aggregate size, curing regime and initial compressive strength on the residual compressive strengths were investigated. The samples were tested in the unstressed conditions whereby the preload to the specimens is zero before heating commences and then the specimens are loaded to failure after the target temperature is reached. Strength reduction in all samples occurred between ambient temperature and 400 °C which was attributed to the damage caused by the differential thermal gradients between the aggregates and paste whilst strength increase was attributed to the formation of improved alumina-silicate networks between 400 and 600 °C. Increase in compressive strength in some geopolymer concrete samples between 600 and 800 °C was explained by sintering of the geopolymer matrix filling the voids in the material [18]. Sarker et al. [19] found that geopolymer concrete cylinders have a higher conductivity than their OPC concrete counteracts due to their higher content of metal ions such as silicon, aluminum and iron. No spalling occurred and specimens with initial compressive strengths of 39–58 MPa had residual compressive strengths in the order of 83–59% at 650 °C, 27–29% at 800 °C and 16–18% at 1000 °C. Strength loss was attributed to cracking and SEM confirmed the geopolymer matrix becoming denser at elevated temperatures which may have provided the resistance to spalling. Sarker et al. [19] also reported the geopolymer specimens exhibiting a dull red color after exposure to 1000 °C as reported by [17,20]. Abdulkareem [21] investigated the effects of elevated temperatures on the thermal behavior of geopolymer pastes, mortars and concretes. At 800 °C, the geopolymer paste undergoes complete damage with no residual compressive strength which is in contrary to previous research. SEM analysis showed that the densification and swelling processes of high unreacted silicate portion significantly weaken the fire resistance of the geopolymer concrete samples. Ranjbar et al. [22] investigated the compressive strength of fly ash/palm oil fuel ash based geopolymer mortar under elevated temperatures and concluded that strength increases up to a peak of around 300–500 °C. This was attributed to water release during heating which causes discontinuous nano-pores and strength increase. Above 500 °C, strength reduces sharply due to differential thermal gradients between the paste and sand aggregate.

Sakkas et al. [23] tested small concrete panels, 400 × 400 × 200 (approximately 14 MPa in strength) to a RWS (Rijkswaterstaat) fire curve for 120 min. No signs of spalling were observed and the temperatures did not reach greater than 120 °C before 90 min and then increased to less than 190 °C between 90 and 120 min. No residual compressive strength was measured. Turkmen & Findik [24] found that the compressive strength, thermal conductivity, and flexure strength of mineral admixture lightweight geopolymer mortars decreased at elevated temperatures between 500 and 800 °C. Pan et al. [25] studied the effect of aggregate size on the spalling of geopolymer concrete in fire and found that geopolymer concrete containing 10 mm aggregates spalled whilst the ones with 14 mm did not spall. This was attributed to the fracture process zone length that increases with increasing aggregate size. Zhao & Sanjayan [20] found that no spalling occurred when geopolymer concrete cylinders were exposed to a rapid fire exposure. Kong & Sanjayan [26] observed that the size of the aggregate influences the residual compressive strength of the geopolymer concrete after exposure to elevated temperatures. Smaller size aggregates (<10 mm) promote spalling and extensive cracking leading to strength loss. Large aggregates (>10 mm) provided geopolymer concrete to be more stable at elevated temperatures. The thermal incompatibility between the geopolymer matrix and its aggregate components was also determined to be the most likely cause of strength loss in geopolymer concrete specimens at elevated temperatures. Topcu et al. [27] stated that geopolymers have good fire resistance up to 1000 °C without emitting toxic gas. McNulty [28] compared fire resistance of two types of normal Portland cement with two types of geopolymer cement and stated that geopolymer cements exhibit higher compressive strength. Kong & Sanjayan [29] investigated the damage behavior of geopolymer composite exposed to elevated temperatures. After 800 °C temperature exposure, geopolymer paste gained 53% in strength whilst the