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Effect of temperature on bond characteristics of geopolymer concrete

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HIGHLIGHTS

- Bond between geopolymer concrete and rebar at elevated temperatures are quantified.
- Bond characteristics of geopolymer concrete is compared with conventional concrete.
- Temperature induced bond strength degradation in geopolymer concrete is evaluated.

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ABSTRACT

This paper presents experimental results on the bond behavior between geopolymer concrete and rebar. Pull-out tests on geopolymer concrete specimens embedded with plain and ribbed rebars were carried out at ambient temperature and after exposure to 100, 300, 500 and 700 °C. Two batches of geopolymer concrete with compressive strength of 48 and 64 MPa respectively, and five rebar diameters (of 10, 12, 14, 18 and 25 mm) were used for preparing the test specimens. Comparative benchmark tests were also conducted on ordinary Portland cement (OPC) concrete specimens. Results from these tests show that geopolymer concrete exhibits insignificant reduction in bond strength till exposure to 300 °C, but undergoes significant degradation beyond 300 °C. Data from the tests indicate that rate of bond strength degradation in geopolymer concrete is close to that of splitting tensile strength, but higher than that of compressive strength. Also, results infer that geopolymer concrete exhibits similar or better bond properties than OPC concrete, both at ambient temperature and after exposure to elevated temperatures. Thus geopolymer concrete can be a practical alternative to OPC concrete in reinforced concrete structures when fire resistance is one of the main design considerations.

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1. Introduction

Concrete industry is believed to be one of the major contributors to global warming, and this is mainly attributed to the use of Portland cement as the binder. Cement production is thought to be responsible for about 8% of global CO_2 emission, based on production data in 2014 [1]. To reduce the environmental impact of concrete industry, efforts are on to find alternatives to Portland cement. Geopolymer, a new environmentally friendly inorganic binder, derived by alkaline solution activating aluminosilicate source material (such as metakaolin, fly ash and slag), has attracted significant attention in recent years as a practical alternative to Portland cement [2–5]. With efficient use of industrial by-products, geopolymer binder greatly reduces greenhouse gas (CO_2) emissions and energy requirements during its production. There is an estimated 44–64% reduction in greenhouse gas emissions for a typical Australian geopolymer product, compared with ordinary Portland cement (OPC) [6].

Geopolymer concrete is reported to have comparable mechanical properties as that of OPC concrete. A great amount of experimental work in the literature has showed that fly ash based geopolymer concrete, cured at 60–80 °C temperature, exhibit a high early mechanical strength and low dry shrinkage [7], excellent fire resistance [8,9], and good durability properties [10,11]. In the case of curing at ambient temperature, fly ash based nano-silica modified geopolymer concrete [12], and metakaolin (MK)-fly ash (FA) based geopolymer concrete [13], also show excellent mechanical strength, compared to conventional heat cured geopolymer concrete and OPC concrete.

For reinforced concrete to be effective as a composite material, reinforcing bar is to be well bonded to the surrounding concrete. Therefore, evaluating bond behavior between geopolymer concrete and reinforcing bar is critical for the use of geopolymer concrete as

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an alternative to OPC concrete in reinforced concrete structures. Many attempts to evaluate bond characteristics between geopolymer concrete and reinforcing bar are reported in the literature [14–18], but the experimental data on bond behavior of geopolymer concrete with reinforcing bar at elevated temperatures are not established. A recent study [19] investigated the influence of compressive strength of geopolymer concrete, diameter of reinforcing bar, concrete cover thickness and anchorage length on bond behavior between MK-FA based geopolymer concrete and reinforcing bar at room temperature. The current study presents experimental results on bond behavior of MK-FA based geopolymer concrete with reinforcing bar after exposure to elevated temperatures. These experimental results are of great significance for the use of geopolymer concrete in building applications where provision of fire resistance is a major design requirement.

2. Experimental program

Direct pull-out tests were conducted on 90 geopolymer concrete cubic blocks embedded with reinforcing bars of different diameters, at ambient and after exposure to elevated temperatures, to evaluate the effect of temperature on bond characteristics of geopolymer concrete. Comparative benchmark bond tests were also conducted on 30 OPC concrete specimens.

2.1. Raw materials

Geopolymers used in this study are derived by alkaline-silicate solution activating metakaolin (MK) and fly ash (FA) blend. The chemical composition and particle sizes of MK and FA are detailed in Ref. [20]. The alkaline-silicate activator with desired SiO_2/K_2O molar ratio of 1.0 was formulated by blending commercial potassium silicate solution with 15.8 wt% K_2O, 24.2 wt% SiO_2 and 60 wt% H_2O (SiO_2/K_2O molar ratio is 2.4), and potassium hydroxide flakes with 95% purity, and tap water. The alkaline-silicate activator was prepared one day prior to use.

For generating comparative benchmark data, specimens made of ordinary Portland cement (OPC, Grade P.O.32.5) concrete were also tested. To enhance the strength of OPC concrete, polycarboxylate superplasticizer was added in the preparation of OPC concrete specimens.

The coarse aggregates for geopolymer and OPC concretes consisted of graded gravel with sizes of 10–20 mm and fine aggregates consisted of locally available river sand with a maximum size of 2 mm.

Six groups of rebars, with different surface (plain and ribbed rebars) and different nominal diameters (10, 12, 14, 18 and 25 mm), were used in geopolymer concrete blocks for pull-out tests. The geometric characteristics of ribbed rebars were measured through a vernier caliper. Samples of rebars were tested through a universal material testing machine to obtain their actual yield and ultimate strength. Full details of rebars, together with their mechanical properties, are presented in Table 1.

2.2. Mix proportions

Two batches of geopolymer concretes (GC1 and GC2) and two batches of OPC concretes (CC1 and CC2) were used for preparing pull-out test specimens. The mix proportions of geopolymer concrete and OPC concrete are tabulated in Table 2. Geopolymer concretes were derived by adding alkaline activator into metakaolin (MK) and fly ash (FA) blend precursor, and then mixed with coarse and fine aggregates. Details on preparing geopolymer concrete can be found in Ref. [20]. Slumps of geopolymer concretes GC1 and GC2 are 173 mm and 97 mm respectively, measured through casting geopolymer concretes into a standard truncated conical mold.

2.3. Specimen preparation and test procedure

Pull-out tests were carried out as per specifications in Chinese GB 50152-92 [21] and RILEM standard [22]. The sizes of a typical test specimen are shown in Fig. 1. The rebar was uniaxially embedded in the center of a geopolymer or OPC concrete cubic block of size 150 mm × 150 mm × 150 mm, with a bond length of 5*d*, where *d* is the diameter of the rebar. Six groups of reinforcing bars, listed in Table 1, were used in geopolymer concrete specimens, but only R-12 and R-14 rebars were used in OPC concrete specimens. To prevent local stress concentration at the loading end of the pull-out rebar, the rebar near the loading end was encased in a plastic tube with a length of (150-5*d*) (see Fig. 1).

It is reported that the chemical reaction in geopolymers is a rapid polymerization process and geopolymers can gain high strength at early curing age [20,23]. Fig. 2 presents the comparison on compressive strength development with curing age of geopolymer concrete tested in authors' previous study and that of OPC concrete calculated by the proposed empirical formula in Ref. [24]. It can be seen from Fig. 2 that the compressive strength of geopolymer concrete at 7-days reached 96% of that at 28-days, which is much higher than the strength development rate of OPC concrete at 7-days (account for 59% of 28-day strength). Therefore, geopolymer concrete specimens were only cured for 7 days in a tank at a constant 22 °C temperature and 95% humidity before undertaking pull-out tests. OPC concrete pull-out specimens were cured under same conditions for 28 days.

The reinforcing bar in test specimens was gripped at the bottom by a UTM5205X universal material testing machine, and secured at the top through a specially designed loading frame. Two displacement meters were placed at the free end of the rebar and the surface of concrete respectively, to monitor the relative displacement of the rebar during loading. The reinforcing bar was pulled out slowly, at a pulling rate of 1.2 mm/min. The pull-out force and displacement data were recorded during the tests.

For undertaking pull-out tests on high temperature exposed specimens, the specimens were first heated in an electrical furnace, at an incremental heating rate of 5 °C per minute. Two thermocouples were mounted on the surface and center of the specimen respectively, to evaluate the difference between surface and center temperatures during heat exposure. Once the predetermined

Table 1
Geometric characteristics and mechanical properties of rebars.

Group	Surface	Rib height/spacing	Rib phase angle (°)	Diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)
P-10	Plain	–	–	10	312.00	502.36
R-10	Ribbed	0.14	45	10	420.64	606.31
R-12	Ribbed	0.14	62	12	470.40	620.15
R-14	Ribbed	0.14	45	14	437.37	600.04
R-18	Ribbed	0.15	45	18	365.15	520.00
R-25	Ribbed	0.16	45	25	445.78	596.79

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