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Experimental evaluation of quasi-static and dynamic compressive properties of ambient-cured high-strength plain and fiber reinforced geopolymer composites

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HIGHLIGHTS

- High strength geopolymer is synthesized at ambient room temperature.
- Hybrid-mix of steel and HSPE fibers is used to reinforce the geopolymer matrix.
- SHPB tests are performed to investigate the material behaviours at high strain rates.
- Compressive behaviours of geopolymer materials are sensitive to loading rates.
- Use of hybrid-fiber mix improves the energy absorption capability of geopolymers.

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ABSTRACT

Heat cured geopolymer binders have been studied extensively to establish their mechanical behaviour under quasi-static loading conditions and it has been found that they are capable of achieving comparable and in some cases better properties than ordinary Portland cement (OPC). However, as a novel binding material, minimal research has been conducted to understand their dynamic material response. This paper presents the dynamic compressive properties of a newly synthesized high-strength ambient cured geopolymer mortar and hybrid steel-polyethylene fiber reinforced geopolymer composite (FRGC). Dynamic compressive tests are carried out using the Ø100-mm split Hopkinson pressure bar (SHPB) apparatus with pulse shaping technique whereas a 160-ton hydraulic test machine is used for quasi-static compressive tests. The dynamic compressive properties of plain and FRGC including stress–strain curves, strength enhancement, impact toughness and energy absorption capability are obtained and compared with those observed under quasi-static actions. A high-speed camera is used to record the failure processes of samples under impact. The test results show that the dynamic compressive mechanical properties of plain and FRGC exhibit strong strain rate dependency. The DIFs (dynamic increase factors) of samples increase approximately linearly with the average strain rate in a logarithmic manner. Obvious binomial relationships are noticed between the energy absorption capacity and average strain rate of tested samples, such that the strain rate sensitivity threshold exists at 30 s^{-1} and 66 s^{-1} for plain and FRGC materials, respectively. Empirical DIF relations are proposed which can be used to model the developed composite materials and structures subjected to static and impact loads.

1. Introduction

Concrete is used extensively for construction of buildings, dams, roads, and bridges, where the most primary ingredient used in the composite is ordinary Portland cement (OPC). However, the process of manufacturing OPC is highly energy intensive since it involves the calcination of limestone and sintering of ground materials to form clinker. As a result, carbon dioxide (CO_2) is released both during the calcination and through the burning of the fossil fuels. Due to an overwhelmingly increasing demand to reduce the global anthropogenic CO_2 emissions from cement industry

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(typically 5–7%) [1], recent decades have seen a new wave of research on alkali-activated cementitious materials (AACMs) [2]. Unlike OPC, the synthesis of these binders involves activating potential hydraulic waste products (fly ash (FA) and slag) with an alkaline solution. Previous studies have established their improved thermal stability [3,4], lower water permeability [5], enhanced resistance to acid or sulfate attacks [6], and better durability [7]. However, in reality, the use of AACMs which can broadly be classified as alkali-activated slag [8] or alkali-activated FA (commonly known as "Geopolymer") [9] has been limited. The main reason is primarily related to their early age properties, i.e. the geopolymer formulations containing low calcium FA as the only binder do not achieve noticeable strength at room temperature and may not be feasible for cast in-situ concrete applications [10], while AAS cement may experience shrinkage problems [11].

Nevertheless, some recent research efforts with the focus on geopolymer material preparation have demonstrated the advantages of combining FA and slag materials together [12]. The studies conducted at the microstructural level have explained the rationale behind the strength development, indicating the co-formation of sodium aluminosilicate hydrate (N-A-S-H) and calcium silicate hydrate (C-S-H) / calcium aluminium silicate hydrate (C-A-S-H) type gels [13,14]. It has been observed that similar to OPC concrete, a range of mixing parameters can influence the mechanical properties of geopolymer mortar and concrete mixtures [15]. However, with an array of mixture designs, fiber reinforcements, and preparation techniques [16], most of the previous studies on geopolymer binders were limited to investigating the material performance under quasi-static loading conditions, i.e. under uniaxial compression, split-tensile and flexural loads only [17,18]. Little efforts have been made to understand the impact behaviour or dynamic material properties of these novel binders.

Generally, all structures during their design life are likely to be vulnerable to natural hazards such as an earthquake, high-velocity impact or blast. It is well-documented that the response of engineering materials and structures under impulsive loadings could be strikingly different to that observed under quasi-static loading conditions [19,20], where for concrete-like materials, it has been noticed that both the compressive and tensile strengths increase with the strain rate. A numerical fraction of the dynamic strength and the quasi-static strength, also known as the Dynamic increase factor (DIF), is used to quantify the enhancement [21]. Based on the extensive testing data set available for a wide range and type of mortar and concrete mixes as reviewed in [22], the Comite Euro-International du Beton (CEB) has suggested some guidelines to estimate the DIF for critical compressive stress for OPC concrete subjected to high strain-rate loadings [23], as expressed in Eqs. (1) and (2).

$$\mathrm{DIF}_{fc} = f_{c,imp,k}/f_{cm} = (\dot{\varepsilon}_c/\dot{\varepsilon}_{c0})^{0.014} \quad \dot{\varepsilon}_c \leqslant 30\,s^{-1} \tag{1}$$

$$\mathrm{DIF}_{fc} = f_{c,imp,k}/f_{cm} = 0.012(\dot{\varepsilon}_c/\dot{\varepsilon}_{c0})^{1/3} \quad \dot{\varepsilon}_c > 30\,s^{-1} \tag{2}$$

where, $f_{c,\ \mathrm{imp},\ \mathrm{k}}$ is the impact compressive strength; f_{cm} is the mean compressive strength; $\dot{\varepsilon}_c$ is the strain rate in s^{-1} and $\dot{\varepsilon}_{c0}$ is the reference strain rate of $30 \times 10^{-6}\ s^{-1}$.

However, very few researchers have investigated the dynamic material properties of geopolymer binders. For those undertaken, the key differences are related to the type of source materials, activating solutions, the presence of aggregates in test samples, sample sizes, and the loading rates achieved during the tests [24–30]. A majority of the researchers used heat curing method for the synthesis of geopolymer which on its own could be a major limitation. Nevertheless, the existing literature on the dynamic compressive behaviour of geopolymer binder includes the experimental investigation carried out by Khandelwal et al. [25] who studied the dynamic compressive properties of geopolymer mortar at four different low strain rates, i.e. $1e^{-5}$, $5e^{-5}$, $1e^{-4}$ and $5e^{-4}\ s^{-1}$. The samples were prepared under the influence of heat curing. It was concluded that the ultimate compressive strength and elastic properties of geopolymer mortar increased with the strain rate. Similarly, other researchers [26–30] used different types of geopolymer concrete (GC) mixtures to study their impact behaviour at higher loading rates. Interestingly, the reported outcomes in these studies are conflicting. In order to apprehend a succinct comparison, the DIF scatters for strength from these investigations are plotted in Fig. 1 alongside the CEB recommendations. A brief review of the mix ingredients and results are presented thereafter.

As seen, three types of GC mixtures and one geopolymer mortar mix (not shown in the graph) was tested by Feng et al. [26]. Groups of three different activator combinations were used to prepare the mixes under the influence of heat curing. It was concluded that the quasi-static compressive strengths of these mixtures were highly dependent on the potency of alkali-activating solutions, i.e. the sodium hydroxide (SH) and sodium silicate (SS) based activators were more effective in comparison to a combination of potassium hydroxide (KOH) and SS solutions. For dynamic tests, it was specified that the prevailing CEB recommendations may be used to establish the DIF_{fc} for different GC mixtures since the strength enhancement trend in GC is similar to that of OPC concrete. However, it can be established from Fig. 1 that their reported test results do not match the CEB guidelines precisely. Moreover, the CEB formulae were found to underestimate the $\mathrm{DIF}\varepsilon_c$, i.e. the increase in critical axial strain at peak stress with an increase in average strain rate. On the other hand, Gao et al. [27] studied the quasi-static and dynamic compressive material properties of AAS concrete samples. The dynamic material tests were conducted up to a strain rate of $130\ s^{-1}$. Contradictorily to the conclusions conveyed by Feng et al. [23], the rate of strength increase in AAS concrete samples was significantly lower than OPC concrete samples at higher loading rates. Similarly, no obvious relationship was observed between the increase in average strain rate and critical axial strain values. Instead, the critical axial strain corresponding to the maximum stress fluctuated within a small range.

Recently, Luo et al. [28] prepared GC specimens with the combined use of FA and slag (FA/slag = 0.33) at three different water/binder ratios. The source materials were activated with SS and SH solutions. To overcome the inherent brittleness of geopolymer material, the matrix was reinforced with basalt fibers of 15 μm diameter and 18 mm length. However, it should be noted that the geopolymer mixtures used in this study contained a relatively higher volume fraction of slag and SS/SH ratios (6.70, 4.20 and 3.50) which may not be useful in reducing the carbon footprint typically associated with this novel binder. Nonetheless, it may be seen (see Fig. 1) that the synthesized material exhibited strong strain rate dependency at strain rates 30 – 100 s^{-1} and the results suggest higher sensitivity of geopolymer binder in comparison to OPC. Based on the test data, empirical relationships of DIF_{fc} with the strain rate were proposed. Likewise, in other studies, Xin et al. [29,30] also used a combination between FA and slag to synthesize the GC mixtures with two different types of activators. Despite the fact that no information was presented in their studies in regards to the mix proportions, it was concluded that GC mixtures prepared with SS and SH based activators exhibit increased deformation upon impact as compared to the other activators. The test data showed that the strain rate sensitivity threshold for GC is apparently lower than that of OPC, i.e. 28.89 s^{-1} instead of 63.1 s^{-1} [31]. However, different to other researchers, the critical axial strain was found to increase initially up to 66.7 s^{-1} with an increase in the average strain rate and decreased later for the other test cases at higher strain rates. Strong strain rate dependency for compressive strength of the material was noticed as the DIF of