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# Dynamic mechanical properties of geopolymer concrete after water immersion

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**Abstract**

This paper aims to investigate the influence of water immersion on dynamic mechanical properties of geopolymer concrete (GC). Dynamic compressive tests on specimens placed indoors ($GC_N$) and specimens with water immersion ($GC_W$) were conducted by a split Hopkinson pressure bar system. The results indicate that the dynamic strength and impact toughness of $GC_N$ and $GC_W$ display an increasing trend as strain rate increases, while the elastic modulus is not rate-sensitive since no obvious trends can be observed with strain rate. The quasi-static strength of GC decreases after water immersion. Under impact loading, however, water immersion exhibits a strengthening and stiffening effect on GC as confirmed by the higher dynamic strength and higher dynamic elastic modulus of $GC_W$. And the absorbed water within specimen also improves the rate sensitivity of GC's strength performance. Besides, water immersion has a minor influence on the impact toughness of GC. However, as compared with $GC_N$, $GC_W$ dissipate less impact energy prior to the peak load and have a lower average deformation during the impact procedure. In general, the impact damage of $GC_W$ is less serious than that of $GC_N$ at approximately the same strain rate. The fragment size of $GC_W$ distributes in the coarser grained side.


*Key words:* Geopolymer concrete; Water immersion; Dynamic mechanical properties; Rate sensitivity

## 1. Introduction

Geopolymer concrete (GC) is a new sustainable and environmentally-friendly composite with great potential to replace conventional concrete produced by ordinary Portland cement (OPC). The binder materials used for GC, such as fly ash and blast furnace slag, are mostly the industrial wastes or by-products containing high contents of silica and alumina, which can be applied as pozzolanic components for geopolymerization in alkaline environments [1]. Compared with the production of Portland cement, the manufacturing of these pozzolanic materials consumes less energy and emits less $CO_2$. Hence, in view of the sustainable development and environmental issues, the production of concrete using geopolymers as the binder has aroused growing interest among scholars. A wealth of research works [2–5] conducted in the past several decades indicate that geopolymer composites can not only provide comparable properties in strength and workability, but also exhibit better durability and corrosion resistance as compared with OPC composites. Thus GC is a promising material to be used in civil engineering, especially for concrete structures located in water environment (e.g. dams, ship locks, offshore platforms, abutment piers of bridges, etc.). However, due to the porous characteristics of concrete materials, the underwater concrete will inevitably be in saturated or semi-saturated states [6]. The resultant moisture gradient and pore water pressure will further affect the mechanical properties of the wet concrete. Therefore, it is necessary to probe into the changes in the behaviors of GC after water immersion in order to guarantee the safety and simulate the responses of hydraulic structures constructed by GC. In addition, this is also helpful to generalize the application fields of GC.

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In recent years, an increasing number of experimental research works [6–13] have been carried out on the mechanical performances of wet OPC concrete, which mainly focus on the elastic modulus, tensile strength, compressive strength, flexural strength, Possion's ratio and constitutive model. The results obtained from these research works, in general, highlight the effects of pore water on concrete. In brief, the pore water within the wet concrete should not be neglected in design. Nevertheless, the existing research works are primarily conducted under quasi-static loading. Limited research has been carried out on the mechanical behaviors of wet concrete under high strain rate loading [14,15]. Since concrete is a typical rate-sensitive material, its mechanical behavior and failure mechanism change significantly as the loading rate increases [16]. Some researchers even propose that water content is one of the main factors inducing the rate effects of concrete materials [17,18]. In practical engineering, many underwater structures, due to natural hazards or man-caused accidents, may undergo dynamic loadings from the earthquake, underwater explosion and shock, hydrodynamics of water flow, etc. As a result, studies on the dynamic mechanical properties of wet concrete are indispensible for both civil and military applications.

The main objective of this paper is to explore the influence of water immersion on dynamic mechanical properties of GC. Dynamic compressive tests were conducted by a split Hopkinson pressure bar (SHPB) system at different strain rates. Variations in dynamic compressive strength, dynamic elastic modulus, impact toughness and post-failure fragments were investigated.

## 2. Experimental details

### 2.1. Materials and specimen preparation

Binder materials used in the production of GC include type F (low-calcium) fly ash with specific gravity of 2.05 g/cm$^3$, and slag with specific surface area of 491.6 m$^2$/kg. Natural river sand with fitness modulus of 2.8 and crushed limestone with particle size between 5 and 20 mm were used as fine and coarse aggregates, respectively. Alkaline activators in this study consisted of NaOH with a purity level over 99.0% and $Na_2SiO_3$ with a modulus ratio ($M$) equal to 3.1–3.4 (where $M=SiO_2/Na_2O$, $Na_2O \geq 8.2\%$ and $SiO_2 \geq 26.0\%$ by mass). Table 1 lists the chemical compositions of fly ash and slag. Table 2 shows the mix proportion of GC.

All the materials were mixed in a forced mixer and then cast into cylindrical molds. After being cured for 24 h in molds, the specimens were demoulded and stored in a standard curing room (with a temperature of $20 \pm 2$ °C and a relative humidity of 95%) for additional 60 days. At last, two kinds of specimens were prepared by cutting and smoothing, i.e. cylinders with dimensions of $\Phi 98 \times 200$ mm and cylinders with dimensions of $\Phi 98 \times 50$ mm. The former was used for quasi-static compression test and the latter was used for dynamic compression test.

Table 2
Mix proportion of GC (kg/m$^3$).

| Slag | Fly ash | Sodium hydroxide | Sodium silicate | Sand | Crushed limestone | Water |
|---|---|---|---|---|---|---|
| 249 | 110 | 25 | 88 | 810 | 1016 | 88 |

### 2.2. Experimental methods

All the produced specimens were firstly left for 3 days in room conditions, after which the original weight and UPV value were measured by using an electronic balance and a commercially-available ultrasonic device, respectively. Later, half of these specimens were immersed in the tap water at room temperature. The rest specimens were still placed indoors. For the convenience of representation, specimens with water immersion were labeled as $GC_W$, specimens put in indoor environment were labeled as $GC_N$. After 180 days, $GC_W$ were removed from the water and dried with a paper towel. The weight and UPV value were measured again before the further testing. It should be noted that the water-immersed specimens, in this paper, cannot be considered completely saturated despite a long-time water immersion. With the increase of immersion time, the water absorption rate of specimen decreases mainly due to the moisture-related swelling of the gel structures [19]. It is thus hard for $GC_W$ to reach the real saturation state under normal atmosphere. This is supported by the results in [20–22].

Quasi-static compression tests were conducted by a servo-hydraulic testing machine with a loading rate of 0.5 MPa/s [23]. Dynamic compression tests were carried out by a SHPB apparatus with 100 mm diameter (see Fig. 1). Both ends of the specimen were lubricated with a thin layer of grease to reduce end friction. Based on the principle of one dimensional wave propagation theory, the stress, strain and strain rate histories of the specimen under impact loading can be calculated as below:

$$\begin{cases} \sigma(t) = \frac{A}{2A_S} E[\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)] \\ \varepsilon(t) = \frac{C}{L_S} \int_0^t [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)]dt \\ \dot{\varepsilon}(t) = \frac{C}{L_S} [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)] \end{cases} \quad (1)$$

Table 1
Chemical compositions of fly ash and slag (mass %).

| Oxides | $SiO_2$ | $Al_2O_3$ | CaO | $Fe_2O_3$ | MgO | $Na_2O$ | $TiO_2$ | $K_2O$ | $P_2O_5$ | $SO_3$ | Loss on ignition |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fly ash | 45.8 | 21.4 | 13.7 | 12.6 | 1.3 | 1.1 | 0.2 | 1.8 | 0.1 | 1.9 | 0.1 |
| Slag | 29.2 | 19.4 | 38.6 | 5.8 | 2.8 | 0.2 | 0.6 | 0.1 | – | 2.6 | 0.3 |