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Mechanical properties of ambient cured high-strength plain and hybrid fiber reinforced geopolymer composites from triaxial compressive tests

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HIGHLIGHTS

- Triaxial compressive behaviour of ambient cured geopolymer composites was studied.
- Fifteen different levels of confining pressures between 0 and 100 MPa were used.
- Normalized peak axial stress increases in parabolic form with a rise of confinement.
- Willam-Warnke failure criteria provides good failure envelope for geopolymers.
- Fiber reinforced samples retain their integrity at higher levels of confinement.

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ABSTRACT

Geopolymer binders have evolved as a promising alternative to ordinary Portland cement (OPC) in concrete over the last few decades. However, many aspects of their mechanical behaviour such as their performance under multiaxial stress conditions are still unknown, which are of primary importance for their structural application. In this paper, the triaxial compressive behaviour of newly developed ambient-cured high-strength geopolymer (HSG) mortar, and fiber reinforced geopolymer composites (FRGC) is studied. A series of Ø50 × 100 mm cylindrical samples were prepared using low-calcium fly ash and ground granulated blast furnace slag, while hybrid steel-polyethylene fiber reinforcement with fiber volume fraction of 2% was used to reinforce the brittle geopolymer matrix. Standard triaxial tests with fifteen different levels of confining pressures [(σ_3); ranging between 0 and 100 MPa] were employed to comprehensively investigate the triaxial stress-strain characteristics of synthesized materials from low to high range of confining pressures. According to test results, the unreinforced HSG samples exhibited linear elastic stress-strain behaviour under uniaxial stress condition and showed catastrophic brittle failure. Instead, the samples tested under confinement showed pseudo-ductile behaviour. On the other hand, the inclusion of hybrid-fiber reinforcement has meaningfully helped to improve the ductility of HSG matrix. The peak axial stress and the corresponding axial strain was found to increase with the increase of confining pressure, although the influence of active lateral confinement was more pronounced on the triaxial strength of HSG samples. The two most commonly used failure criterions for OPC concrete, i.e., Power-law and Willam-Warnke failure criterion were used to develop the empirical relations to predict the peak axial stress as a function of confining pressure for the studied materials. The proposed relationships can be used for the calibration of existing concrete material models. The obtained test results were also compared with the existing triaxial compression test data on high strength cement based concretes and composites in the literature to highlight the differences between geopolymers and OPC concrete.

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1. Introduction

With an ever growing demand for using sustainable alternatives to ordinary Portland cement (OPC), the modern construction

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materials have seen a new cementless binder in the form of "Geopolymer" [1]. The specific advantages of using by-product source materials [2], high early-age strength [3], improved fire resistance [4], and reduced carbon dioxide (CO_2) emissions [5] have driven an increased research interest in these new alkali-activated cementitious materials (AACMs). Previous studies on geopolymer materials have identified numerous factors, such as, the nature of silico-aluminous materials [6], types of alkali-activators [7], mixing sequences [8], and curing conditions [9] that could significantly influence their mechanical properties. Some other investigators focused on improving their structural resistance, toughness, and flexure tensile strength by introducing epoxy-resins [10] and a range of fiber types in different geopolymer formulations [11].

However, for practical use of geopolymers in civil engineering applications, the availability of constitutive relationships which can empirically predict their behaviour under combined stress states is still a grey area for these novel binders. Generally, the compressive strength of concrete is the fundamental property commonly used in the design of reinforced concrete structures. However, in the majority of the cases, the failure of concrete in a structure occurs under complex stress states [12]. Besides, it is well established that owing to an inherent microstructural variation, almost all engineering materials deform distinctively. Thus it is the information on failure mechanism under complex loading conditions that form the basis of developing constitutive models or failure criteria for them [13]. A thorough understanding of the behaviour of geopolymer binders under multiaxial stress states is necessary. In this regard, the stress-strain behaviour of the materials is usually investigated under a series of lateral confinements or more commonly referred to as "triaxial stress" conditions.

In the past, starting from as early as 1929, Richart et al. [14] made the pioneer investigation to understand the triaxial behaviour of concrete. Many researchers have studied the behaviour of ordinary and cement affluent, high and ultra-high strength fiber reinforced concretes (NSC, HSC or UHSFRC) under multiaxial compression. Various stress-strain models have been proposed, which can adequately regenerate the load-deformation behaviour of concrete under confinement, e.g., for the concrete material used in infilled steel tubular columns or concrete columns confined with high tensile strength fiber-reinforced polymer fabric and steel reinforcements, etc. [15]. Other researchers, e.g., [16–22], used the triaxial compression test results to predict the generalized strength enhancement, material deformation, residual strength capacity, and volumetric expansion for OPC concrete. However, some apparent differences in these studies are related to the type of concrete materials, including NSC or HSC, the presence of fibers, sample sizes, and the range of low or high confining pressures used during the tests.

On the other hand, the existing database on the triaxial compressive behaviour of geopolymer mortar, concrete, and composite materials is trivial. The existing studies only provide preliminary information on the triaxial stress-strain behaviour of geopolymer pastes. For example, amongst the very few, Giasuddin et al. [23] investigated the stress-strain characteristics of two differently graded geopolymer pastes, (i.e., high (85 MPa) and low (28 MPa) under a range of low confining pressures, i.e., $\sigma_3/f'_c \leq 0.40$, where σ_3 is the confining pressure, and f'_c denotes the compressive strength. Based on their test data, linear strength constitutive model as per Mohr coulomb's failure criteria and modified parabolic relation of Xiao et al. [24] with slightly different material constants was proposed. They concluded that the trend of strength enhancement of geopolymer paste is similar to OPC concrete under confinement. However, previous studies show that the constitutive relationships proposed for low levels of confinement ratios (σ_3/f'_c) may lead to an erroneous prediction of the material behaviour at higher levels of confinement [25]. Similarly, for critical axial strain corresponding to peak axial stress, they also modified Xiao et al. [24] parabolic equation proposed for axial deformation. The constant in the constitutive relation for geopolymer paste was found to be significantly lower than that of NSC or HSC. The fitted curves suggested increased stiffness in geopolymer material as compared to OPC concrete. Given that the conclusion may be valid for geopolymer binders due to their ceramics-like nature, however, it is believed that the finding may also stem from the difference in the employed load paths. In Xiao et al.'s tests [24], the longitudinal axial stress was only applied after the confining pressure reached a specified target value (i.e., proportional load path) instead of a standard loading path used by Giasuddin et al. [23]. The slopes of ascending portions of the stress-strain curves tend to be lower than that of the samples tested in uniaxial compression in the latter case and could be otherwise as reported in other investigations [21,26].

In another investigation [27], metakaolin based geopolymer mixtures containing varying silicon dioxide to sodium oxide (SiO_2/Na_2O) molar ratios were tested under uniaxial and triaxial compressive stress states. The primary goal of this research was to identify the influence of various SiO_2/Na_2O molar oxide ratios on the microstructure development of geopolymers and their modification under a set of low confining pressures. The microstructure of geopolymer intrinsically relied on the level of polymerization and the formation of Q^4 (nAl) network within the binding gels which control their failure modes under confinement. The research concludes that a well-formed geopolymer material fails in a brittle manner in uniaxial compression, while with an increase in the confining stress the failure mode changes from brittle to ductile.

Very recently, with an objective of using geopolymer cement in carbon storage sequestration wells, Nasvi et al. [28] carried out a numerical study to investigate the influence of various confining pressures (from 5 MPa to 25 MPa) on geopolymer materials prepared under different curing temperatures (i.e., from 23 °C to 80 °C). According to test results, at a given confining pressure, the deviatoric strength increased for geopolymer binders synthesized up to a temperature of 60 °C beyond which the increase in deviatoric strength reduced by 15% for all levels of curing temperatures. However, the geopolymer paste synthesized at 80 °C had lower uniaxial compressive strength in comparison to the samples cured at 60 °C or more moderate temperatures. As such, the stress-strain curve used for the calibration of the numerical model had lower peak axial stress value. Hence, a noticeable reduction in the deviatoric strength increase was not a surprise. Besides, for a given curing temperature, the increase in deviatoric strength at lower confinement levels (5 MPa–15 MPa) was more as compared to higher lateral confinements (20 MPa and 25 MPa). Although, as reasonable as this finding may be, the exact reason for the observed mechanical behaviour is unknown.

As apparent from the technical review, for the broader use of geopolymer composites in the construction of structures that could be potentially at risk of experiencing moderate to high levels of confinement, no research data are available in the literature. In the same way, no literature exists for the case where fibers are present in geopolymer mixtures to improve their ductility and the cracking is restrained from other sources such as confinement apart from the fiber reinforcement. Also, as highlighted above, two out of three investigations utilized heat curing method for the synthesis of geopolymer which could be a significant limitation for the proposed mixtures in a more generalized cast-in-situ situation. To the best knowledge of the authors, no study has been carried out in the past which comprehensively investigates the triaxial compressive behaviour of high-strength ambient cured geopolymer mortar and fiber-reinforced composite materials under a high level of confining stress.

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