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Mechanical properties of ambient cured one-part hybrid OPC-geopolymer concrete

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HIGHLIGHTS

- An ambient cured one-part hybrid OPC-geopolymer concrete is developed.
- Slump, setting time, compressive strength and microstructure are affected by OPC content of binder.
- Novel non-hygroscopic solid potassium carbonate activator is used.
- The type/amount of activators has some influence on the strength of hybrid OPC-geopolymer mixes.

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ABSTRACT

To produce geopolymers, a large amount of highly corrosive and hygroscopic alkaline activators, i.e, sodium hydroxide and potassium hydroxide, are commonly used. In this study, one-part hybrid ordinary Portland cement (OPC)-geopolymer concrete mixes were developed, in which solid potassium carbonate (7.5 wt% of the total geopolymeric raw materials) was used as the main activator and the OPC as a source of silicate and poly silicate was blended with geopolymeric raw materials (fly ash and ground granulated blast furnace slag) in different proportions. The influence of OPC content on the workability, setting time, compressive strength development and microstructure of the concrete mixes was investigated. It was found that the inclusion of OPC in geopolymer mixes reduced the workability and setting time but significantly increased the early age and ultimate compressive strength due to the quick reaction of OPC with alkali activators. By the inclusion of just 10% OPC in the binder system, the compressive strength at 28 days increased from 11.4 MPa to 33.4 MPa. Furthermore, control OPC concrete mixes were also prepared and tested. It was found that the percentage of strength increase at 28 days due to alkali activation decreased from 82.5% to 24.4% as the OPC content increased from 10% to 60%. Microstructural analysis was also conducted, which confirmed the coexistence of geopolymeric and CSH gels in the one-part hybrid OPC-geopolymer binder system.

1. Introduction

Geopolymeric materials have emerged as sustainable alternatives to Portland cement for a few decades. The term "geopolymer" was initially introduced by Davidovits [1]. Conventional forms of geopolymers are synthesised from a three-part mix, including high alkaline solutions of sodium hydroxide and sodium silicate with suitable concentration and geological origin materials such as metakaolin or industrial by-products such as fly ash and ground granulated blast furnace slag as a source of aluminosilicate [2]. To obtain suitable mechanical properties, heat treatment is often required during the geopolymerisation process to accelerate the reaction [3]. The outstanding properties of geopolymers such as high resistance to elevated temperatures and fire, high resistance to acids, salts and other corrosive materials, along with their environmentally friendly nature have resulted in considerable research and practical applications [4–6].

However, there are also two major drawbacks associated with the production of the conventional geopolymer concrete. Firstly, dealing with high concentration of corrosive and viscous alkaline solutions represents one of the main barriers for commercial applications. Secondly, the need of heat curing prevents the wide application of fly ash based geopolymer concrete since this type of concrete cannot be cured at ambient condition [7]. The geopolymer systems are usually subjected to heat curing for hours or even days at a temperature higher than 50 °C [8].

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In order to improve the geopolymerisation at room temperature, researchers incorporated various additives, such as slag, high calcium fly ash, calcium hydroxide and OPC, as additional calcium sources in geopolymer mixes [9–17]. The calcium sources were found to play an important role to shorten the setting time and improve the mechanical properties. For example, Nath and Sarker [9] replaced up to 12% of fly ash by OPC as a source of calcium silicate. In this experiment, alkaline activator solution of combined sodium silicate and sodium hydroxide was used, whilst the curing regime was ambient curing for all specimens. The authors concluded that the optimum mixture was achieved when OPC was used to replace 5% of the total binder and the ratio of liquid activator to the binder was 0.4. The mixture was cured at ambient temperature and set reasonably well compared to OPC concrete. Suwan and Fan [16] evaluated the effects of OPC replacement and mixing procedure on properties of geopolymers. The replacement ratio of fly ash with OPC varied from 5% to 70%, and its influence on the setting time, compressive strength and microstructure of the geopolymer was studied. Meanwhile, the sequence of adding fly ash, sodium silicate and sodium hydroxide was changed in the specimen preparation. Results showed that by increasing the amount of OPC from 5% to 70%, the setting time of geopolymer was significantly reduced from 24 h to 0.5 h while the early strength at 3 days increased from 0 to 21.91 MPa. It was also reported that the mixing sequence could directly affect the properties of geopolymer. A total of three mixing methods were adopted. In the first mixing method, fly ash was initially mixed with sodium hydroxide solution for 90 s before the sodium silicate was added. In the second method, sodium silicate and sodium hydroxide solutions were premixed and left over night and then fly ash was added during mixing. In the last method, fly ash, sodium hydroxide and sodium silicate were dry-mixed before adding water. It was found that only the third mixing sequence ensured the setting of the mix within the first 24 h. However, the mixes prepared using the first and second methods showed higher early strength as a result of enhanced chemical reaction. In another study conducted by Shehab et al. [17], mechanical properties of fly ash based geopolymer concrete mixes with a partial replacement of OPC were investigated by varying the OPC replacement ratio and activator solution concentration. The authors found that the mix with 50% OPC replacement had the highest compressive strength, splitting tensile strength, bond strength and flexural strength at 28 days.

One-part "just add water" geopolymer mixes are a newly developed class of geopolymers and their production is almost similar to that of conventional OPC concrete [18]. The development of one-part geopolymers aims to promote the large scale application of geopolymers in construction industry. For most recently developed one-part mixes, aluminosilicate precursors were blended with solid activators and reactions began once water was added to the solid mix. Hajimohammadi et al. [18–20] conducted studies to address the kinetics of geopolymerisation in one-part mixes. In their experiments, geothermal silica was utilised as a source of solid silica and solid sodium aluminate as a source of alkali and alumina. The water content was found to play a major role in the formation of crystallites as a result of rapid dissolution of the alumina and slow dissolution of the silica sources in low water conditions. Furthermore, the early availability of silica and alumina is essential for geopolymer development. However, in their research, the procedure of purifying the raw geothermal silica was rather complicated and also the samples required heat curing at 40 °C for 2 weeks which limits the large scale application of this type of concrete. They also recently evaluated the nanostructure, microstructure and mechanical properties of the one-part fly ash-based binders at different H_2O/Na_2O molar ratios [21]. The one-part mix with Si/Al molar ratio of 3.6 and H_2O/Na_2O molar ratio of 12 gave a compressive strength of 65 MPa after 3 weeks. Attempts by other research groups have also been made to synthesise one-part mixes under ambient temperature curing conditions by incorporating commonly used aluminosilicate sources with solid activators. Yang et al. [22] and Yang and Song [23] performed some studies in which pure fly ash and pure slag were activated using either sodium silicate powder or combination of sodium silicate and sodium hydroxide powders at ambient temperature. When 100% slag was used, the 28-day compressive strength could reach 50 MPa; but the corresponding figure was just 9.45 MPa for pure fly ash systems. To avoid the use of highly hygroscopic and corrosive sodium hydroxide powder, Nematollahi et al. [24] attempted to improve the strength of one-part geopolymer mixes by using different grades of sodium silicate activators, whilst different combinations of fly ash, slag, hydrated lime and three different grades of sodium silicate and a combination of sodium silicate and sodium hydroxide powders were used. The authors reported the feasibility of synthesising one-part geopolymers using solid silicate activators, and obtained a compressive strength of 37 MPa under ambient temperature curing conditions.

Previous efforts to make one-part geopolymers, however, were mainly focused on geopolymer pastes and mortars. To promote the application of one-part geopolymers in engineering practice, further studies on geopolymer concrete are required since the coarse aggregate strikingly affects the mixture properties. Moreover, the commonly used solid activators are hygroscopic and in case of their movement to the surface of concrete during curing or in service, there could be a tendency toward efflorescence, high permeability and water absorption [24]. It has been found that adding OPC in one-part geopolymer systems in the presence of non-hygroscopic alkaline salts such as sodium carbonate and potassium carbonate as activators remarkably enhanced the compressive strength and accelerated the setting time at ambient temperature [25]. This type of blended OPC-geopolymer is relatively cheap and has currently been produced on commercial scale. Typically, it comprises 80% OPC and 20% of geocement, where the calcium silicate and alumina-silicates as geopolymeric materials are activated by potassium carbonate and retarded with citric acid. Also this blended cement-geopolymer has been recognised in the construction industry for its potential to rapidly achieve very high early strength [26]. Moreover, using potassium instead of sodium was reported to reduce efflorescence as potassium is more strongly bound to the aluminosilicate gel framework and potassium carbonate crystals are usually less visually evident than their sodium counterparts [27].

The aim of the present study is to develop ambient temperature cured one-part hybrid OPC-geopolymer concrete mixes using solid potassium carbonate as the main activator. It is expected that the one-part concrete mixtures can be directly used to cast structural members. In this regard, one-part hybrid OPC-geopolymer mixes with different replacement ratios of geopolymeric raw materials (fly ash and slag) by OPC ranging from 10% to 60% were activated by solid potassium carbonate. To evaluate the contribution of alkaline activation to strength development, control OPC mixes were also made, which had the same proportions as the hybrid OPC-geopolymer mixes but without any activator. As the mixes with high percentage of OPC (30–60 wt%) had a high risk of flash setting as a result of rapid chemical reaction between calcium silicates (in the OPC and slag) and alkaline activators [16], citric acid was used as a retarder. The influence of additional calcium hydroxide and sodium silicate in the activator on the strength development is also evaluated. Furthermore, the influence of OPC content and the use of solid potassium carbonate on the workability, setting time, compressive strength development and microstructure of the concrete mixes are investigated. Microstructural analyses were also performed to explain the observed behaviour.