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Pervious concrete made of alkali activated slag and geopolymers

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HIGHLIGHTS

- Alkali activated slag and geopolymers were synthesized for pervious concrete.
- Ambient cured clinker-free alkali activated materials were used.
- Alkali activated materials are suited for the in-situ production of pervious concrete.
- Better mechanical properties and water permeability than those of cement were reached.
- Metakaolin-slag geopolymer showed best mechanical properties and water permeability.

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ABSTRACT

In this paper, clinker-free cementitious binders were synthesized to produce ambient temperature cured pervious concrete of high aggregate-to-binder ratio. The binders are alkali activated slag, metakaolin geopolymer and metakaolin-slag geopolymer. Effects of aggregate size and binder type on the physical properties of resultant pervious concrete were studied in terms of compressive strength, density, total porosity and water permeability. Reaction products of binding materials were measured using X-ray diffraction (XRD) to study the reaction mechanisms. The pervious concretes produced in this work are not only environmentally friendly, but also achieved better mechanical properties and water permeability than cement pervious concretes.

1. Introduction

Pervious concrete, also known as permeable concrete, is a special type of concrete with high porosity used for concrete flatwork [1]. The carefully controlled amount of cement paste, which in some cases contains supplementary cementitious materials (SCM) and chemical admixtures, plays the role of coating and binding the aggregate together [2]. Unlike conventional concrete, aggregates used for pervious concrete are normally of uniform particle size or have a narrow particle size distribution [1–3]. Due to the limited quantity or absence of fine aggregate, substantial amount of interconnected macro-pores are formed in this concrete system [4,5]. Generally, the porosity of pervious concrete is in the range of 15% to 35% by volume [1]. Studies have demonstrated that pervious concrete pavement possesses environmental benefits of decreasing storm water runoff, reducing the Urban Heat Island (UHI) effect, removing water pollutants, maintaining groundwater levels, etc [6–8]. All these make pervious concrete an eco-friendly strategy for the low-impact development of pavements [9]. Field investigations of sidewalks, parking lots, recreation squares constructed using pervious concrete have been conducted in many countries [6]. The high porosity content of pervious concrete contributes to water infiltration, but results in significant decrease in mechanical strength [1,6]. As summarized by many authors [1,10], the typical water permeability of cement pervious concrete is 2–12 mm/s, while the corresponding compressive strength varies in the range of 25–5 MPa. To date, increasing attention has been drawn from academic and industrial fields to balance the water permeability and mechanical strength of pervious concrete products.

The general aggregate-to-binder ratio of cement based pervious concrete is in the range of 4–6 by mass [1]. Studies have demonstrated that increasing the aggregate-to-binder ratio results in the significant decrease in both compressive strength and static elastic moduli of the resulting pervious concrete [11,12]. Ghafoori and Dutta reported that aggregate gradation has significant influence on the properties of pervious concrete [13]. The addition of fine aggregate not only contributes to increase mechanical strength, but also improves the freeze-thaw resistance of resultant products [14,15]. Kevern [16] stated that the freeze-thaw deterio-

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ration of pervious cement concrete is directly related to aggregate type. Recently, polymers have been used to modify the performance of pervious concrete. Studies have shown that polymer fibers are helpful in increasing permeability, improving tensile strength, or enhancing the freeze-thaw resistance of cement pervious concrete [17,18]. However, special attention should be paid on the selection of polymer, since some macro-synthetic fibers, for example polypropylene, were reported to reduce the permeability of resulting pervious concrete [19].

The main part of the ecological footprint of pervious concrete results from the use of ordinary Portland cement (OPC). Statistical results show that over 3000 MJ of energy is consumed to produce one ton of cement even using the best available techniques (BAT) in European [20]. The worldwide average CO_2 emission is approximately 0.82 kg of per kg cement, making the cement industry accounts for around 5% of global CO_2 emissions [20,21].

Over the years, efforts have been made in reducing the greenhouse gas emission for sustainable development of road. Reducing the consumption of cement clinker by blending SCMs is one of the effective practices. Yang and Jiang [22] revealed that the addition of silica fume in cement pervious concrete could obviously enhance its strength. In addition, the combination of silica fume and superplasticizer had synergistic effect on improving the abrasion resistance of pervious concrete [22]. A ternary cementitious system containing cement, slag and fly ash provided a better workability, higher strength and a better long-term performance than its OPC counterpart [23,24].

To better meet the sustainable development of pavement, work has been ongoing in looking for clinker-free cementitious binders. Alkali activated materials (AAM) are among the most widely researched alternative binders for construction. The alkali activation system is generally classified into alkali activated slag (AAS) and geopolymer, depending on the chemistry of structure dominating gels. The main reaction product of AAS is calcium aluminosilicate hydrates (C-A-S-H) gel [21,25]. C-A-S-H differs from C-S-H (main product of OPC hydration) in chemical composition and structure, since the penetrated Al^{3+} mainly exists in tetrahedral bridging sites within the silicate chains of C-A-S-H [25]. In contrast, the alkali activation of metakaolin (MK) and siliceous fly ash (FA) forms geopolymer, which is composed of highly cross-linked, structurally disordered aluminosilicate gels (N-A-S-H) [26,27]. In contrast to C-A-S-H, the geopolymer is poor in calcium [21]. Though they lack long-range crystalline order, geopolymers are reported to share the nanostructural features of zeolites in chemical sense [21]. By investigating the coordination of silicon and aluminium geopolymer, Duxson et al. [28] reported that substitution of silicon by aluminium takes place inside the gel framework and the associated negative charge is balanced by alkali cations. In spite of the differences in composition and nanostructure between C-A-S-H and N-A-S-H, both gels are estimated to possess excellent mechanical and physicochemical durability properties [28,29]. Therefore, superior mechanical properties to traditional cementitious binders are certainly achievable by AAM under well-designed synthesis procedure [29]. In addition, AAM is reported to be environmentally friendly because it can reduce CO_2 emission by 9–97% in comparison with OPC [21].

Environmentally friendly pervious concretes have been developed using FA geopolymer as binder [30–32]. According to Thoin et al. acceptable compressive strengths of 8.4–11.4 MPa were obtained even increasing the aggregate-to-binder mass ratio to 8 [30]. In a study conducted by Sata et al. [32], effect of aggregate type on performance of FA geopolymer pervious concrete was investigated. FA geopolymer pervious concrete manufactured using natural coarse aggregate achieved the highest mechanical strength, while those made using recycled aggregate from crushed structure concrete had the best water permeability. However, due to the low reactivity of FA, pervious concrete produced using FA based geopolymer normally require curing at elevated temperatures. This brings difficulty to the in-situ application of FA geopolymer pervious concrete.

In this work, ambient cured binders, i.e. AAS using ground-granulated blast furnace slag (GGBS) as solid precursor, MK geopolymer (MKG) and MK-GGBS geopolymer (MGG), were synthesized. To test the suitability of these binders for the production of superior pervious concrete, a high aggregate-to-binder ratio was used. Effects of aggregate size on the compressive strength, density, total porosity and water permeability of resultant pervious concrete were studied. Properties of pervious concretes produced using different binders were compared. Reaction products of AAS, MKG and MGG were analysed using X-ray diffraction (XRD) to study the reaction mechanism. The results of this work might be valuable for the development of sustainable pervious concrete.

2. Materials and methods

2.1. Materials

Commercially available MK and GGBS were used in this study. The bulk chemical compositions were determined using X-ray fluorescence and are listed in Table 1. The Blaine specific surface area value of MK and GGBS were 5397 cm^2/g and 4224 cm^2/g, respectively.

Powder XRD measurement was applied to study the mineral composition of MK and GGBS, the obtained data were then quantitatively analysed using Rietveld refinement method (details about the measurement are given in section 2.5 and quantification method can be found in [33,34]). The XRD patterns of MK and GGBS are shown in Fig. 1, and the quantitative results are listed in Table 2.

Our previous study [34] has demonstrated that mainly the amorphous phase in MK and GGBS undergo geopolymerization. Zhang et al. [35] recommended to use the composition of amorphous phases to assess the suitability of solid precursors for AAM synthesis. Chemical compositions of amorphous phases in MK and GGBS were obtained by subtracting the mineral components from the bulk composition and are shown in Table 3.

NaOH solution of 9 mol/L and commercial sodium silicate solution ($Na_2O(SiO_2)n{\cdot}xH_2O$, containing 23.7 wt% SiO_2, 16.4 wt% Na_2O and 59.9 wt% H_2O, with a SiO_2/Na_2O molar ratio of 1.5) were used as alkali activators in this work. Analytical grade NaOH pellets were first dissolved in deionized water, and stored in an airtight container for at least 24 h prior to use for cooling down to room temperature.

Three sets of binders were synthesized for the manufacture of pervious concrete. The oxide molar ratios of each set are listed in Table 4. The oxide molar ratios were calculated based on the chem-

Table 1
Bulk chemical composition of MK and GGBS, given in % by weight.

	Al_2O_3	SiO_2	CaO	Fe_2O_3	MgO	P_2O_5	TiO_2	MnO	Na_2O	K_2O	Sulfur[a]	Sulfide	LOI[b]
MK	32.58	61.24	0.13	1.17	0.15	0.05	1.64	n.d.[c]	0.17	0.63	0.07	n.d.[c]	1.76
GGBS	10.53	40.28	34.54	0.39	8.63	0.15	0.40	1.14	0.59	1.62	2.19	0.71	0.47[d]

a, sulfur as SO_3; b, loss on ignition up to 950 °C; c, non-detected; d, tested in protective gas atmosphere.