



Carbonation resistance of fly ash and blast furnace slag based geopolymer concrete

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HIGHLIGHTS

- The carbonation resistance of fly ash (FA) & blast furnace slag (BFS)-based geopolymer (GP) concrete were investigated in detail by theoretical analysis and the accelerated carbonation test.
- Carbonation rates of the ambient cured GP concrete and GP mortar were modeled by power functions.
- The influencing factors of carbonation rate of GP concrete were clarified, including retarder addition, BFS's ratio and fineness, NaOH content, and curing temperature, etc.
- The relationship between carbonation resistance and compressive strength of GP concrete was discussed.

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ABSTRACT

For putting geopolymer (GP) to practical use in reinforced concrete, the carbonation resistance of GP concrete should be clarified. In this study, the carbonation depths of various GP concrete and GP mortar, of which the aluminosilicate materials were fly ash (FA) and ground blast furnace slag (BFS), were measured by the accelerated carbonation test at different elapsed times. The relationship between the carbonation depth and the elapsed time were further examined based on the experimental results and by theoretical analysis. A root function was proposed to describe the carbonation rate of FA&BFS-based GP concrete. Finally, the influencing factors of carbonation resistance of FA&BFS-based GP concrete were discussed through a comparison of carbonation rate coefficients. It is mainly concluded that the carbonation resistance of FA&BFS-based GP concrete cured at room temperature is lower than usual concrete using Ordinary Portland Cement (OPC). The carbonation resistance increases with the increase of BFS ratio in active fillers (AF), NaOH content in active activator solution (AS), and BFS fineness, or with the decrease of AS/AF ratio, and water/AF ratio. Moreover, heat curing and the use of the retarder are benefit to the carbonation resistance of FA&BFS-based GP concrete.

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1. Introduction

Ordinary Portland Cement (OPC) is produced along with much energy consumption and limestone decomposition. Cement industry emits so much CO₂ that accounts for 5–7% of national CO₂ emission [1,2]. Geopolymer (GP) is a type of inorganic polymer that can make from industrial waste or by-product, and can harden even at room temperature so that it would function as a binder in concrete like OPC. GP has been proved to be advantage over OPC concrete in early strength growth, and in the resistances to fire and aggressive

chemicals [3–6], thus it is considered as a potential alternative to OPC.

The most readily available source materials of GP are fly ash (FA) and ground granulated blast furnace slag (BFS), which are aluminosilicate minerals composed of aluminum, silicon, and oxygen, etc. FA-based geopolymer can cut down about 60% CO₂ emission, compared to OPC [7]. However, in order to improve the strength of FA-based geopolymer cured at room temperature, BFS has to generally be blended. In addition, alkali-activated slag is also thought to be an alternative to OPC.

There are many investigations on the three kinds of alkali-activated materials-FA, BFS, and FA&BFS-based GP concrete. But these investigations are mainly focused on recipes, mechanical properties, and reaction products. However, for putting GP to

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practical use in reinforced concrete, detailed investigation of GP concrete's durability, especially carbonation resistance, is very necessary [8].

Adam, et al. [9] compared the carbonation resistances of FA-based GP concrete cured at 80 °C, BFS-based GP concrete, and BFS-OPC blended concrete by the accelerated carbonation test in the ambient air of 20 °C, 70% R.H., and 20% of CO₂ concentration. The latter two concretes were cured at room temperature. They found that the FA-based GP concrete didn't show a clear boundary between the carbonated and non-carbonated area after sprayed the phenolphthalein solution. Also, it was found that BFS-based GP concrete has a lower carbonation resistance than FA-based GP and OPC-BFS blended concretes since BFS-based GP concrete specimen had more inside micro-cracks, and its C–S–H gel has in general a lower Ca/Si ratio than the C–S–H in OPC concrete. The C–S–H gel with low Ca/Si ratio is thought to carbonate faster than the general C–S–H gel. Adam, et al. [10] also measured the pH changes of FA-based GP mortars, which were mixed with different alkali activators, during accelerated carbonation under 20 °C, 70% R.H., and 5% of CO₂ concentration. The pH values of the GP mortars fell from 12 to 11 after carbonated. Initial pH (=12) of GP mortar was smaller than that (pH = 13) of OPC concrete, but final pH (=11.0) was higher than OPC concrete (pH = 9.0). This results are nearly consistent with the Davidovitz's finding that pH ranges of GP concrete are 11.5–12.5, and 10.0–10.5, respectively before and after carbonation [11]. Based on this result, Adam, et al. concluded that GP concrete with the pH value of over 11, which is a safe value for preventing reinforcing steel from corrosion, would be achieved by using adequate alkali activator and aluminosilicate materials.

Song, et al. [12] investigated the carbonation resistance of BFS-based GP mortars, mixed with different amounts of alkali activator and cured in sealed state, by measuring their carbonation depths and the micro-structures before and after carbonated. They found that before carbonation, there were C–S–H gel and few aluminum compounds but no portlandite (Ca(OH)₂) in the BFS-based GP mortars. However, the C–S–H gel is more vulnerable to CO₂ than that in OPC paste. After carbonation, the C–S–H gel changed to silica gel, and the aluminum compounds completely disintegrated. Thus, the carbonation resistance of BFS-based GP is lower than that of OPC. However, they suggested that as the alkali activator content increased, the carbonation resistance of BFS-based GP was improved.

Bernal, et al. [13] detected and compared the changes in the nano-structures of BFS-based GP, FA-based GP, and FA&BFS-based GP before and after carbonation in detail. It was found that N–A–S–H is a main product in FA-based GP and almost can't be disintegrated by carbonation, and only the alkali activator in the pores is neutralized by CO₂. However, once BFS is blended in GP, the C–A–S–H gel is also formed. The C–A–S–H gel would be decalcified in CO₂ environment to cause the structural transformation at a relatively greater degree.

Criado, et al. [14] examined the effect of curing condition on the early carbonation, and concluded that heat curing with surface sealing can prevent the early carbonation and make the alkali activated FA paste to reach a high degree of polycondensation reaction. The reaction degree affects GP paste's strength and carbonation resistance.

Pasupathy, et al. [15] investigated continuously the carbonation degrees of two kinds of FA&BFS-based GP concretes in the air for 8 years. On basis of supposing that the carbonation depth of GP concrete is a root function of elapsed time (t, year) as $x = K\sqrt{t}$, the authors concluded that the carbonation rate coefficient K (mm/ $\sqrt{\text{year}}$) is positively correlated to the permeability, porosity, and pore size of GP concrete. They also found that the GP concrete, only using NaOH or KOH solution as alkali activator, had a greater car-

bonation resistance than that using NaOH or KOH together with sodium silicate.

In summary, up to now, 1) there are still few studies on the carbonation resistance of GP concrete, 2) most of studies are for the GP concretes cured at elevated temperature, 3) influencing factors of carbonation resistance were not yet clarified, and 4) there is no carbonation rate model to predict the carbonation depth of GP concrete at any age. However, the carbonation rate of concrete correlates closely with the service life of reinforced concrete.

In fact, if curing in the ambient air, FA-based GP concrete sets slowly, and has a small ultimate strength [16]. In order to attain a practical compressive strength, BFS is generally mixed together with FA. With the mix of BFS, the setting time becomes short but the strength increases [16,17]. The similar results were observed in our experiments [18]. Even if FA & BFS-based concrete has practical strength, too short setting time or handling time less than one hour would result in a difficulty of practical use in construction site. Li, et al. successfully developed a retarding admixture for FA&BFS-based GP concrete [19]. The retarder can prolong the setting time of FA&BFS-based GP concrete by 1.5–2.3 times, together with almost not giving bad effect on the compressive strength. However, the carbonation resistance of FA&BFS-based GP concrete using retarder has not yet been investigated.

FA&BFS-based GP concrete not only can recycle much waste discharged from thermal power station, but also it has a practical strength even though cured in the ambient air. In order to clarify the carbonation resistance of FA&BFS-based GP concrete, in this study we first investigated the carbonation depths of FA&BFS-based GP concretes and mortars by the accelerated carbonation test. Then a carbonation rate model was proposed to describe the relationship between the carbonation depth and the elapsed time. Furthermore, the influencing factors of the carbonation rate of FA&BFS-based GP concrete were discussed, including alkali activator content, replacing ratio of BFS, alkali activator sort, fineness of BFS, retarder, ratio of alkali activator to active filler, curing temperature, and compressive strength, etc.

2. Experimental program

2.1. Raw materials used

Besides the fly ash that met the quality standard of JIS (Japanese Industrial Standards) fly ash grade II, three kinds of BFS with different fineness were used as active filler (AF) of GP concrete in this study, of which physical properties and chemical compositions are shown in Table 1. Fine aggregates used in GP concrete and GP mortar were river sand and sea sand with specific gravity of 2.60 and 2.57, respectively. Coarse aggregate used in GP concrete was crushed limestone with specific gravity of 2.70, and a maximum size of 20 mm. The specific gravity of aggregate was measured in the saturated surface-dry state. Fine and coarse aggregates were used under the saturated surface-dry condition. The retarder (R) is an inorganic compound with specific gravity of 1.78.

Four kinds of alkali activator solutions (AS), named AS₁, AS₂, AS₃ and AS₄ were used in GP concretes. They were mixtures of water glass aqueous solution (WG) and sodium hydroxide solution (NH) according to the volume ratios shown in Table 2. The WG was prepared by diluting JIS No.1 grade water glass with distilled water by a volume ratio of 1:1. The concentration of NH was 10 mol.

2.2. Mix proportions of GP concrete and mortar

In our experiments, 14 kinds of GP concretes and 9 kinds of mortars with different mix proportions, as summarized

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