



An assessment on parameters affecting the carbonation of alkali-activated slag concrete



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ARTICLE INFO

Article history:

Received 7 October 2016

Received in revised form

1 April 2017

Accepted 14 April 2017

Available online 22 April 2017

Keywords:

Alkali activated

Concrete

Slag

Carbonation

Microsilica

Alkaline solution

Curing

ABSTRACT

This study investigated the factors affecting the carbonation of alkali-activated slag concrete (AASC). Concrete durability plays an important role in the longevity of concrete structures, but aggressive chemical agents can leave major undesirable impacts on the durability of concrete. One of such chemical agents is CO₂ gas, whose penetration into concrete leads to a carbonation process which facilitates the electrochemical corrosion of steel reinforcements. One of the weaknesses of alkali-activated slag concrete in comparison with Portland cement concrete is its lower resistance against carbonation. Thus, in this paper, we studied the effect of such parameters as alkaline solution to slag ratio, partial replacement of slag with microsilica, compressive strength, and curing method on the carbonation of alkali-activated slag concrete. The samples were subjected to accelerated carbonation by being placed in a CO₂ gas chamber for two cycles of 14 and 28 days, and then the resulting depth of carbonation was measured and analyzed. A sample of ordinary Portland cement concrete was used as the control sample. The SEM images taken from the samples were studied to determine the changes in the structure of the cement paste. The results showed that the replacement of 15% of slag with microsilica has a significant positive effect on the carbonation depth of alkali-activated slag concrete. Compared with the exponential relationships offered for ordinary concrete in the literature, the relationship between compressive strength and carbonation depth of AAS concrete was linear. The results showed that carbonation depth decreases with increase in compressive strength and decrease in AAS concrete permeability.

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1. Introduction

The desirable features of Portland cement concrete such as the ample availability of the raw materials and valuable technical features have marked it as one of the best and most popular construction materials (Rashad and Zeedan, 2011). One of the drawbacks of using this concrete, however, is the production process of Portland cement, as producing one ton of this cement takes about one and a half tons of raw materials and releases 0.94 ton of carbon dioxide into the environment (Gartner, 2004; Rashad and Zeedan, 2011). The dual role of concrete and cement, i.e. their positive effect on building industry and their adverse effect on the environment, has encouraged further research on the development and use of new technologies to reduce the consumption of cement in concrete production. Partial replacement of Portland cement with pozzolanic materials, such as microsilica and fly ash, or

cementitious materials, such as blast furnace slag, is one of the available strategies for producing environment-friendly concrete and reducing Portland cement consumption and its associated negative effects. Blast furnace slag is of significant importance in this regard, as its high calcium content allows it to function like ordinary Portland cement. In presence of an alkaline solution, the slag reacts with water and creates a binding property, and when mixed with sand and gravel, it creates alkali-activated slag concrete. The environmental impacts of the production of alkali-activated slag concrete and its energy consumption are 70% and 60% less than those of the ordinary concrete, respectively. Thus, alkali-activated slag concrete can be used as an alternative in concreting applications (Li et al., 2004; Weil et al., 2009). Although, fly ash can be used as an alternative binder in alkali-activated concretes, strength development of these concretes at room temperature is slow, limiting the application of the material (Kovtun et al., 2016). Yang et al. (2013) reported that the reduction rate of CO₂ emission of alkali-activated concrete commonly ranged from 55% to 75% of that of the ordinary Portland cement (OPC) concrete.

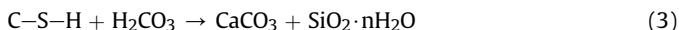
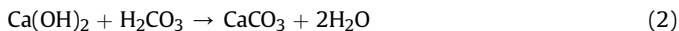
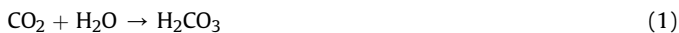
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Also, Yang et al. (2014) showed that the CO₂ emission of alkali-activated slag foamed concrete was considerably lower (from 85% to 93%), compared to that of the typical OPC foamed concrete. Shojaei et al. (2015) demonstrated that the CO₂ footprint of AAS concrete efficiency was approximately 29% less than that of the comparable concrete containing 100% OPC binder. Mithun and Narasimhan (2016) evidenced that alkali-activated slag concrete mixes with copper slag as fine aggregate provide several environmental and economic benefits.

Durability of reinforced concrete has been widely studied. The process of carbonation caused by penetration of CO₂ into concrete is considered as one of the major factors behind the deterioration of reinforced-concrete structures. The outer surface of the steel embedded in concrete is covered by a very thin oxide layer, which protects it against corrosion. This oxide layer is formed and remains stable in concrete's strongly alkaline environment (pH of about 13). However, when the carbonation process reduces the pH of the environment to about 9, it destroys this layer and clears the path for the corrosion of the reinforcement (Oh et al., 2003).

Carbonation process starts as CO₂ reacts with water, producing weak carbonic acid, Eq. (1). This weak acid, then, reacts with cement hydration products, Eqs. (2) and (3), to form the calcium carbonate and water, leading to the reduced alkalinity of the concrete (Steffens et al., 2002; Torgal et al., 2012).



The two main factors that initiate the reinforcement corrosion process through the elimination of the alkaline protective cover are carbonation and chloride penetration (Tuutti, 1982; Kazmierczak, 1995; Hussain and Ishida, 2010). Some researchers have investigated the effects of carbonation on chemical composition, reduced porosity, and permeability of cement paste (Peter et al., 2008; Fabbri et al., 2009; Tonoli et al., 2010; Almeida et al., 2013). Others have provided mathematical and statistical models for estimating the rate and depth of carbonation (Liang and Lin, 2003; Monteiro et al., 2012; Silva et al., 2014; Kari et al., 2014; Zha et al., 2015; Kashef-Haghighi et al., 2015).

Kuosa et al. (2014) examined the effect of freezing-thawing cycles, carbonation, and chloride penetration on the durability of concrete. The results of the study showed that freezing-thawing cycles increase the migration of chloride ions and the depth of carbonation, and that the presence of chloride lead to lower carbonation depth. Several studies have investigated using recycled aggregates and their impact on carbonation depth (Kou and Poon, 2012, 2013; Amorim et al., 2012; Pedro et al., 2014; Cartuxo et al., 2016). The results have indicated that using recycled aggregates increases carbonation depth. Some researchers have studied the relationship between compressive strength and carbonation depth under accelerated conditions (Rabehi et al., 2013; Lo et al., 2016). The results have shown that higher compressive strength lead to lower carbonation depth. Researchers have also studied the extent to which carbonation depth is a function of such factors as applying paint on a concrete surface (Park, 2008; Franzoni et al., 2013; Lo et al., 2016), using such minerals as microsilica and limestone, or such mix design parameters as water-cement ratio and cement type (Leemann et al., 2015). Shi et al. (2016) studied the effect of three types of superplasticizer on carbonation depth, and reported an optimal value for each type. Overall, they demonstrated that using superplasticizer reduces the carbonation depth. Mo et al. (2016) investigated the carbonation process of Portland cement

mortars and using magnesium oxide (MgO) and fly ash as alternatives for cement. The results indicated that replacing cement with magnesium oxide and fly ash reduces the carbonation resistance of the resulting mortar.

Alkali-activated slag binders provide better mechanical properties and penetration resistance than Portland cement (Bernal et al., 2014a,b). Recently, researchers have developed alkali-activated binders with different mixtures, including the mixture of slag and fly ash (Dombrowski et al., 2007; Bernal et al., 2013; Ismail et al., 2013; Abdalqader et al., 2016), the mixture of fly ash and metakaolin (Ruiz-Santaquiteria et al., 2012), and the mixture of slag and metakaolin (Buchwald et al., 2007; Yip et al., 2008; Bernal et al., 2011; Burciaga-Díaz et al., 2013; Bernal, 2015). According to some researchers, one of the disadvantages of alkali-activated binders, as compared with Portland cement, is their weak resistance against carbonation (Deja, 2002; Palacios and Puertas, 2006; Puertas et al., 2006). Recent research has indicated that the carbonation mechanism in alkali-activated binders highly depends on the type of the precursor (Bernal et al., 2010; Bernal et al., 2013, 2014), the type of the activator (Palacios and Puertas, 2006), and the conditions of the accelerated carbonation test (Bernal et al., 2012; Bernal et al., 2015). Duan et al. (2016) studied the effect of nano-TiO₂ on the depth of carbonation in fly ash-based geopolymer paste. The results of the study showed that using nano-TiO₂ improves the carbonation resistance of the paste. Bernal (2015) assessed the effect of activator dose and using metakaolin on the carbonation depth of alkali-activated slag mortars. The results indicated some optimal doses for this application. Badar et al. (2014) investigated the carbonation of reinforced geopolymer concrete. They used three types of fly ash with different calcium contents and showed that fly ash-based geopolymer concrete with lower calcium content has better resistance against carbonation. Research has also indicated that alkali-activated materials are more vulnerable to accelerated carbonation conditions (Bernal et al., 2012). Bernal et al. (2014a,b) reported that carbonation depth in alkali-activated slag binders depends on the chemical compounds of the slag, and particularly on its MgO content. They demonstrated that Spain slag, which has a higher MgO content, has a lower carbonation depth.

The average CO₂ concentration in the atmosphere is about 400 ppm (0.04 percent) (Earth System Research Laboratory, 2016). Consequently, the rate at which CO₂ penetrates a hard surface, such as concrete, is extremely low. As a result, different methods have been developed to accelerate the assessment of carbonation depth in cementitious materials. These methods are based on exposing a sample to high CO₂ concentrations under controlled conditions. The majority of standards have suggested that accelerated carbonation tests must be performed in tanks which provide full control over ambient conditions including CO₂ concentration, relative humidity, and temperature. Most of these standards have recommended CO₂ concentration of 3 ± 2 percent, relative humidity of 60 ± 10 percent, and temperature of 21 ± 3 °C for these tests (NT Build 357, 1989; LNEC E 391, 1993; AFPC-AFREM, 1997; EN 13295, 2004; ISO/CD 1920, 2012). The common practice for measuring carbonation depth is using phenolphthalein solution (Villain et al., 2007; EHE-08, 2008; Morandea et al., 2014, 2015), but curcumin has also been suggested as an alternative to phenolphthalein (Chinchón-Payá et al., 2016).

The type of relationship between compressive strength and carbonation depth in AAS concrete has not been studied previously. The present study, using accelerated carbonation tests, investigated the effects of different values of alkaline solution to slag ratio (AS/S = 0.55, 0.50, 0.45, 0.4), replacing slag with microsilica (5 wt%, 10 wt%, 15 wt%), compressive strength, and curing method including water curing and curing under a plastic cover, on the

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