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Effect of nano-silica on the efflorescence of waste based alkali-activated inorganic binder



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HIGHLIGHTS

- Nano-silica reduced the efflorescence extent of waste based alkali-activated inorganic binder.
- Nano-silica improves the microstructure of alkali-activated inorganic binder.
- Compressive strengths of samples were improved by addition of nano-silica.
- Nano-silica accelerated the geologic polymerization reactions of alkali-activated inorganic binder.

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ABSTRACT

The efflorescence caused by carbonate weathering is one of the dominant causes of deterioration of alkali-activated inorganic materials. In order to inhibit the efflorescence of waste based alkali-activated inorganic binder, the effects of nano-silica on the compressive strength, carbonate ions concentration, hydration rate and pore size distribution of the obtained alkali-activated inorganic binder have been investigated, and the efflorescence inhibition mechanism has been also analyzed. The results revealed that compressive strength and microstructural properties could be further developed with inclusion of nano-silica in alkali-activated inorganic binder. In addition, the efflorescence decreased with increasing nano-silica content and decreasing of the nano-silica particle size. Besides, the hydration rate results indicated that the hydration of waste based alkali-activated inorganic binder was accelerated before hydration for 3d with the incorporation of nano-silica. The suggested inhibition mechanisms discussed were mainly; micro-aggregate filling effect, induced nucleation, and accelerated hydration effects of nano-silica.

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1. Introduction

Granulated blast furnace slag (GBFS) and steel slag are latent hydraulic materials which can be activated by alkaline solutions, such as $\text{Na}_2\text{O}\cdot n\text{SiO}_2$, NaOH , Na_2SO_4 and Na_2CO_3 , to form alkali-activated inorganic materials, which were initiated reported by Davidovits [1]. Alkali-activated inorganic materials have drawn much attention recently due to their wide range of raw materials, low energy consumption and lower emission of CO_2 than that of Portland cement [2]. Compared with cements, ceramics and

metals, Alkali-activated inorganic binder materials offered a number of important performance advantages, such as early high strength [3–7], high frost resistance [8], strong anti-erosion ability [9–11], low permeability [12–14] and good fire resistance behavior [15–18]. However, the application of alkali-activated inorganic binder materials is limited because of some disadvantages existed that cannot be ignored, such as high drying shrinkage [19], high rate of carbonation [20] and the efflorescence [21].

At present, the widely accepted theory about hydration mechanism of alkali-activated inorganic binder is that, raw materials containing aluminosilicate (usually in the form of amorphous as well) could be dissolved to free $\text{Al}(\text{OH})_4^-$ and $\text{SiO}(\text{OH})_3^-$ ions under strong alkaline condition, and then gradually polymerized to form $(-\text{Si}-\text{O}-\text{Al}-)$, $(-\text{Si}-\text{O}-\text{Al}-\text{O}-\text{Si}-)$, $(-\text{Si}-\text{O}-\text{Al}-\text{O}-\text{Si}-\text{O}-\text{Si}-)$ structure with

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increasing of the precursor $\text{Al}(\text{OH})_4$ and $\text{SiO}(\text{OH})_3$ ions [22], or to form C-A-S-H or C-S-H gel [23,24]. Thus, the industrial solid waste containing aluminosilicate can be effectively used to prepare the geopolymeric materials or alkali-activated materials, which improved the utilization rate of industrial solid waste. However, high content of soluble alkali were used to prepare alkali-activated inorganic materials, and the soluble alkali ions can be dissolved out from alkali-activated inorganic binder material surface and reacted with carbon dioxide in the air to form bicarbonate, which hindered the practical application of alkali-activated inorganic materials.

Efflorescence usually produced on the surface of the porous building materials [25] and generally appeared as white powder, nodular or floccule [26]. It is like vitiligo in the architecture surface, which seriously affects the beauty of buildings and engineering projects evaluation. In addition, it also affects the construction quality of the base and surface layers, such as the quality of decorative coatings and the veneers bonding [27,28]. Therefore, the efflorescence is a very important aspect that should be reduced in development of alkali-activated inorganic materials.

Some studies referring to the efflorescence of alkali-activated inorganic binder materials have been reported. However, most of them were based on fly ash-based alkali-activated inorganic binder material and the literatures on adopting nano materials to reduce efflorescence of alkali-activated inorganic binder were few. Najafi et al. reduced the extent of efflorescence of alkali-activated inorganic materials by increasing curing temperature and adding Al-rich mineral admixtures such as metakaolin, ground granulated blast-furnace slag, and three types of calcium aluminate cements [28]. Zuhua Zhang et al. found that fly ash based alkali-activated inorganic materials specimens get less and slower efflorescence by using sodium hydroxide as activator than that of silicate [21]. Besides, they discussed the relationship between composition, pore structure and efflorescence of fly ash-based alkali-activated inorganic materials, and indicated that the efflorescence rate depended on the activation conditions, slag addition and curing temperature [21]. Minfang Han et al. reduced the efflorescence extent of fly ash-based alkali-activated inorganic materials specimens by incorporating of 5A zeolite powder and confirmed that the adding of 5A zeolite powder lead to the less pore volume of macro-pores [29]. Peigang He et al. [30] prepared metakaolin based alkali-activated inorganic materials and studied the effects of Si/Al ratio on efflorescence, and they found that the alkali-activated inorganic materials with Si/Al ratio of 4.0 showed higher efflorescence extent than that with Si/Al ratio of 2.0 attributed to their higher residual free K^+ . F. Pacheco-Torgal et al. [31] reported that the sodium efflorescence was lower in alkali-activated inorganic materials based on mineral waste mud when calcined at a temperature of 950 °C for 2 h. Mostafa Vafaei [32] studied waste glass based alkali-activated inorganic materials by addition of three types of calcium aluminate cements, and they concluded that all three types of calcium aluminate cements significantly reduced the tendency towards efflorescence formation due to mineralogical composition of the source materials.

In recent years, it was reported that the properties of alkali-activated inorganic materials can be greatly improved by adding a small dosage of nano-silica, especially the early age strength gain [33,34]. Thus, the application of nano-silica in alkali-activated inorganic materials is becoming attractive [35–37]. Kang Gao et al. [38] revealed that the geological polymerization reactions were accelerated when 3.0 wt% nano-silica particles with the average particle size of 10 nm were added to the alkali-activated inorganic materials, and the amount of produced gels was increased and hence the compressive strength was improved. Assaedi [39] prepared fly ash based alkali-activated inorganic binder containing nano-silica by the wet-mix and the dry-mix methods, and found that the

microstructure of alkali-activated inorganic materials and flexural and compressive strengths were improved by nano-silica. Partha Sarathi Deb et al. [34] drew similar conclusions and attributed the strength increase to the densification of the microstructure with the addition of nano-silica. Although the studies of effects of the nano-materials on the mechanical properties and durability [40] of alkali-activated inorganic binder materials have been investigated by many researchers, the mechanisms that control the formation of precursor and final hydration products are poorly understood, thus the effects of nano materials on the properties of alkali-activated inorganic materials remain to be further studied.

This study aims to investigate the effect of nano-silica content, different nano-silica particle size on the efflorescence and the compressive strength of alkali-activated inorganic binder prepared using steel slag and blast furnace slag as resource material and activated by water glass after curing for 1, 3, 7 and 28 days. Relevant results have been rarely reported. Cumulative porosity, pore size distribution, heat of hydration, thermogravimetric (TG) analysis, scanning electron microscopy (SEM) and X-ray diffraction (XRD) of samples with different amount of nano-silica were performed. All of these results aim to provide a comprehensive explanation for efflorescence inhibition mechanism of nano-silica on waste based alkali-activated inorganic binder.

2. Experimental materials and methods

2.1. Raw materials

In this paper, the sources of alumino-silicate to produce alkali-activated inorganic binder were steel slag and blast furnace slag, produced in Shandong steel group, its specific surface area were 376 m²/kg and 436 m²/kg, respectively. The specific surface area of steel slag and blast furnace slag and nano-silica were studied using Brurauer Emmerr Teller (BET) Procedure. The composition of steel slag and blast furnace slag were tested and shown in Table 1. Amorphous nano-silica with two different particle sizes chosen was produced by Aladdin Industrial Corporation. The purity of nano-silica was more than 99.7% and the physical parameters were illustrated in Table 2. To obtain feasible solution with low $\text{SiO}_2/\text{Na}_2\text{O}$ ratio, a previously approved method of mixing sodium hydroxide with sodium silicate was used [41]. The sodium silicate (liquid water glass) was supplied by Jinan HuaRui Group. The chemical composition of water glass supplied consists of 9.15% Na_2O , 28.58% SiO_2 and 62.72% H_2O with $\text{SiO}_2/\text{Na}_2\text{O}$ ratio of 3.22. The sodium hydroxide was supplied by Tianjin FuYu Fine Chemical Co., Ltd. and the purity of sodium hydroxide was not less than 98.5%.

The particles diameter of steel slag and blast furnace slag were tested by Beckman Coulter LS 13 320 and were illustrated in Figs. 1 and 2. The particle size distribution of steel slag (Fig. 1) indicated that the average particle size (X_{av}) was 9.847 μm and the median particle size (X_{50}) was 3.857 μm . The particle size distribution of blast furnace slag (Fig. 2) showed that the average particle size (X_{av}) was 11.78 μm and the median particle size (X_{50}) was 9.892 μm .

2.2. Specimens preparation

Nano-silica was used as substitute of waste powder such as steel slag and blast furnace slag at levels ranging from 0% to 2.5% with an interval of 0.5% in this experiment. The steel slag and blast furnace slag were mixed according to a ratio of 1:1. Alkaline silicate solution was prepared 24 h prior to use and the aim was to cool the solution to 20 °C. Sodium hydroxide were added to liquid

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