Construction and Building Materials 167 (2018) 372–380

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of source and particle size distribution on the mechanical and microstructural properties of fly Ash-Based geopolymer concrete

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HIGHLIGHTS

- The fly ash source has a significant effect on fly ash-based geopolymer concrete compressive strength.
- The particle size distribution (PSD) has a direct effect on the compressive strength.
- The fly ash source has a significant effect on fly ash-based geopolymer concrete microstructure.
- The finer the fly ash particle size distribution, the more significantly permeable void ratio was reduced.
- Fewer microcracks were observed when finer fly ash was used.

ARTICLE INFO

Article history:
Received 16 August 2017
Received in revised form 18 December 2017
Accepted 31 January 2018

Keywords:
Alkali-activated fly ash concrete
Fly ash source
Average particle size distribution (PSD)
Silica fume activating solution
Microstructure
Geopolymer concrete

ABSTRACT

Geopolymer concrete has demonstrated promising mechanical and microstructural properties in comparison with conventional concrete; however, the variability found in fly ash sources and properties may be an obstacle to implementation. To better understand this variability, this study investigates the effects of particle size distribution and fly ash source on the mechanical and microstructural properties of fly ash-based geopolymer concrete. Two fly ash sources were studied including ordinary McMeekin and Wateree Station fly ash. McMeekin fly ash has three different fly ash particle grades, including the ordinary McMeekin fly ash (38.8 μm), Spherix 50 (17.9 μm), and Spherix 15 (4.78 μm). The Wateree Station is a thermally beneficiated fly ash, while McMeekin is a STAR Processed fly ash. A mixture of silica fume, sodium hydroxide, and water was used as an activating solution. The microstructure of fly ash-based geopolymer paste was observed using SEM. The density, absorption and permeable void ratios were estimated based on ASTM C642. Test results indicate that the resulting compressive strength is linearly affected by the average particle size distribution. The compressive strength of geopolymer concrete was decreased when McMeekin fly ash was used. In addition, the permeable void ratio and absorption after immersion ratio were decreased as a smaller particle size of fly ash such as Spherix 15 (4.78 μm) was used. The fly ash source influences the permeable voids, apparent density, bulk density, and absorption after immersion ratio.

1. Introduction

Concrete is the second most used material after water. It has been reported that manufacturing one ton of Portland cement produces approximately one ton of CO_2 gas even though only about 50 percent of CO_2 is derived from the burning of fossil fuels [1]. Portland cement is responsible for 7–10% of CO_2 emissions worldwide [2]. Therefore, the need for an alternative sustainable cementitious material with similar or better properties is being sought. Recently, an effort is being put forth toward the enhancement of sustainable cement and the performance of geopolymer cement.

Geopolymer cement is a mixture of an alumina-silicate with an activating solution and additional water for increasing workability. The most common activating solution is a mixture of sodium silicate, sodium hydroxide, and water. However, an alternative activating solution is a mixture of silica fume, sodium hydroxide flakes, and water. Geopolymer cement can reduce greenhouse gas emissions by 44–64% compared to conventional Portland

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Abbreviations: FGC, Fly ash-based Geopolymer concrete; PSD, Particle size distribution; SEM, Scanning Electron Microscopy.

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https://doi.org/10.1016/j.conbuildmat.2018.01.193

cement [3]. Good alumina-silicate sources include fly ash, slag, and metakaolin, which are waste materials. Geopolymer cement not only reduces CO_2 emissions, it also utilizes waste materials, which positively impacts the environment.

Several studies have been conducted to investigate alkali activated fly ash or fly ash-based geopolymer concrete (FGC) properties and performance. It was found that geopolymer concrete has positive durability properties including excellent resistance against sulfate and acid attack, high early age strength, and superior performance under high temperature [4–11]. The early and long-term compressive strengths achieved in ambient conditions may be improved when compared to conventional concrete [12]. In addition, a compressive strength around 110 MPa [16,000 psi] was achieved with fly ash-based geopolymer concrete using elevated heat [13]. It has been reported that the fly ash source plays a dominant role, particularly in chemical composition and particle size distribution [12]. Fly ash-based geopolymer concrete has potential for replacing conventional Portland cement concrete in some applications, however, fly ash source variations should be addressed and assessed.

Studies have been conducted to investigate the effect of fly ash sources and chemical composition. For instance, the effect of the fly ash type and source on determining the final properties of the geopolymer matrix has been studied. It was found that some unreacted fly ash particles play dominant roles in the performance of the newly formed microstructure [14]. Fernandez-Jimenez et al. have shown that perfect spheres, particle size distribution, and type of activating solution can significantly affect the geopolymerization process [15]. X-ray diffraction, compressive strength, RAMAN spectroscopy, and setting time were utilized to investigate the effect of particle size distribution (PSD) and chemical composition of different fly ash sources on the fresh and hardened geopolymer properties. It was reported that factors including PSD played a significant role [16]. Tmuujin et al. have studied the effect of mechanical activation of one fly ash type on the mechanical activation of fly ash. It was reported that the mechanical activation of fly ash enhanced the reactivity of fly ash with the alkaline liquid [17]. Furthermore, the effect of fly ash on the rheology and strength development of fly ash-based geopolymer concrete and paste were investigated. The fly ash spherical particles were proven to have a significant impact on the rheology and compressive strength [18]. S. and R. Kumar have studied the effect of mechanically activated fly ash and non-linear dependence on the particle size and reactivity of the fly ash. They have also reported that the mechanically activated fly ash increased the compressive strength properties [19]. Several tests were utilized including scanning electron microscopy, X-ray fluorescence, X-ray diffraction, and Fourier transform infrared to observe the effect of fly ash and palm oil fuel ash on the compressive strength of geopolymer concrete. It was observed that particle shape, surface area, and chemical composition had a dominant role in the density and compressive strength of geopolymer mortar [20]. Variation of chemical composition and particle size distribution was studied by Gunaskara et al. observing that the chemical composition and carbon content were the reasons for varied compressive strength results [20].

However, the above literature has not investigated the effects of different particle size distribution from the same fly ash source on the mechanical and microstructural properties; nor absorption, and permeable voids ratio of geopolymer concrete, which may help to predict the durability of long-term performance.

In this investigation, two different fly ash sources were studied to investigate the effect on the compressive strength, absorption, and microstructure of fly ash-based geopolymer concrete. The McMeekin and Wateree power stations were used as fly ash sources for this research. In addition, three different average particle size distributions were investigated for the same fly ash source, including ordinary McMeekin, McMeekin Spherix 50, and McMeekin Spherix 15 with a mean particle size of 38.8 μm, 17.9 μm, and 4.78 μm respectively. The effect of fly ash source and average particle size distribution on the compressive strength, bulk and apparent density, permeable void ratio, and absorption were studied. X-ray Fluorescence (XRF), scanning electron microscopy (SEM), thermal gravimetric analysis (TGA), and the absorption test in conformance with ASTM C642 [21] were used to observe the microstructure, chemical composition, particle size effect, and permeable voids ratio of the resulting fly ash-based geopolymer concrete.

2. Materials and methods

Three different concrete batches were mixed to assess compressive strength and absorption according to ASTM C642, and a paste mixture was made for SEM observation. For fly ash-based geopolymer concrete and paste, the mixture procedure followed Tempest (2009) and Assi et al. (2016) [22,23,13].

The materials used for fabrication of the test specimens included fly ash (ASTM class F), activating solution (silica fume and sodium hydroxide solution mixed in water), fine and coarse aggregates, water, and a superplasticizer (Sika ViscoCrete 2100). Two fly ash sources were utilized in the investigation: (a) McMeekin and (b) Wateree with average particle size 42.5 μm. Both sources are from power stations in South Carolina. Three batches were made using fly ash containing average particle size of higher than 38.8 μm, 17.9 μm, and 4.78 μm (commercially referred to ordinary McMeekin, Spherix 50, and Spherix 15, respectively). The Wateree Station fly ash source was subjected to a proprietary carbon burnout process, while the McMeekin fly ash was processed with a STAR process. Chemical compositions of all fly ash sources and thermal gravimetric analysis (TGA) are shown in Table 1 and

Table 1
XRF chemical analysis of fly ash.

Chemical analysis	Wateree Station wt.%	Ordinary McMeekin wt.%	McMeekin Spherix 50 wt.%	McMeekin Spherix 15 wt.%
Silicon Dioxide	53.1	53.5	52.9	51.0
Aluminum Oxide	27.7	28.5	28.6	29.3
Iron Oxide	9.81	9.41	6.60	6.52
Sum of Silicon Dioxide, Aluminum Oxide	90.6	91.4	88.1	86.8
Calcium Oxide	2.40	1.61	2.90	4.10
Magnesium Oxide	0.90	1.32	1.01	1.21
Sulfur Trioxide	0.22	1.01	0.10	0.22
Sodium oxide	0.11	0.16	0.21	0.41
Potassium oxide	2.41	0.40	2.81	2.90
Moisture Content	0.10	0.10	0.10	0.11
Total Chlorides	–	<0.002	–	–
Available Alkalis	1.20	1.92	2.01	2.30