Construction and Building Materials 172 (2018) 677–684

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effects of the mechanical milling method on transport properties of self-compacting concrete containing perlite powder as a supplementary cementitious material

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HIGHLIGHTS

- Perlite powder could be used in concrete as a SCM.
- Effects of mechanical milling method on transport properties of hardened concrete were evaluated.
- Influence of perlite powder on the concrete resistance to chloride ions ingress was investigated.
- Rheological and mechanical properties of SCC were investigated.

ARTICLE INFO

Article history:
Received 26 December 2017
Received in revised form 9 March 2018
Accepted 21 March 2018

Keywords:
Mechanical milling method
Self-compacting concrete
Perlite powder
Pozzolan

ABSTRACT

The purpose of this study is to measure the effects of increasing the specific surface area of perlite natural pozzolan in self-compacting concrete (SCC) by the mechanical milling method. The use of SCC in construction projects allows for a reduction of human resources and equipment, which significantly decreases the labor cost and time of construction. SCC often needs chemical additives to achieve workability requirements. However, the usage of a greater amount of chemical additives as well as cement materials in the mixing designs increases the cost of mixing. Incorporation of inexpensive natural pozzolans as an alternative to cementitious materials can improve the fresh properties and durability of concrete. Moreover, reducing the hydration heat and controlling the shrinkage of SCC mixtures, which mainly contain significant amounts of powdered materials, is another benefit of the natural pozzolans. However, the reactivity of natural pozzolans, specifically in the early ages, is always a concern when using these supplementary materials. In this study, several methods have been proposed to improve the reactivity of these materials. Increasing the specific surface area of pozzolanic materials by mechanical milling is one of the most economical and efficient methods implemented so far. This study measured the performance of various levels of perlite powder, a natural pozzolan, for fresh, mechanical and durability properties. In addition, the effects of increasing the specific surface area of perlite powder on properties of concrete were measured and evaluated. According to the results, an increase in the specific surface of perlite powder improved the compressive strength and durability index as a result of increased reactivity. This was accompanied by a substantial improvement in the properties of SCC mixtures in the workability and stability tests.

1. Introduction

The development of self-compacting, or self-consolidating, concrete (SCC) has resulted in a great advancement in concrete technology with regard to its applications in the construction industry. Committee 237 of the American Concrete Institute (ACI)

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https://doi.org/10.1016/j.conbuildmat.2018.03.205

[1] defines SCC as a highly fluid and non-segregating concrete that can spread through even dense reinforcement and can fill formwork homogenously without using external mechanical consolidation. In its fresh state, SCC can flow and consolidate under its own weight while remaining stable as well as fill in formwork with complicated shapes and congested areas of reinforcement without any vibrational effort; this feature can offer a significant reduction in noise and vibration-related injuries [2]. Indeed, three main requirements for fresh concrete properties of SCC are passing ability, flowing ability, and stability. SCC technology has better productivity and efficiency levels compared with conventional concrete by allowing increased casting speed as well as a reduction in workforce, energy, and cost of equipment [3,4].

In order for SCC to reach a high level of workability during construction, expensive chemical admixtures along with a high volume of cementitious material or powder material are usually used, which increases the cost compared to conventional concrete mixtures [5–7]. One possible solution for decreasing the costs related to SCC manufacturing is to utilize local and inexpensive supplementary cementitious materials (SCMs), such as natural pozzolans, as partial replacements for Portland cement [8,9]. SCMs with siliceous or aluminous materials react with calcium hydroxide $Ca(OH)_2$ in the presence of moisture and form C-S-H gel [10]. It has been well established that incorporating some SCMs in SCC mixtures leads to substantial enhancement in both workability and durability properties [4,11]. Moreover, the use of SCMs in concrete applications has been observed to significantly improve durability of the concrete, especially with regards to vulnerability to chemical attack or mitigation of alkali-aggregate reactions [12].

Pozzolans are classified into natural and artificial categories. The most widely used SCMs are industrial by-products, such as slag, fly ash and silica fume. However, the problem with these SCMs is that they either are rarely available or costly in some regions. According to Mehta [7], the cement industry is responsible for nearly 7% of all carbon-dioxide emissions worldwide; therefore, reducing cement consumption is an inevitable strategy towards sustainable development. That is why finding local sources of available yet low-priced SCMs, such as natural pozzolans, is essential to the future of the concrete industry. Natural pozzolans are the products of volcanogenic activities [13] and include natural rocks or volcanic sediments, such as clay, shale, laterite, bauxite, kaolinite, volcanic glass, pumice, rhyolite, tuff, zeolite, diatomite, and volcanic ash [14,15]. Resources of some types of natural pozzolans, such as perlite, which has glass structure (crystalline) that is produced from the rapid cooling of volcanic lava process [16], are abundantly available, and have been utilized successfully in industrial projects.

Due to relatively low costs, perlite has considerable potential for use in the cement and concrete industries. As a hydrated volcanic product, a comparatively high water content of 2–6% distinguishes perlite from other hydrous volcanic glasses, such as pumicite and hydrated volcanic ash [17]. Erdem et al. [18] tested several types of cement with different fineness values (3200 cm^2/g and 3700 cm^2/g) and different amounts of perlite (20% and 30% by weight of cement). In order to produce a blended cement, they tested intergrinding or separate grinding techniques and observed that less energy was required to produce blended cement by intergrinding the perlite and the clinker. Also, using the same amount of perlite and Blaine fineness, blended cements produced by intergrinding resulted in slightly higher values in compressive strength [18]. Kotwica et al. [19] reported using perlite to obtain strength gains up to over 50%. In addition, the introduction of the perlite led to increasing the chemical durability of the hardened material.

The chemical composition of a natural pozzolan does not necessarily have a direct effect on the reactivity. Factors that have more direct influences on the performance of a natural pozzolan include the mineralogical composition, processing temperature for calcined materials, and specific surface area or fineness [20]. Calcination, prolonged grinding, acid treatment, and elevated temperature curing are among the various efforts to increase the reactivity of natural pozzolans in concrete products. However, some techniques are too expensive to be employed [21]. In addition, some methods do not show a significant efficacy, such as thermal activation that involves elevated temperatures to heat the starting materials. Moreover, the increase in strength due to calcination was not high enough to counteract the increase in energy required to calcine the material [14]. Ramezanianpour et al. [16] calcined the crushed perlite rocks for 1 h at a temperature of 850 °C and ground the material to obtain the same fineness as that of ordinary Portland cement (OPC); they demonstrated that calcined perlite powder (CPP) could be used as an acceptable SCM [22].

Mechanical methods, such as prolonged grinding of a natural pozzolan, are used most often [23]. Using milling to reduce particle size has implemented to prepare other materials, such as SCMs. The mechanical activation of solid substances is conducted by mechanochemistry methods [24]. Mechanical treatments by using high-impact and friction materials generate more active materials in very short periods of time at ambient pressure and temperature [21]. This increase in reactivity is caused by an increase in the specific surface area of the material. Thus, increasing the grinding time results in increasing the pozzolanic index [21].

According to Pourghahramani et al. [25], previous researchers have indicated "that mechanical activation improves the most important characteristic of compressive strength" [26,27], "enhances the pozzolanic reactivity" [28,29], "accelerates cement hydration reactions" [30], "facilitates rapid hardening of cement" [31], and "improves durability" [25,26]. Vizcayno et al. [21] reported a satisfactory performance at an early stage for pozzolan materials, "obtained by mechanochemical treatment of a kaolinite clay with a high quartz content...". They observed the pozzolanic index and the mechanical resistances attained by grinding were similar to that when using thermal treatment [32]. Pourghahremai and Azami [25] found that intensive milling caused structural refinement and plastic deformation on rock materials. They identified mechanically activated perlite as a suitable additive into the cement by a 30% replacement level.

Various studies have tested the increasing SCM reactivity by means of milling. These studies mostly used high-energy ball mills working at a speed of 500 rpm [33–36], which are not feasible for the large scale used in industry [37]. In industry, large rotary ball mills are usually implemented at slow levels of rotational speed [37,38]. An increase in fineness that exposes more specific surface area of the natural pozzolan may accelerate early pozzolanic reactions. Burris and Juenger [30,39] reported that milling zeolites more than four hours resulted in the greatest reactivity due to decreased particle sizes. There are several methods to indicate the fineness of the material, including particle size distribution, Blaine fineness, and a surface area analysis using Brunauer-Emmet-Teller (BET) absorption [20]. Many studies have reported that there is an excellent correlation (linearly proportioned) between pozzolan cement strength and Blaine fineness of the pozzolan [20].

The purpose of this study is to evaluate the effects of increasing the specific surface area of perlite powder on fresh and hardened properties of SCC. Slump flow, loss of slump flow over time, J-ring, V-funnel flow, and U-Box tests were conducted to evaluate properties of fresh SCC mixtures. Hardened properties of the SCCs were investigated in terms of compressive strength and durability. The effects of perlite in various percentages on the compressive strength of SCCs were assessed at 7, 28, and 90 days. The durability properties were investigated, including electrical resistivity, water penetration, the rapid chloride migration test (RCMT), and the