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Pretreatment of natural perlite powder by further milling to use as a supplementary cementitious material

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HIGHLIGHTS

- Replacement of OPC with perlite powder slightly increases the water demand of fresh concrete.
- There is a significant improvement in the transport properties of concrete mixtures by replacing OPC with perlite powder.
- Effects pretreatment of natural perlite powder on transport properties of hardened concrete were evaluated.

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ABSTRACT

Replacing a portion of ordinary Portland cement (OPC) with natural pozzolans may be an effective solution to reduce the carbon footprint of the concrete industry and construction costs, and to improve concrete durability in general terms. However, some natural pozzolans, such as perlite, need to be pretreated to be reactive enough and satisfy the minimum standard qualifications of the concrete industry. This research investigated the effectiveness of milling of natural perlite as an alternative to calcination, which is the more common reactivation method. For this purpose, the effects of replacing OPC with natural perlite powder (NPP) were studied at three different levels of fineness and replacement ratios. A variety of tests for the mechanical and transport properties of the concrete were carried out, including a compressive strength test, a surface electrical resistivity test, a water penetration test, a rapid chloride permeability test, and a rapid chloride migration test. These tests conducted on 14 different types of concrete mixtures with various ratios of water-to-cementitious materials (W/Cm), cement content, and replacement ratios. The results demonstrated that increasing the fineness of natural perlite could be an effective method to reactivate NPP, leading to almost the same compressive strength while improving the transport properties significantly.

1. Introduction

Cement plants are the major industrial contributor to CO_2 emissions, second after electric power generation. It comprises 5% of the total CO_2 emissions that represent the environmental carbon footprint of the concrete industry [1]. A possible solution to help mitigate the substantial environmental effects of the concrete industry is to replace a portion of the OPC used in the concrete mixture design with supplementary cementitious materials (SCM). Reducing the consumption of OPC helps to develop a sustainable concrete that also may cost less or have better mechanical or durability properties [2–5].

SCMs can be categorized as industrial waste materials, such as silica fume or fly ash, and natural pozzolans, either raw pozzolans, such as pumice, or calcined pozzolans, such as metakaolin. Industrial waste materials like fly ash has been the predominant pozzolan for use in concrete construction since the 1930's. However, the availability has become a problem in recent years due to reduction in the use of coal for electric power generation. That is why natural pozzolans like perlite powder has recently got more attention.

Pozzolans are aluminosilicate materials that can react with hydroxide calcium, and they generate a calcium-silicate-hydrate (C-S-H) gel. Generating a C-S-H gel may help improve the mechanical and durability properties of cementitious materials by making the pore structure denser, cutting the connectivity of pores, and affecting the chemical properties of the pore solution [2,7]. This

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may lead to suppressing both internal and external attacks to the concrete [3,6].

Natural pozzolans are formed by amorphous or vitreous volcanic-eruption materials that have quickly cooled under various environmental conditions [8]. However, they are not active enough, intrinsically, to satisfy the minimum standard requirements for concrete mixtures. Therefore, pretreatment is required by means of either pre-calcination, alkaline activation, or further milling [9–12].

Some studies [13–15] have investigated the effectiveness of further milling as a pretreatment method for SCMs. Increasing the specific surface area of SCMS leads to making them more efficient by increasing both the filler effect and the heterogeneous nucleation effect. On the other hand, it results in more secondary pozzolanic reactions due to the higher contact surface between the pozzolan and calcium hydroxide ($Ca(OH)_2$) [16]. The secondary pozzolanic effect becomes more substantial at greater ages than the other two effects.

The benefits of SCMs may help concrete materials to resist against either internal or external attacks more effectively. Internal attacks may be prevented by choosing the right raw materials or construction method. Bektas et al. [17] demonstrated how replacing OPC with either expanded perlite powder (EPP), or natural perlite powder (NPP) can suppress alkali-silica reactions (ASR) of reactive aggregate as one of the most important sources of internal attacks. The first line of defense against external attacks are the mass transport properties of concrete, which can be evaluated by a variety of test methods [18,19]. Ramezanianpour et al. [20] investigated the effects of replacing a portion of OPC with EPP on various transport properties of concrete mixtures. They found almost constant mechanical properties while transport properties were remarkably improved mainly because of both the consumption of hydroxide ions (^{-}OH) in the pore solution and the reduction in the connectivity and volume of pores [6,21].

Kotwica et al. [23] showed that replacing OPC with expanded perlite powder, which is an industrial waste material, results in the increasing 1 and 28-day strength of mortar and concrete mixtures. They studied replacement ratios up to 35%. Investigation of the microstructure of mixtures revealed that the main reason of increasing the strength of cement-based materials is pozzolanic reaction of waste expanded perlite powder. On the other hand, another study on NPP indicated that early-age strength loss is possible as a result of replacing a portion of OPC with perlite powder in the mixture design; however, the results getting closer over time, maybe because of the pozzolanic reactions with a lower rate [22]. Few investigations have been done on studying microstructure and degree of hydration of such mixtures to prove this hypothesis.

This paper investigates the effectiveness of further milling as a pretreatment method to reactivate NPP in order to replace a portion of OPC in a proportion design for concrete mixtures. Replacing OPC with NPP may be advantageous regarding the concrete's properties, but it also may adversely affect these properties due to the dilution effect. This is why it was necessary to investigate the efficiency of various milling methods as well as the optimized replacement ratio.

For this purpose, concrete compressive strength, surface electrical resistivity (SER), water penetration (WP) resistance, rapid chloride permeability (RCP), and rapid chloride migration (RCM) were evaluated and compared for 14 concrete mixture designs at three different ages (7, 28, and 91 days). It was expected that although replacing OPC may lead to lower mechanical strength at earlier ages, relatively, the concrete's durability would improve significantly at greater ages and still have almost the same mechanical strength as for fine NPP.

2. Experimental program

2.1. Materials and mixture proportions

Chemical composition and physical properties of OPC Type I and NPP used in this study are shown in Table 1, following ASTM C150 and C618 specifications, respectively. A high-range water-reducing agent (HRWRA) based on neutral polycarboxylate ether (PCE) satisfied a requirement from ASTM C494. Natural river sand was used as a fine aggregate, having a fineness modulus of 2.95, a specific gravity of 2.56, and water absorption of 1.82%, which addressing a specification from ASTM C33. Crushed calcareous aggregates were used as the coarse aggregate, with a nominal maximum size of 19 mm, a specific gravity of 2.58, and 1.61% water absorption, according to ASTM C33. Drinkable treated tap water from the municipal pipeline was used to mix concretes and for curing.

In the laboratory, a simple rotational ball mill that was 450 mm in length and 420 mm in diameter was used for the grinding operation, as it is a commonly used method in the cement industry. The rotation speed was selected as 30 rpm. The charge of the mill contained 96-kg spherical balls and cylpebs in total. Prior to milling, natural perlite was dried in a 105 °C oven for one day, and 7 kg of dried material was ground in each cycle to make sure of having uniformly ground material at the end of the procedure. Periodically, a 100-gr sample was taken throughout the milling procedure to measure the specific gravity and Blaine fineness, and the procedure continued until the materials reached the desired Blaine fineness (3100, 3500, and 3900 cm^2/g) [16]. Particle size distributions of the grounded NPPs are presented in Fig. 1.

Concrete mixture proportions were designed based on the unit volume method. No air-entraining agent used, and it was assumed that the air content for fresh concrete would be around 3%. Table 2 presents the mixtures in detail. Two different ratios for water per cementitious materials (W/Cm), equal to 0.32 and 0.4; the cementitious materials content, and OPC replacement ratios were considered in the design of concrete mixtures as well as three different levels of fineness for NPP. Various dosages of HRWRA were used to achieve the design slump (7.5 ± 2.5 cm) based on the fresh properties of each mixture.

2.2. Specimen preparation and test methods

All concrete mixtures were prepared using a laboratory pan mixer. Specimens were taken, and cured in lime-saturated water at 23 ± 2 °C by the testing age, following ASTM C192. To evaluate the fresh workability of the mixtures, slump tests were conducted immediately after mixing, based on ASTM C143.

Table 1
Chemical and physical properties of cementitious materials.

Chemical Composition[a] (%)	OPC	NPP
CaO	65.3	1.12
SiO_2	20.8	70.28
Al_2O_3	4.3	12.97
Fe_2O_3	2.2	1.46
MgO	2.17	0.41
K_2O	0.63	4.51
Na_2O	0.36	2.96
Loss in ignition (%)	0.91	3.02
Physical properties		
Specific gravity	3.15	2.87
Fineness (cm^2/gr)	2800	–

[a] Chemical composition determined based on ASTM C114.

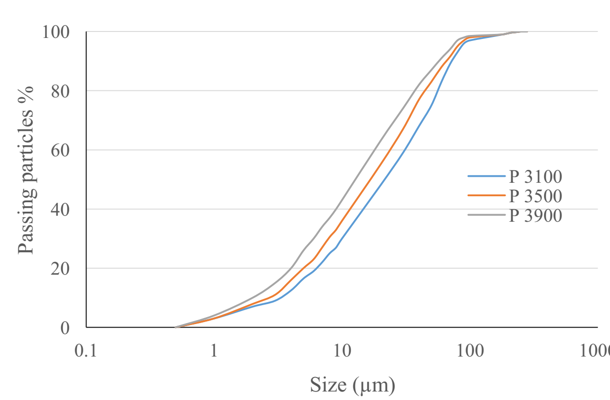

Fig. 1. Particle-size distribution of grounded natural perlite powder.