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Durability performance and engineering properties of shale and volcanic ashes concretes

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HIGHLIGHTS

- Using natural pozzolana and volcanic ash in concrete production may reduce Portland cement consumption.
- At low to moderate replacement level, these two pozzolanas provide satisfactory performance.
- Overall, SA pozzolana seems to perform better than NP.

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ABSTRACT

Designing a sustainable concrete has become a vital requirement for today's concrete. Introducing various cementing and pozzolanic materials in concrete in replacement of Portland cement seems to be the appropriate way to lower the environmental impact of concrete industry.

This paper reports results on concrete performance produced with two types of pozzolanas including natural pozzolana (NP) obtained from volcanic ash and shale ash (SA) used, in various proportions ranged from 10–45%, as a partial substitute of Portland cement (PC). Concrete mixtures were designed with a wide range of water-to-cementitious ratios (w/c) ranged from 0.79 to 0.45. The key mechanical properties and durability performance of binary blended cement concretes were investigated.

Using both NP and SA has resulted in a strength loss; while SA seems to perform better than NP in terms of strength development and durability performance. The blended cement concretes with 10–15% pozzolanas was found to have a good resistance to carbonation and chloride ions ingress and are freeze–thaw durable. However, with replacement level higher than 20%, the durability factor, chloride ions and carbonation resistance drop down.

Overall, the results indicate that the mechanical and durability performances of binary blended cements with NP and SA are strongly linked to their intrinsic characteristics including chemical composition, fineness, particle size distribution and potential reactivity.

1. Introduction

Portland cement industry is one of the heaviest contributors to the global CO_2 emission with an estimated contribution of approximately 5–7% of the global CO_2 emissions [1]. The annual cement production has passed from 2.6 billion tonnes in 2007 [2] to 4 billion tonnes in 2013 [3] and a rapid increase is expected in the coming years. As the pressure to reduce CO_2 emissions is rising under the new environmental regulations, research is being directed towards increasing the replacement levels of clinker and optimising different combinations of supplementary cementitious materials (SCMs). Thus, the cement industry is now putting considerable efforts to reduce the CO_2 emission by minimising clinker production and using blended cements, in which part of the clinker is replaced by SCMs or fillers. In fact, SCMs whether natural pozzolans (volcanic tuff, zeolite and diatomite) or thermally treated clays (metakaolin) or by-products industrial wastes such as silica fume, fly ash, slag have been used for many years to develop Portland-composite cements not only for environmental considerations and sustainable development issues but also to enhance concrete strength and durability performance [4].

Indeed, environmental issues are one of the major concerns but also cost reduction, energy saving, the use of conventional raw material or industrial by-products as well as concrete performance improvement, are among the main objectives targeted by the use of different mineral admixtures in concrete production. The benefits of natural pozzolana (NP) and shale ash (SA) as well as other

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SCMs used as a partial replacement of Portland cement (PC) are now well established. In 2006, around 300 million tonnes of various natural pozzolanas were estimated available while only 50% are used [5].

The BS EN 197-1 (2000) identifies type II cements (CEMII/A-LL 32,5/42,5) that may contain various materials as main constituents, in percentages ranging from 6% to 35%. Natural pozzolana, fly ash, slag and limestone are the main materials that are permitted by the EN 197-1.

Natural pozzolanas such as diatomite have been widely used as a partial substitute of Portland cement in many applications because it contains reactive SiO_2 and due to their beneficial effects including reduction in heat evolution, decreased permeability and increased resistance to chemical attack [6,7]. However, NP are often associated with a reduction in early-ages strength [8–10] but an improved hydration and strength at medium and later ages when moist-cured for longer time [11]. Adding 10% raw diatomite to PC resulted in a comparable strength with respect to the reference concrete while beyond this limit, compressive strength decreases due to the high water demand induced by the increased fineness. The strength development of diatomite concrete was reported to increase depending on the increased diatomite content and reactive silica content [12].

Recent results revealed that ternary system containing 20% limestone (LS) filler and 30% NP has led to improved early and long-term compressive and flexural strengths and enhanced durability against sulphate, acid and chloride ions ingress [11].

The use of shale ash is, however, limited and shown less success and efficiency compared to the other types of pozzolanas. Several authors [13,14] have reported that the use of burnt shale in cement pastes increased the water demand and prolonged the setting time. The burnt shale ash has a low pozzolanic activity which results in a lower strength development of concrete/mortar compared to control mixture as reported by some authors [13,15]. Meanwhile, Baum et al. [16] have found that shale ash concrete exhibited less shrinkage than PC concrete while Bentur and Grinberg [14] have reported that shale ash increased drying shrinkage of concrete.

In this paper, the effect of volcanic ash and shale ash on concrete performance is investigated. Attention is particularly directed to the key mechanical and durability performances of concrete specimens made with these two types of SCMs as a partial substitute of Portland cement. The results presented herein are part of an extensive research project aims to develop concrete made with various Portland-composite cements.

2. Research significance

Today's concrete industry is facing multiple challenges, especially ensuring adequate mechanical and durability performance with low environmental impact. There is no doubt that the use of various pozzolans and SCMs in concrete production have considerable beneficial effects not only on mechanical and durability performance of concrete but also economical and environmental advantages. Since many decades, Silica fume (SF), fly ash (FA), and slag are the most popular cementing materials that are widely used in concrete. Whereas, NP and SA have been first used in cement-based materials since several decades before the development and effective use of SF, FA and slag, their use as cementing materials is still limited and only limited data on their overall performances are yet available.

This research highlights the mechanical and durability performance of binary concrete designed with various proportions of NP and SA. Contrary to what has been established by some authors, SA has a great potential of use as a cementing material and performs much better than NP.

3. Experimental work

3.1. Materials

Portland cement CEM I 42.5 N conforming to EN 197-1:2000 was used in all control mixtures while various proportions of NP and SA were added as a partial substitution of PC to obtain binary binders. These binary binders were formulated varying the replacement (by weight) of PC by NP from 0% to 45% and the replacement of SA from 0% to 40%. The Natural Pozzolana used is a volcanic dust with a rough surface texture while the burnt shale ash has a high inherent fineness. The chemical and mineralogical compositions along with physical properties of PC and the two pozzolanic admixtures (NP and SA) used are given in Table 1; and their particle size distribution are shown in Fig. 1. Both NP and SA used could, relatively, be considered as high siliceous.

Two size fractions of 5–10 mm and 10–20 mm of crushed granite were used as coarse aggregate (CA) while river sand 0–5 mm was used as fine aggregate. To obtain a nominal targeted slump value of 75 ± 5 mm, a superplasticizer conforms to BS 5075: Part 3 with a proper content (expressed by % of weight of cement) was introduced while an air-entraining agent conforming to BS 5075: Part 2 was used for the purpose of freeze–thaw resistance of air-entrained concrete.

3.2. Details of mixtures, concrete mixing and specimens

Both PC and binary concretes were designed with a wide range of water to cementitious materials (w/c) of 0.79, 0.65, 0.60, 0.52 and 0.45. The cement content was varying from 235 to 410 kg/m^3. The total coarse aggregate content was kept constant (1200 kg/m^3) while the fine aggregate content was slightly adjusted to maintain the yield. Table 2 provides the mix proportions of both PC and binary cements concretes investigated. All concrete mixtures were produced in a planetary concrete mixer and were appropriately labelled as given in Table 2. After mixing, slump test was carried out before concrete was cast in the moulds.

For all concretes types, three samples of both Portland cement and binary cement concretes containing natural pozzolana and shale ash, referred to as PC, NP and SA respectively, are examined. Blended mixtures NP and SA label are followed by a number designating the replacement level of PC by NP and SA. Concrete specimens were cast in metal moulds (cubes, cylinders and prisms) in

Table 1
Chemical composition and physical properties of cement and pozzolanas used.

Constituents	PC	NP	SA
Chemical composition, %			
SiO_2	21.4	58.1	56.1
Al_2O_3	4.7	13.1	23.6
Fe_2O_3	2.7	4.4	8.2
CaO	65.2	9.2	2.3
MgO	1.0	2.6	1.9
SO_3	2.9	–	0.27
TiO_2	–	0.6	1.2
Total alkali, Na_2Oe	0.55	1.053	2.023
LOI	0.9	6.4	3.2
Bogue composition, %			
C_3S	67.3	–	–
C_2S	10.6	–	–
C_3A	7.9	–	–
C_4AF	8.2	–	–
Physical properties			
Density, kg/m^3	3140	2480	2670
Fineness, m^2/kg	381	453	1590
Residue on 45 μm, %	6.2	32.3	21.7