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Early-age activation of cement pastes and mortars containing ground perlite as a pozzolan

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ABSTRACT

Perlite is a natural pozzolan abundant in several countries which are major producers of cement. This makes perlite attractive for producing sustainable concretes. Strength development and heat evolution of perlite-containing mixtures, and the influence of chemical and thermal activation on their early and later age properties were investigated using five activator chemicals and four curing temperature-duration combinations. Chemical activation could increase the 1-day, or 3-day compressive strengths of 25% perlite mortars to above the cement-only control but was not very beneficial to 50% perlite mixtures. Thermal activation could increase strength at ages up to 28 days, and even above the room-temperature control at 1 day. Perlite content affects the maximum value of the isothermal calorimetry heat evolution rate but not its time of occurrence. Chemical and thermal activation influence both the height of the rate peak and its timing, which are linearly correlated for activated or non-activated pastes with a given perlite content.

1. Introduction

The use of natural pozzolans in portland cement-based mixtures dates back more than two millennia [1]. Mielenz et al. [2] wrote “When selected, processed, and used properly, pozzolans can reduce costs, improve quality of concrete, protect concrete against effects of reaction between aggregate and cement alkalis, and inhibit attack by aggressive waters.” Proper selection of a pozzolan requires knowledge of its chemical composition and its reactivity with portland cement. Although several types of “natural” pozzolans, such as diatomaceous earth, and volcanic ashes or tuffs, can be named, each of these types shows variability with respect to reactivity. It is therefore difficult to relate results in the literature obtained by using a particular natural pozzolan from a specific location, to one’s own pozzolan. For this reason, it can be useful to determine the behavior of natural pozzolans which show limited variability and are also abundant and widely available. One such material is perlite.

Perlite is a volcanic glass which contains 2–6% chemically combined water. It has the interesting property that, upon heating to ~900 °C, this water is lost, expanding it to a cellular material of very low bulk density. Consequently, expanded perlite has been widely used by the construction industry as an aggregate in the production of lightweight concretes, insulation products, etc., in addition to its use in other areas like horticulture and pharmaceuticals [3]. Although much-less known, due to its glassy nature and high SiO_2 (70–75%) and Al_2O_3 (12–15%) content, finely-ground unexpanded perlite also possesses pozzolanic properties, as demonstrated in a recent study [4]. Erdem et al. [5] used ground perlite to produce blended cements and mortars, concluding that the grinding of perlite is less energy-intensive than portland cement clinkers. They found that perlite-containing mixtures conformed to standard limitations on setting time, soundness, and compressive strength. The term “perlite-containing mixture” is used in this text to mean that a fraction of the cement in a paste or mortar has been replaced with ground perlite. Uzal et al. [6] reported normal consistency water contents similar to that of a portland cement-only control and that ground perlite-containing concretes had very low permeability after a few weeks. The strengths were low compared to the control mixture, at all ages up to 91 days. Turanlı et al. [7] reported significant decreases in early-age compressive strength for high volume replacement, compared to a portland-cement only concrete mixture. No studies have yet reported heat of hydration of mixtures containing ground perlite as a pozzolan.

Chemical and thermal activation of mixtures containing high volumes of pozzolans have been suggested to improve particularly their early-age strengths. Sodium sulfate (Na_2SO_4) has been shown to be effective in increasing early-strength and sulfate resistance [8]. Wu and Naik [9] used several chemical activators in mixtures containing high volumes of coal ash and also reported that Na_2SO_4 was one of the most effective and economical chemicals in improving early-age strength. Shi and Day [10] concluded that calcium

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chloride dihydrate ($CaCl_2{\cdot}2H_2O$) was very effective in increasing the pozzolanic reaction rate of lime-natural pozzolan mixtures and that thermal activation increased early strength while decreasing ultimate strength. Allahverdi and Ghorbani [11] reported that sodium hydroxide (NaOH) accelerated the setting of lime-natural pozzolan mixtures. Hydrochloric acid (HCl) treatment of pozzolans to increase reactivity has also been suggested [12,13]. Chemical and thermal activation of mixtures containing only a natural or an artificial pozzolan instead of portland cement, though not new, has also been gaining popularity [14–16]. Sodium silicate has been shown to be an effective activator for activation of ground blast furnace slags [17]. Activation of perlite–portland cement mixtures has not been reported.

With a known total worldwide reserve base over 7 billion tons and reserves exceeding 700 million tons [18], perlite is also quite abundant. The "reserve base" is the inplace demonstrated (measured plus indicated) resource from which reserves are estimated. "Reserves" are defined as the part of the reserve base which could be economically extracted or produced at the time of determination [19]. Turkey, China, Japan, the US, Greece, and Italy share a majority of the reserves. As some of these countries are major producers (and some major users) of portland cement, relatively small increases in the fraction of perlite used in concrete, while still meeting desired strength and durability requirements, can result in significant environmental and economical savings, as well as technical benefits. Perlite lacks the waste reuse advantage of artificial pozzolans while being burdened by the resource depletion disadvantage. However, some regions or countries (such as the eastern part of Turkey) may be rich in natural pozzolans but not generate substantial amounts of artificial pozzolans [20–22]. The amounts of the major oxides in perlite vary less than a few percentage points from one source to another and even less within the same pit, much less than the oxides in artificial pozzolans from a single source do [23,24]. This may greatly improve repeatability and facilitate the widespread adoption of the findings of studies using perlite. Chemical activation of artificial pozzolans using the same chemicals report different "ideal" proportions of activators. It is expected that the results shown in this study will have high repeatability, any variation resulting mainly from differences in the portland cements used. This paper presents results of experimental investigations of the effectiveness of chemical and thermal activation in increasing the early- and late-age strengths of portland cement mortars containing medium and high volumes of unexpanded, ground perlite. The effect of chemical and thermal activation on the heat evolution behavior of pastes is also presented.

2. Experimental

2.1. Materials

A CEM I 42.5R portland cement and perlite from a quarry in Erzincan, Turkey were used as cementitious materials in this study. The cement met the requirements of the relevant standard [25]. Table 1 provides the chemical compositions of the portland cement and perlite used, determined by a private research lab, using X-ray fluorescence (XRF). Fig. 1 shows the Cu Kα X-ray diffractogram for the ground, unexpanded perlite.

Table 1
Oxide analysis of the powder materials used (%).

	CEM I 42,5R	Perlite
SiO_2	19.6	71.1
Al_2O_3	5.0	13.0
Fe_2O_3	3.7	1.6
CaO	64.5	1.6
MgO	1.6	0.5
SO_3	2.4	1.6
K_2O	0.7	3.8
Na_2O	0.8	4.2
Loss on ignition	2.9	2.9

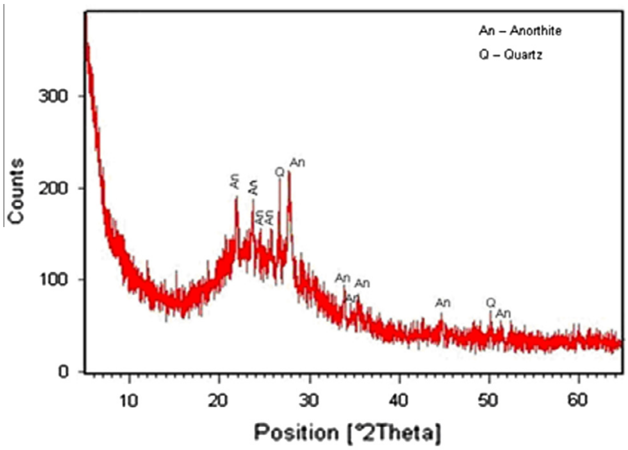

Fig. 1. X-ray diffractogram for the unexpanded perlite used.

The uncertainty of major oxide contents determined by XRF is reported to usually be within 0.5–1% [26]. The Portland cement had a Blaine fineness of 3370 cm^2/g. The perlite was ground alone in a laboratory ball mill to a Blaine fineness of 4580 cm^2/g. The specific gravities of the cement and ground perlite were determined as 3.09 and 2.43, respectively. CEN Standard sand [27] and distilled water were used in preparing the mortars. Five chemicals were used for activation: NaOH, sodium silicate (simply referred to as Na_2SiO_3), Na_2SO_4, $CaCl_2$, and HCl. The NaOH, Na_2SO_4, and $CaCl_2$ were in solid form with >97%, >90%, and 84% purity, respectively. The 38.5% solids Na_2SiO_3 (actual SiO_2:Na_2O ~ 3.0) and 37% HCl were used as solutions. The use of NaOH gave low strengths for the mortars containing 25% perlite and was abandoned for the remainder of the tests.

2.2. Mixture proportions and experimental methods

The study attempted the chemical and thermal activation of pastes and mortars with 25%, 50%, or 75% (by mass) of the portland cement replaced with perlite. The strength development of mortars and hydration heat evolution behavior of the pastes were investigated. Three different amounts of chemicals, 2%, 4%, and 6% by mass of the total cementitious materials (cement + perlite) were used. Based on the initial findings, the 50% and 75% perlite mortars were subjected to 2% chemical activator and thermal activation. Thermal activation involved steam curing at 55 °C or 85 °C for 3 or 10 h. Strength development of mortars with no activation, only chemical activation, and both chemical and thermal activation were compared with each other and with the control mixture containing only portland cement and sand. Table 2 presents the mixture proportions used in the different categories of mortars for which test results are presented.

In accordance with the findings of Uzal et al. [6], the consistency of the mortars did not change noticeably with the addition of perlite and the water-to-cementitious materials ratio for all mixtures was set to 0.485. The sand-to-cementitious material ratio for all mixtures was 2.7. Mortars were mixed at room temperature, following the durations and order of mixing described in [28]. Three $4 * 4 * 16$ cm mortar prisms were cast for each test age. The prisms were first tested under three point bending and then the six halves