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Enhanced physical, mechanical and microstructural properties of lightweight vermiculite cement composites modified with nano metakaolin

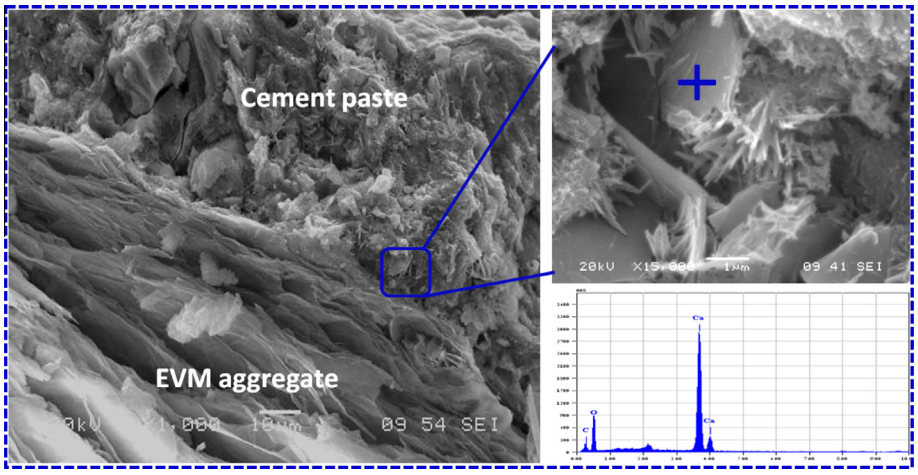
H. Shoukry [a,*], M.F. Kotkata [b], S.A. Abo-EL-Enein [c], M.S. Morsy [a], S.S. Shebl [a]

[a] Housing & Building National Research Center, HBRC, Cairo, Egypt
[b] Semiconductors Technology Lab, Faculty of Science, Ain Shams University, Cairo 11566, Egypt
[c] Chemistry Department, Faculty of Science, Ain Shams University, Cairo, Egypt

HIGHLIGHTS

- Lightweight cement composite with unique physical and mechanical properties is proposed.
- Effect of nano metakaolin on physical, mechanical and microstructural properties has been studied.
- Nano metakaolin has enhanced the compressive and flexural strengths by about 57 and 59%, respectively.
- Considerable improvement in the microstructure has been achieved.

GRAPHICAL ABSTRACT



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ABSTRACT

This article presents a study on the influence of nano metakaolin (NMK) on physical, mechanical and microstructural properties of high volume vermiculite blended white Portland cement (WPC). WPC was replaced with 70 vol% expanded vermiculite (EVM), NMK were incorporated at a rate of 2, 4, 6, 8 and 10% as partial replacement by weight of EVM. The density, thermal conductivity, compressive strength, flexural strength, and capillary water absorption of the blended mixes were determined in accordance with ASTM standards at 28 days of curing. Differential scanning calorimeter (DSC) was used to study the phase transitions. The microstructure characteristics of the hardened samples were investigated by scanning electron microscope (SEM). The experimental results revealed a significant enhancement in both compressive and flexural strength, enhancements of about 57 and 59%, respectively were obtained at 10% NMK replacement. The capillary water absorption generally decreases with increasing replacements of EVM by NMK. A considerable decrease of about 74% was observed at 10% NMK. No significant effect of the NMK content on density and thermal conductivity. NMK led to noticeable improvement in the microstructure characteristics of the hardened blends.

* Corresponding author.
E-mail address: hamadashoukry@yahoo.com (H. Shoukry).

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1. Introduction

Lightweight aggregates are those minerals, natural rock materials, products, and by-products of manufacturing processes used as bulk fillers in lightweight structural cement and concrete, concrete masonry units, precast concrete structural products, road-surfacing materials, plaster aggregates, and insulating fill. Other uses include Architectural wall covers, suspended ceilings, lightweight structural fill, soil conditioners, and other agricultural uses [1]. The lightweight aggregates can be classified into organic and inorganic cellular materials. Examples of organic cellular materials are expanded polystyrene foam (EPS), extruded polystyrene foam (XPS) and polyurethane foam. The inorganic cellular materials are produced from natural and artificial sources such as expanded perlite, expanded clay, vermiculite, ceramic microsphere, glass hollow sphere, etc. [2], These materials are characterized by high porosity and contain a high volume of voids so their densities and thermal conductivities are very low [3]. While lightweight cement pastes and mortars present superior properties such as, thermal insulation [4–6], fire/high temperature resistance and so protection [7], sound insulation [8,9], they are brittle, suffer from cracks and low tensile strength, and exhibit low tensile strains prior to failure [10]. Incorporation of perlite and vermiculite (VM) as fillers into mortar decreases mechanical properties of mortar, due to lack of cohesion. Also, perlite and vermiculite are responsible for voids and high capillarity, water demand and shrinkage [11]. Combined effect of silica fume (SF) and expanded vermiculite on properties of lightweight mortars at ambient and elevated temperatures has been investigated; SF enhanced the mechanical properties of mortar incorporating high volume VM furthermore, increased durability against elevated temperature has been achieved [12]. Recently, due to their unique physical and chemical characteristics, nano materials (NMs) have been strongly used for improving the properties of plain cement, however; studies about the influence of NMs on the properties of cement incorporating high volume replacements are limited. Previous studies indicated that, incorporating 2 mass, % nano silica (NS) into high volume fly ash-blended cement containing 68 mass, % FA has increased the strength at 28 days by about 56% [13]. The replacement of White Portland Cement (WPC) by 2 mass, % nano clay in 30% WPC and 70% perlite blended mix has improved the indirect tensile strength of the hardened pastes by 25% compared to the cement without nano clay at 28 days of hydration [14]. Nano metakaolin (NMK) was found to be very effective for compensating the loss in flexural strength of WPC incorporating 70% expanded perlite [3]. The focus of this study will be on the effect of NMK on physical, mechanical and microstructural properties of high volume vermiculite blended WPC, replacing 70% of cement. The motivations for choosing the vermiculite can be summarized as follows: Vermiculite is a naturally occurring hydrous phyllosilicate (sheet silicates) mineral. When heated to elevated temperatures up to 600–1000 °C, it expands as much as 8–20 times with respect to their original size providing Accordion-like shape granules [15]. Particles of expanded vermiculite are viewed as thin plates separated by air gaps, i.e. highly porous, lightweight, and have quite low densities and thermal conductivities. Considering the expanded vermiculites high porosities and low densities, they are adequate as lightweight aggregates for developing lightweight cement-based materials with improved thermal resistance for energy efficient building envelopes [12,16]. There are many studies on lightweight aggregates such as pumice, perlite, expanded clay, expanded polystyrene and their usages in lightweight composites. However, studies about the use of EVM are limited.

2. Experimental procedure

2.1. Materials

The materials used in this study were white Portland cement (WPC) (type I), nano kaolin clay (NK) and vermiculite. Nano kaolin was supplied by Middle East Mining Investments Company (MEMCO), Egypt; the vermiculite was supplied by the Egyptian company for manufacturing perlite & vermiculite (E.C.P.V).

Nano Metakaolin (NMK) was obtained by thermal activation (calcination) of NK at 750 °C for 2 h. Calcination was conducted in alumina crucible with Length: 100 mm; Width: 40 mm and Height: 18 mm. Expanded vermiculite (EVM) was obtained by heating raw vermiculite rapidly in a muffle furnace at 600 °C for 3 min.

The oxide compositions of WPC, NMK and EVM were determined by X-ray fluorescence (XRF) as shown in Table 1. The mineralogical analyses of NMK and EVM were performed by X-ray diffractometer and given in Fig. 1. The scanning electron microscope (SEM) was used to investigate the micro morphologies of NMK and EVM and introduced in Fig. 2. The physical properties of EVM are summarized in Table 2.

NMK has plate like structure and characterized by large length to thickness aspect ratio; it is especially favourable in matrix reinforcement, and the platelet thickness is only 1–20 nm, although its dimensions in length and width can be measured in hundreds of nanometers, with a majority of platelets in 200–500 nm range after purification.

The EVM looks like flakes, the flakes have separated from each other, providing highly porous exfoliated structure as a result of flash heating (shock thermal treatment). The rapid heating of raw VM resulted in the transformation of the interlayer water into steam, the pressure of the steam forces the silicate layers to separate forming packets, which are several orders thicker than the fundamental layers so that the particles exhibit "accordion" type morphology.

2.2. Samples preparation

Table 3 illustrates the mix design of the high volume vermiculite blended cement composites modified with NMK particles. WPC was partially replaced with 70 vol% EVM. EVM was then substituted by various amounts of NMK at a rate of 0, 2, 4, 6, 8 and 10 mass, %. The dry WPC and EVM were mixed at a speed of 50 rpm using an electric mixer for 2 min to obtain a homogenous mix. The NMK particles were first dispersed in the mixing water (without surfactant) using high intensity ultrasonic bath (frequency: 20 kHz) for 15 min to assure a good dispersion and to avoid agglomeration then, added to make the freshly blended cement mortars.

The blended cement mortars were prepared using the water of standard consistency in order to maintain a constant degree of workability between different samples. Three groups of samples were cast for testing as shown in Fig. 3, the first group was cast as cubes $5 \times 5 \times 5$ cm^3 for density, capillary water absorption and compressive strength tests, the second group was cast as prisms $4 \times 4 \times 16$ cm^3 for flexural strength test and the third group was disks (5 cm Dia. & 2 cm height) for thermal conductivity test. The fresh mortars were kept in moulds for 24 h, and then de-moulded and allowed to cure under water for 27 d.

2.3. Testing

2.3.1. Compressive strength

This test was performed using control compression machine (DARTEC) according to ASTM C 109 with a constant loading rate of 0.75 kN/s. Every result of the compressive strength was reported as the average value of measurements carried out on 5 test cubes.

2.3.2. Flexural strength

The flexural strength test was performed on $4 \times 4 \times 16$ cm^3 prisms using 600 KN machine (DARTEC) in accordance with ASTM C348-08. Three samples per batch were tested, and the average strength was reported.

2.3.3. Capillary water absorption

In this test the specimens were dried in an oven drier at about 60 ± 5 °C until constant mass was obtained. The sides of the specimen were coated with paraffin to achieve unidirectional flow. The specimens were exposed to water on one face by placing it on slightly raised seat (about 5 mm) on a pan filled with water. The water on the pan was maintained about 5 mm above the base of the specimen during the test. The weight of the specimen was measured at regular 30 min interval up to 2.5 h to get the little absorption variation of water. The capillary absorption coefficient (k) was calculated by using the formula: $k = W/(A.\sqrt{t})$ where, W = amount of water absorbed, A = cross sectional area contact with water and t = time [17].

2.3.4. Bulk density

The average bulk density of three cubic samples with dimensions of 5 cm was determined in oven-dry condition according to ASTM 6426-82.