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Ceramic waste as an efficient material for enhancing the fire resistance and mechanical properties of hardened Portland cement pastes

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HIGHLIGHTS

- Ceramic waste (CW) can be used as an efficient material for replacing ordinary Portland cement (OPC).
- Addition of low % of CNTs enhances the compressive strength of OPC-CW pastes.
- Composites prepared by partial replacing of OPC with 5 or 10% CW showed a good thermal resistance behavior.
- The composite made by partial replacing OPC with 10% CW shows the highest residual compressive strength values.
- Addition of 0.1% CNTs to neat OPC and to OPC replaced by 5, 10 and 20% CW causes a notable improvement in the fire resistance.

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ABSTRACT

Utilization of industrial byproducts like ceramic waste (CW) for enhancing the microstructure and mechanical properties as well as the fire resistance of hardened ordinary Portland cement (OPC) pastes is the main goal of this research. Different cement blends were prepared by partial replacement of OPC with 5, 10 and 20 CW (mass%). Besides, the effect of addition of 0.05 and 0.1 (mass%) of carbon nano-tubes (CNTs) on the mechanical properties and thermal resistance of these composites was investigated. The compressive strength values of different composites were determined after 1, 3, 7, 28 and 90 days of hydration. The thermal resistance test of different hardened composites was evaluated. For thermal resistance test, the specimens hydrated for 28 days under tap water were fired at 300, 600 and 800 °C for 3 h. After that, cooling of the fired specimens was done via gradual and rapid cooling methods. The compressive strength test was performed for all fired specimens at each firing temperature. The compressive strength results revealed that, from the economic point of view the optimum replacement of OPC with ceramic waste is 10%, while the optimum addition of CNTs is 0.05 by mass% of the composite. Phase composition and microstructure of some selected samples were studied using XRD, TG/DTG and SEM analyses, the results indicated that, the main hydration products formed are nearly amorphous calcium silicate hydrates, calcium sulphoaluminate hydrate and calcium hydroxide.

1. Introduction

Portland cement (PC) industry produces huge amounts of greenhouse gas [1]. Hence, the industry is looking for substitutions to this familiar material so that, energy use and CO_2 emissions could be decreased. Replacing a portion of PC with waste materials as cementing materials is considered a good solution for solving these problems [2–6]. These materials are sub-products of industrial processes such as fly ash [7] and ground granulated blast furnace slag [8–12]. Consumed glass, scrap tires, plastics and byproducts of paper industry are considered the most important materials.

Ceramic waste (CW) is categorized as non-recyclable wastes in South Africa, except for being used normally as filling main source material in cement industry [13]. In general, CW is divided into two types, which are as follows; (1) all fired wastes resulted from red pastes utilized by structural ceramic factories to manufacture their products, such as bricks, blocks, and roof tiles; (2) all fired wastes generated by stoneware's ceramic such as the wall, floor tiles and sanitary wares [14,15].

Replacing of cement in concrete by ceramic wastes (CWs) leads to enormous saving of energy and has important environmental

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benefits. Besides, it will have a major impact on reducing concrete cost, since the cost of cement represents more than 45% of the concrete cost [16,17].

Actually, ceramic waste has good properties as it is tough, highly resistant to biological, chemical and physical degradation forces. In addition, ceramic waste can be transformed into useful coarse aggregate. The characteristics of ceramic waste coarse aggregate are acting as well as within the range of the values of concrete making aggregates [18]. In general, ceramic waste coarse aggregate concrete shows nearly the same properties of conventional concrete. As a result, ceramic waste coarse aggregate concrete has become widely used, because of its different benefits over other cementitious materials [19].

In fact, the chemical composition and grain size of ceramic aggregates are the reason for their slight pozzolanic activity and so, their pozzolanic activity is enhanced by increasing their surface area [20]. Evidently, recycled ceramic aggregates show a more irregular shape than natural aggregates (NAs), which contribute strongly in formation of stronger bond between recycled ceramic aggregates and the cement paste [21].

It was found that, the mechanical properties of ceramic waste aggregate concrete or mortar are improved by adding FA. Moreover, it maintains a workable concrete even by increasing the aggregate to 100% in concrete [22].

Addition of very small amounts of nanomaterials (NMs) to Portland cement shows a substantial improvement in the compressive strength values, rheological properties and microstructure of the paste, mortar and concrete. Nano silica [23–26] and Carbon nanotubes (CNTs) are considered one of the significant nanomaterials that show a great effect in concrete or mortar [27].

Carbon nanotubes (CNTs) are classified into two types (a) single-walled (SWCNTs), which consist of a single graphene layer coiled up into an ordered cylinder and (b) multiwalled (MWCNTs), which contain two or more cylindrical shells of graphene sheets that ordered coaxially into a central cavity core with van der Waals forces between adjacent layers [28–31].

Evidently, CNTs have desirable mechanical properties, high thermal conductivity and low electrical resistivity. In addition, under compression, composites containing CNTs show a 'piezoresistive response' whereas; the electrical properties vary according to the various compress levels [32,33].

Carbon nanotubes are unique tubular structures with nanometer and large length/diameter ratio. The nanotubes have high Young's modulus and tensile strength, which make them preferable for composite materials with enhanced mechanical properties [34–38].

Actually, the mechanical properties of nanocomposites containing CNTs are improved due to strong interfacial bond. In general, the addition of CNTs in cement produces chemical bonds between the carboxylic groups of the CNTs and the hydration products as CSH of the cement matrix, which enhance the transfer of stresses [39].

Addition of CNTs in cementitious nanocomposites can act as effective bridges to minimize and limit the propagation of microcracks through the matrix, with some conditions such as, CNTs should be well dispersed within the matrix and also should contain good bonding with the surrounding hydrated cement matrix [40]. In addition, further studies have been done on OPC blended with other materials such as fly ash, nano-clay, Nano-Fe needles, bagasse fiber and carbon nanofibers by addition of CNTs [41–44].

It was concluded that, addition of carbon nanotubes to fly ash (FA) cement mortar produces a notable improvement in the compressive strength values. The reason for this improvement is the good interaction between carbon nanotubes and the FA cement matrix, as CNTs fill the pores in the cement matrix and produce a denser microstructure as well as higher strength values were obtained when compared to the reference fly ash mix without CNTs [45].

Addition of CNTs to OPC – nano-metakaolin (NMK) composite improves its compressive strength. The existence of NMK facilitates the CNTs dispersion and improves the interfacial interaction between the CNTs and the cement phases, because of its small size [46].

The addition of carbon nanotube to OPC pastes blended with different amounts of homra (clay bricks waste) causes a good improvement in both the thermal and mechanical characteristics of these hardened composites. Evidently, CNTs act as bridges between hydrates and across cracks, which improve the thermal stability of the composite blends up to 800 °C [47].

The aim of this study is to investigate the effect of replacing OPC with different amounts of ceramic waste, as well as the effect of addition of CNTs on the mechanical and fire resistance of hardened blended OPC pastes.

2. Materials and methodology

2.1. Materials

Ordinary Portland cement (OPC-I, 42.5N), with a Blaine surface area of 3170 cm^2/g delivered from Lafarge cement company, Suez, Egypt, was used in this investigation, its chemical analysis and mineralogical phase composition as calculated from Bogue equations [48,49] are given in Table 1.

Powdered ceramic waste with Blaine surface area of 3200 cm^2/g was delivered from Cleopatra company, Egypt. Table 2, shows the chemical analysis of ceramic waste.

Multi-walled carbon nanotubes (CNTs) used in this study was provided by Egyptian Petroleum Research Institute (EPRI), Cairo, Egypt. CNTs has a surface area of 93.81 m^2/g and purity >90%. The outside estimated length and diameter of CNTs ranged from 5–10 μm to 10–40 nm, respectively. CNTs density was about 2.1 g/cm^3 and their electrical conductivity was more than 100 S/cm. Morphology and microstructure of CNTs are shown in Fig. 1.

The surfactant used in this study was polycarboxylate super plasticizer (Sika Viscocrete 5230 L) with specific gravity of 1.08 g/mL was supplied from Sika Company, Elobour City, Egypt, to help the good dispersion of the MWCNTs.

2.2. Methodology

2.2.1. Preparation of the hardened cement pastes

Different series of dry mixes were prepared by replacing OPC with different percentages of ceramic waste (CW). Table 3 shows the percentage composition of the all prepared mixes and their designations. Each dry cement blend was mechanically mixed in a porcelain ball mill for 8 h to assure the complete homogeneity of the dry mixture.

Carbon nanotubes (CNTs) dispersions were carried out by adding CNTs to an aqueous solution (containing the whole mixing water) using different ratios of surfactant. The CNTs/surfactant ratio was of 1:3 and the resulting suspensions were sonicated at room temperature for 1 h.

Table 1
Oxide analysis and mineralogical phase composition of OPC.

Oxides	Mass (%)
SiO_2	19.4
Al_2O_3	4.65
Fe_2O_3	3.82
CaO	64.11
MgO	1.85
SO_3	3.16
Na_2O	0.31
K_2O	0.27
Cl^-	-
L.O.I	2.1
LSF	99.37
Mineral composition according to Bogue calculation (%)	
C_3S	67.81
C_2S	4.49
C_3A	5.87
C_4AF	11.61