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Influence of multi-walled carbon nanotubes on the residual performance of concrete exposed to high temperatures

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HIGHLIGHTS

- High temperature mechanical properties of carbon nanotubes reinforced concrete are presented.
- Mechanical properties of concrete containing carbon nanotubes show promise.
- The microstructure of nano-modified concrete exhibits crack bridging capability.
- Energy absorbing capacity of nano-modified concrete enhances spalling mitigation.
- Brittleness of light weight concrete reduces by carbon nanotubes inclusion.

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ABSTRACT

Residual mechanical properties of lightweight concrete (LWC) and normal strength concrete (NSC) containing multi-walled carbon nanotubes (MWCNTs) after exposure to high temperatures are presented. Mechanical properties such as compressive strength ($f'_{c,T}$), tensile strength ($f'_{t,T}$), stress-strain response, compressive toughness (T_c) and mass loss of the analyzed formulations were studied and have been elaborately discussed. A heating ramp of 5 °C per minute was selected to expose the cylindrical specimens to target temperatures up to 800 °C. The test data indicated that the inclusion of nano-reinforcements in concrete can significantly improve the residual mechanical properties. Morphological changes in microstructure, crack formation and interfacial interaction between aggregate and mortar were studied using scanning electron microscopy (SEM). Furthermore, the data obtained from high temperature material property tests were utilized to develop mathematical relationships for expressing residual mechanical properties of CNTs modified concrete as a function of temperature.

1. Introduction

To cope with the demand and persistent pursuit of taller, durable and sustainable construction new composite materials that allow cheaper and lighter construction are gaining importance. One such material is structural lightweight aggregate concrete (LWC). The higher strength to weight ratio of LWC results in smaller cross-sections of load bearing members and responding reduction in foundation size [1,2]. LWC is being used in decks of long-span bridges, construction of partition and panel walls in framed structures alongside beams, slabs and other structural members of framed concrete and composite structures. Further, advantages such as better strain capacity and lower coefficient of thermal expansion due to the presence of air voids make LWC suitable for application where acoustic and thermal insulation is desired [2,3].

During its serviceable life concrete is subjected to various deleterious effects such as wearing, freeze-thaw, chemical attack, spalling and cracking due to corrosion in reinforcement, and dynamic loading. One of such destructive effects is exposure to fire. Concrete is a composite material that derives properties from its multiphase and multi-scale ingredients. These ingredients are thermally inconsistent and during fire conditions start to dissociate, leading to degradation of concrete's strength, durability and associated mechanical properties [4]. The deterioration of concrete with an increase in temperature is due to the initiation and propagation of cracks [5]. Cracking mainly occurs due to two reasons, one being the pore pressure buildup and the other is the development of thermal stresses due to the thermal gradient [6]. Concrete being brittle in nature and weak in tension cannot restrain the development of these cracks. To improve the ductility and tensile

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capacity of concrete, strong and durable materials are often incorporated to reinforce concrete or are attached to the concrete surface to attain direct mechanical enhancement. Among such techniques, the inclusion of fibers into concrete has been proven an effective approach [7]. Fibers aim to bridge the separated components and provide mechanical enhancement, especially at the post-cracking stage. Fiber reinforced concrete (FRC) provides a higher level of fire safety by improved tensile capacity and crack bridging action of fibers. In general, fibers being used today such as glass, steel, natural and synthetic range from a few micrometers to centimeters and are effective in bridging the micro and macro cracks [8]. A nano-scale reinforcement that can inhibit the development of cracks at nano-level is considered more effective.

Since the inception of nano-carbons, a significant shift towards their effective usage in cementitious matrices has been reported [9–12]. Nano-carbons such as carbon nano-fibers (CNFs), carbon nanotubes (CNTs) and graphite nano-platelets (GNPs) possess exceptional strength, fractural toughness, and thermal endurance unlike other fibers such as poly-propylene that tend to decompose around 170 °C [7]. The revolutionary thermal and mechanical properties can be the key elements that may influence the performance of such nano-intruded cementitious matrices exposed to fire. The most widely used among the nano-carbons are the carbon nanotubes (CNTs). CNTs, if effectively dispersed in host cementitious matrices can enhance the mechanical properties and fracture characteristics [12–14]. CNTs enhance these properties by restricting the development of nano-cracks and their propagation to micro level [15]. Further, CNTs tend to improve the packing density of cementitious matrices, provide assistive nucleation sites for the growth of hydrates and compensate the shrinkage cracks [16,17]. CNTs refine the microstructure of host-matrix, and unlike the ordinary concretes, the nano-intruded composites have reduced porosities, thus have a greater inclination towards the pore pressure accumulation. Pore pressure build-up has damaging effects, as it undermines the performance of concrete, leading to spalling and subsequent failure of structural members. In literature, the nano-modification of concrete has been elaborately studied with a focus on dispersion techniques, mechanical properties, microstructural improvement and multifunctional properties. However, information about its behavior under fire conditions is lacking.

It has been well established that inclusion of fiber reinforcement into concrete can enhance mechanical properties as well as the fire endurance [18,19]. However, the effects of nano-reinforcement on fire endurance of concrete needs to be identified. The present study will provide new insights by observing changes in the mechanical and microstructural properties of LWC modified with carbon nanotubes. A comparison with normal strength concrete (NSC) and its modified counterpart has also been drawn after subjecting specimens up to target temperatures of 800 °C.

2. Research significance

Carbon nanotubes (CNTs) possess superior properties in terms of electrical and thermal conductivities, as well as the mechanical properties, such as stiffness, toughness, and strength. When added to concrete, these properties of CNTs lead to advanced cementitious composites resulting in the possibility of numerous applications. This enhances concrete's ability to uniformly scatter the thermal stresses and withstand adequate tensile stresses. Moreover, when added to high-performance cementitious composites, CNTs find their application in specific usages such as oil and gas, and nuclear industry [20]. Effectively distributed CNTs not only improve the mechanical properties by microstructural refinement but also curb the cracks at nano level and prevent their growth by providing an anchor across. The higher crack bridging capability at nano-scale in cementitious matrices offers the perfect solution to create a concrete that can withstand thermal cracking under elevated temperatures.

Each emerging concrete type is a novelty providing many benefits in the form of improved compressive and tensile strength, durability, toughness, better stress-strain behavior, fire resistance, in addition to many architectural applications. However, the design properties of these concrete types become challenging under different extreme service conditions and designers mostly resolve to conventional normal strength (NSC) and high strength concrete (HSC) properties. Although, high temperature performance of conventional NSC and HSC are well established, but concrete added with CNTs is expected to behave in an unpredictable manner if used in infrastructure for high temperature applications for which the thermal and mechanical performance evaluation of new concrete types is desired. For performance evaluation, this study aims to investigate the high temperature residual mechanical properties of nano-modified concretes added with CNTs and characterize its microstructural behavior.

3. Experimental investigation

3.1. Materials

Ordinary Portland cement (OPC) Type-I (BS CEM-I Grade 42.5-N) in compliance with ASTM C150 [21] was used in the preparation of all the concrete formulations. The cement was composed up of 65.81% CaO, 18.83% SiO_2, and 6.94% Al_2O_3 as major elemental compounds. Natural sand was used as a fine aggregate in a saturated surface dry (SSD) condition for the preparation of various formulations. Lightweight aggregate concrete (LWC) was prepared using expanded shale while crushed limestone was used in the preparation of normal strength concrete (NSC). The elemental composition of all the ingredients was obtained using X-ray fluorescence (XRF). Physical and chemical properties of both the fine and coarse aggregates are presented in Table 1. Multi-walled carbon nanotubes (MWCNTs) used to prepare the modified formulations were synthesized by chemical vapor deposition (CVD) technique, Table 2 mentions the various properties of used nanotubes. Acacia gum (AG) powder was utilized as a surfactant for the effective dispersion of nanotubes in the host cementitious matrix. AG powder particles had an average particle size (d_{50}) of 207 μm and contained 49.20% CaO, 21.3% Fe_2O_3, and 16.21% SiO as major elemental compounds. To perform the mixing and curing operations, ordinary tap water was used.

3.2. Dispersion and characterization of carbon nanotubes

An optimum dosage of nanotubes was incorporated in all the modified mixes. Shah, et al. [22] established 0.08 wt% MWCNTs by cement as an optimum amount. Above the optimal value of 0.08 wt% re-agglomeration of MWCNTs occurs in a cementitious matrix. Attempts have been made with amounts ranging from

Table 1
Physical and chemical properties of OPC.

Chemical composition	Content (%)	Physical property	Content
CaO	65.81	Insoluble residue (% mass)	0.55
SiO_2	18.83	Specific gravity (g/cm^3)	3.15
Al_2O_3	6.94	Specific surface area (m^2/g)	0.83
Fe_3O_3	3.47	Particle size (d_{50}) (μm)	16.58
MgO	1.94	Loss on ignition (% mass)	2.21
SO_3	1.32		
$Na_2O + K_2O$	1.2		