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Mechanical and thermal properties of graphene sulfonate nanosheet reinforced sacrificial concrete at elevated temperatures

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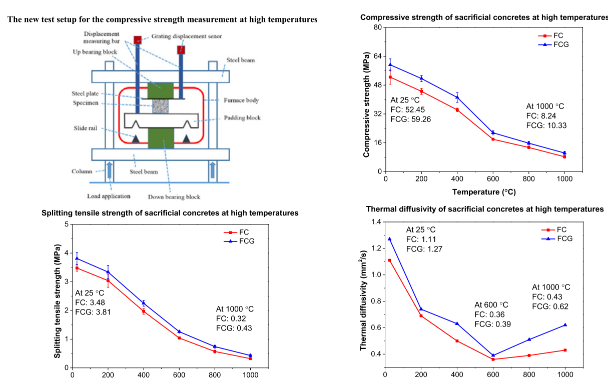
HIGHLIGHTS

- New test setups for mechanical properties measurement at high temperatures are presented.
- Microstructure of sacrificial concrete is improved due to the incorporation of GSNSs.
- Compressive strength of sacrificial concrete increases by 12.98–25.36%.
- Splitting tensile strength of sacrificial concrete increases by 8.66–34.38%.
- Thermal diffusivity of sacrificial concrete rises by 25.00–103.23%.

GRAPHICAL ABSTRACT



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ABSTRACT

Progress in the field of nanomaterials presents an opportunity to improve the performance of cementitious composites via graphene or its derivatives. This paper presents an experimental study on mechanical and thermal properties of sacrificial concrete without and with graphene sulfonate nanosheets (GSNSs) during high temperature exposure. The microstructure, porosity, mechanical strengths, thermal analysis, coefficient of thermal expansion, thermal diffusivity and ablation behaviour of sacrificial concrete during exposure to various temperatures up to 1000 °C were comprehensively investigated. Two new experimental apparatuses were developed and used to measure mechanical strengths of sacrificial concrete at elevated temperatures. It was found that the compressive strength, splitting tensile strength, thermal diffusivity and decomposition enthalpy of sacrificial concrete were increased by 12.98–25.36%, 8.66–34.38%, 25.00–103.23% and 4.23% respectively when adding 0.1 wt% GSNSs, while the porosity and ablation velocity of sacrificial concrete were reduced by 3.01–6.99% and 4.14% respectively due to the incorporation of GSNSs.

1. Introduction

Cementitious composites are the most important and widely used civil engineering materials. Recent progress in the field of nanotechnology has provided an opportunity to improve the performance of cementitious composites by incorporating nano-

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sized materials, such as nano-SiO_2 [1–3], nano-TiO_2 [4], nano-Al_2O_3 [5,6], nano-Fe_3O_4 [7] and carbon nanotubes [8–10]. When small particles were evenly distributed in cementitious materials, they served as nucleation sites, as a result of which the degree of cement hydration can be improved [11]. In addition, the nanomaterials contribute to the microstructural regulation of cement composites and the microstructure of cementitious materials can be improved significantly by adding nanomaterials [12], and nanomaterial has nano-filler effect on cementitious materials [13].

Nowadays, graphene as a new kind of nanomaterial has attracted a lot of interest. Graphene manifests a single atom thickness of 2D carbon atoms planar sheet with sp^2 bonded pattern and has distinguished optical, electrical, thermal and mechanical properties [14]. The electrical conductivity, thermal conductivity, tensile strength and elastic modulus of graphene are 2000 S/cm, 5300 W/mK, 130 GPa and 1 TPa [15–17], respectively. The specific surface area of one single graphene sheet is 2630 m^2/g [16]. Because of its excellent properties, graphene has a promising prospect when combined with cementitious composites. However, the use of graphene is still hampered by its poor water dispersing ability and high production cost. As derivatives of graphene, graphene nanosheets (GNSs) and graphene oxide nanosheets (GONSs) are also carbon nanomaterials composed of graphene stacks or graphene sheets [18–21]. GONSs are oxides of GNSs and contain oxygen functional groups that attach on the basal plans and edges of graphene oxide sheets. The functional groups can modify the van der Waals interactions between the GONSs and thus lead to the improvement of the water dispersing capability of GONSs [22]. Moreover, the GNSs and GONSs are lower-cost nanomaterials as compared to graphene.

So far, an increasing number of studies have been conducted to investigate the influence of graphene or its derivatives on properties of cementitious composites. Horszczruk et al. [23] reported that the Young's modulus of cement paste was significantly enhanced by adding 3 wt% graphene oxide. Bulut [24] explored the effect of graphene nanopellets on mechanical properties of basalt/epoxy composites and found that the mechanical properties of basalt/epoxy composites could be significantly improved due to the addition of 0.1 wt% graphene nanopellets. Murugan et al. [25] observed that the addition of 0.02 wt% GONS by weight of cement can lead to an increase of up to 70% and 23% respectively in the 7-day and 28-day flexural strength of cement paste. Lu et al. [26] concluded that the compressive strength and flexural strength of cement paste were increased by 11.05% and 16.20%, respectively, when adding 0.05 wt% graphene oxide. Apart from enhancing mechanical properties, the self-sensing ability of cementitious materials can also be improved due to the addition of conductive nanomaterials. Le et al. [20] found that the GNSs could be used to characterise the damage in cement composites due to their extraordinary electrical conductivity. The self-sensing ability of GNSs reinforced cement composites was found to be similar to the self-induction of carbon fibre reinforced conductive concrete [27]. Although a great deal of research has been conducted on cement paste or mortar reinforced with graphene or its derivatives, there are only few investigations of the use of them in concrete. In addition, there is no publication devoted to properties of graphene sulfonate nanosheets (GSNSs) reinforced concrete. Compared to GONSs, the production cost of GSNSs is lower. The sulfonic groups contained in GSNSs are similar to that of hydroxyl functional (—OH) groups in GONSs, thus the GSNSs may also be used to improve the properties of cementitious materials.

As a key component of European Pressurized Water Reactor, sacrificial concrete is designed to reduce the leakage potential of radioactive materials in severe nuclear accidents through its encasing function [28]. Ferro-siliceous sacrificial concrete and siliceous sacrificial concrete are the two most widely used sacrificial concrete. On one hand, sacrificial concrete can melt and mix with corium (a molten mixture of fuel material, partially or totally oxidized cladding, non-volatile fission products and various structural materials) reducing the temperature of corium. On the other hand, the SiO_2 from sacrificial concrete can oxidize Zr in the corium and the glassily matrix formed by molten SiO_2 can enwrap the radioactive fission products [29]. In case of fire or nuclear accident, concrete is exposed to elevated temperatures. Although extensive research on the behaviour of concrete subjected to high temperatures has been reported so far [30–34], investigation on the thermal properties of sacrificial concrete is rare, especially on its mechanical properties during elevated temperature exposure. Chu et al. [35] have recently carried out a systematic study on mechanical and physicochemical properties of ferro-siliceous sacrificial concrete after high temperature exposure, and observed that the compressive strength-ultrasonic pulse velocity (UPV) and splitting tensile strength-UPV relationships followed a Weibull distribution and was in exponential form, respectively. It is worth pointing out that the mechanical properties of concrete during high temperature exposure and after exposure (i.e., concrete has been cooled down) are different, as the damage due to elevated temperatures can be retrieved during cooling. Overall, only very little information is available on the properties of sacrificial concrete at high temperatures. Moreover, the effects of GSNSs on thermal and mechanical properties of sacrificial concrete have rarely been studied elsewhere.

The main purpose of this paper is to investigate the mechanical and thermal properties of sacrificial concrete without and with GSNSs before and during high temperature exposure, which extends authors' recently published work [36] from siliceous sacrificial concrete to ferro-siliceous sacrificial concrete. Two new experimental facilities for measuring the compressive strength and splitting tensile strength of sacrificial concrete during elevated temperature exposure are developed. Afterwards, a series of experiments were carried out to estimate the microstructure, porosity, compressive strength, splitting tensile strength, thermal analysis, coefficient of thermal expansion (CTE), thermal diffusivity and ablation behaviour of sacrificial concrete without and with GSNSs before and at different temperatures, i.e., 200, 400, 600, 800, and 1000 °C.

2. Experimental programme

2.1. Materials

Silica fume and Class I fly ash (equivalent to ASTM C 618 Class F fly ash) were used as supplementary cementitious materials in the study. The chemical composition of cement and supplementary cementitious materials are shown in Table 1. The specific gravity of cement and silica fume was 3.15 and 2.22, respectively. The specific surface of cement and silica fume was 362.20 m^2/kg and 2.79×10^4 m^2/kg, respectively. The compressive strength of cement mortar (water/cement/sand = 1:2:6) at 28 days was 62.8 MPa.

Silica sand and iron ore supplied by Nuclear Industry Nonmetallic Mineral Powders Co., Ltd (Liuzhou, China) and Nuclear Science and Technology Co., Ltd (Tongchang, China) respectively were used as aggregates. The silica sand was

Table 1
Chemical composition of cement and supplementary cementitious materials (wt%).

Materials	Cement	Silica fume	Fly ash
CaO	64.70	0.77	8.38
SiO_2	20.40	96.18	47.96
Al_2O_3	4.70	0.96	30.46
Fe_2O_3	3.38	0.85	5.91
MgO	0.87	0.74	2.60
SO_3	1.88	0.50	1.32
K_2O	0.83		1.61
Na_2O			1.76
Loss	3.24		