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Experimental study on the mechanical and thermal properties of basalt fiber and nanoclay reinforced polymer concrete

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ABSTRACT

This paper describes the investigation of the synthesis and improvement of the mechanical properties of quaternary epoxy-based polymer concrete (PC) using basalt fiber and clay nanoparticles. First, the effect of chopped basalt fiber on the compressive, flexural, splitting tensile and impact strengths as well as the effect of different temperatures (up to 250 °C) on the strength of fiber reinforced PC were investigated experimentally. Basalt fiber improved the mechanical properties and increased the thermal stability of PC. In the next step, the effect of nanoclay particles on the mechanical properties and the effect of high temperatures (up to 250 °C) on the strength of basalt fiber-reinforced PC (BFRPC) were analyzed experimentally. Nanoparticles increase the compressive, flexural and impact strength as well as the thermal stability but decrease the tensile strength of the PC. SEM analysis was performed to study the fracture surface and morphology of various concrete specimens. The resulting polymer nanocomposite will be used as a lightweight polymer concrete with high mechanical strength and thermal stability.

1. Introduction

Polymer concrete (PC) composites are used in high performance applications. Different types of materials, e.g., natural fibers and nanofillers, have been implemented for reinforcement and enhancement of the mechanical and physical properties of PCs.

Fiber reinforced polymer concrete (FRPC) is a polymer based concrete composite with random placement of chopped strands fibers. Among the fibers that can be used as reinforcement in polymer concrete, basalt fiber (BF) represents the most interesting because of its remarkable properties, such as considerable mechanical strength, high chemical resistance, thermal stability, extended operating temperature range (−200 °C to 600 °C), non-combustible characteristics, good bonding with resins, dielectric properties and environmental friendliness [1–3]. Several studies proved that basalt fiber, in terms of mechanical and physical properties, is comparable to or better than glass fiber [4–6].

Another feature of basalt fibers is their good compatibility with the matrix phase materials; as a result, they have been used as a reinforcement of polymers such as epoxy, polyester and vinyl ester resins. In particular, because of the good mechanical properties, resistance to moisture absorption, resistance to corrosive liquids and environments, good durability in outdoor environments, low curing shrinkage, and great versatility, the epoxy resin has been the most commonly used matrix for basalt fiber reinforced composites. Implementing basalt fiber as a reinforcement material in concrete enhances the mechanical properties, such as the compressive, flexural, tensile and impact strengths, as reported in the literature [2,7–9]. However, more experimental investigations on the effect of basalt fiber on the mechanical properties of polymer concrete are required.

Nanoparticles integrate into the polymer microstructure because of their nano-scale dimensions. They can improve the mechanical properties of the nanocomposite by promoting the formation of a large number of subcritical micro-cracks or micro-voids. Nanoparticles, such as nanoclay (MMT) [10,11], nano-alumina and iron oxide [12], have been implemented for reinforcement of polymer concretes. Many studies proved that using nanoclay particles as a filler within the polymeric matrix improves the mechanical properties [13,14]. The improvements are caused by an enormously large surface area and high surface-to-volume ratio of the nanoclay particles. In addition, an increment in the glass transition of the nanocomposite with increasing nanoclay content up to 5% was reported. This implies improved adhesion between the polymeric matrix and the nanoclay particle surfaces. In addition, the nanoclay prevents segmental motions of the polymer chains and increases the cross-linked density of the nanocomposite [11]. Introduction of the nanoclay into the epoxy-based PC did not improve the tensile

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and flexural strengths, although the compression strength was enhanced by up to 15.2% [10].

It is necessary to enhance the thermal resistance and durability of concrete because concrete structures undergo different severe thermal cycles and fire hazards during service life. [15]. In addition, because of the incorporation of the polymer binder and the viscoelastic characteristics of the polymers, high temperatures have a significant influence on the mechanical strength of polymer concrete [16–18].

Reis studied the effect of temperatures varying from room temperature to 90 °C on the mechanical properties of epoxy and unsaturated polyester polymer mortars. The results showed that the epoxy mortars are more sensitive than the unsaturated polyester mortars to temperature variations because of the heat distortion temperature of the resins used [19]. Many research studies have been conducted to enhance the thermal stability of concrete systems subjected to elevated temperatures using different materials, such as inorganic fillers, nanoparticles and fibers [20–23]. Chopped basalt fiber reinforced epoxy composites using different curing systems were prepared to enhance the thermal and physical properties of the composites [24]. Sim et al. investigated the applicability of basalt fiber as a strengthening material for structural-cement-based concrete [25] .They showed that the basalt fiber retained approximately 90% of the normal temperature strength after exposure at 600 °C for 2 h, whereas the carbon and the glass fibers did not maintain their volumetric integrity. In addition, the basalt fiber improved both the yielding and the ultimate flexural strength of the beam specimen.

In addition, research studies proved that nanoclay has considerable effects on the thermal stability of polymer nanocomposites. Experimental investigation of PC composed of MMT-UP nanocomposite showed that an increase in temperature from -15 °C to 65 °C decreased the compressive strength, splitting tensile strength, and flexural strength by approximately 18%, 18%, and 22%, respectively. However, the PC containing nanoclay has better thermal performance than that of pure PC [11].

Khosravi and Eslami-Farsani demonstrated that the addition of 5 wt % silane-modified Na$^+$-MMT nanoclay in unidirectional basalt fiber/epoxy composites enhanced the flexural, tensile and compressive strengths by 28%, 11% and 35%, respectively [26].

It can be observed from previous research studies that only a few of them concentrated on the effects of high temperatures on the PC behavior and often considered the maximum operating and test temperature of 100 °C because of the low operational temperature of the polymer matrix. Furthermore, simultaneous use of basalt fiber and clay nanoparticles in polymer concrete should be investigated. Fabrication and experimental investigation of the mechanical properties of a quaternary PC was performed in our previous studies [27,28]. We optimized the weight percentages of the epoxy resin, ultra-fine fly ash, foundry silica sand and crushed basalt aggregates.

The present work attempts to obtain and enhance the compressive, flexural, splitting tensile, and impact strengths as well as the thermal stability of PC using basalt fiber and nanoclay.

First, after adding chopped BF to the presented PC of previous work, the mechanical properties are experimentally investigated. Next, basalt fiber reinforced polymer concrete (BFRPC) is exposed to different high temperatures, and after cooling to room temperature, the mechanical strength and corresponding weight loss are attained. Subsequently, the optimum content of nanoclay to enhance the strength of the BFRPC is experimentally obtained. In the last step, BF-clay-reinforced polymer concrete is exposed to different high temperatures, and the effects of nanoclay on the thermal performance of polymer concrete are discussed.

2. Experiment

2.1. Materials

2.1.1. Resin

A low viscosity DGEBA epoxy resin (CY 184), and the polyamine hardener (Aradur® 2965) from Huntsman (UK) were polymerized with a mix ratio of 100:15.

2.1.2. Fillers

The ultrafine fly ash of class F (Pozzocrete100™) from Dirk Private Ltd (India) was utilized as micro filler with an average particle size of 10 µm.

The montmorillonite nanoclay (281522™) from Sigma-Aldrich (USA) was used as nano filler with layer thickness of 1–2 nm.

2.1.3. Aggregates

The crushed basalt from Kavyan Industry and Stone Company (Iran) was utilized as aggregates with an average particle size of 3 mm.

The silica foundry sand (101^{TM}) from the Silica Sand MFG Company (Iran) was used as aggregates with an average particle size of a 100 µm.

2.1.4. Fiber

Chopped basalt fiber (KV41^{TM}) was supplied by Kamenny Vek Ltd. (Russia) with a monofilament diameter of 13 µm and a cut length of approximately 6 mm. Basalt fiber is ideally suited for demanding applications requiring high temperatures, chemical resistance, durability, mechanical strength, low water absorption and thermal and sound insulation.

2.2. Polymer composite concrete preparation

According to our previous paper, polymer concrete with the optimum mechanical properties can be produced by mixing 25 wt% (wt%) of polymer resin (100 parts of DGEBA with 15 parts of the curing agent), 53.25 wt% of silica sand, 17.75 wt% of basalt aggregates and 4 wt% of fly ash. The polymer concrete has a compressive strength of 94.1 MPa, a flexural strength of 39 MPa and a splitting tensile strength of approximately 11.8 MPa. In this paper, to increase the mechanical and thermal properties of polymer concrete, basalt fibers with different

Table 1
Components of the prepared polymer concrete and their descriptive names.

Sample ID	Resin content (%wt)	Fly ash content (%wt)	Silica sand content (%wt)	Basalt aggregate content (%wt)	Basalt fiber content (%wt)	Nanoclay content (% wt)
PC-BF0 (Plain PC)	25	5	52. 5	17. 5	0	0
PC-BF0.5	24.88	4.97	52.24	17.41	0.5	0
PC-BF1	24.75	4.95	51.98	17.32	1	0
PC-BF1.5	24.63	4.92	51.71	17.24	1.5	0
PC-BF2	24.50	4.90	51.45	17.15	2	0
PC-BF2.5	24.37	4.88	51.19	17.06	2.5	0
PC-BF3	24.25	4.85	50.92	16.98	3	0
PC-BF3.5	24.13	4.82	50.66	16.89	3.5	0
PC-clay1	24.45	4.89	51.35	17.11	1.96	0.24
PC-clay2	24.39	4.88	51.22	17.07	1.95	0.49
PC-clay3	24.33	4.87	51.09	17.03	1.95	0.73
PC-clay4	24.27	4.85	50.98	16.99	1.94	0.97