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Experimental Study on the Effect of Basalt Fiber and Sodium Alginate in Polymer Concrete Exposed to Elevated Temperature

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Citation: Mohammadyan-Yasouj, S.E.; Ahangar, H.A.; Oskoei, N.A.; Shokravi, H.; Koloor, S.S.R.; Petrů, M. Experimental Study on the Effect of Basalt Fiber and Sodium Alginate in Polymer Concrete Exposed to Elevated Temperature. *Processes* **2021**, *9*, 510. https://doi.org/10.3390/pr9030510

Academic Editor: Shaghayegh Hamzehlou

Received: 11 February 2021
Accepted: 8 March 2021
Published: 11 March 2021

Abstract: Polymer concrete contains aggregates and a polymeric binder such as epoxy, polyester, vinyl ester, or normal epoxy mixture. Since polymer binders in polymer concrete are made of organic materials, they have a very low heat and fire resistance compared to minerals. This paper investigates the effect of basalt fibers (BF) and alginate on the compressive strength of polymer concrete. An extensive literature review was completed, then two experimental phases including the preliminary phase to set the appropriate mix design, and the main phase to investigate the compressive strength of samples after exposure to elevated temperatures of 100 °C, 150 °C, and 180 °C were conducted. The addition of BF and/or alginate decreases concrete compressive strength under room temperature, but the addition of BF and alginate each alone leads to compressive strength increase during exposure to heat and increase in the temperature to 180 °C showed almost positive on the compressive strength. The addition of BF and alginate both together increases the rate of strength growth of polymer concrete under heat from 100 °C to 180 °C. In conclusion, BF and alginate decrease the compressive strength of polymer concretes under room temperature, but they improve the resistance against raised temperatures.

Keywords: concrete; basalt fiber; epoxy resin; alginate; raised temperature; compressive strength

1. Introduction

Concrete is an old building material, in use for centuries. Concrete is widely used in the construction of civil engineering structures such as buildings [1,2], bridges [3,4], and other civil structures [5,6]. Reinforced concrete structures are vulnerable to high-temperature conditions, which greatly shortens the service life and hinders its applications [7]. The properties of the mix design parameters have a significant effect on the performance of concrete exposed to elevated temperature [8–11]. Several research studies have been carried out to improve the thermal stability of concrete exposed to elevated temperatures using various materials, such as fillers, nanoparticles, and fibers [12–15].

Sodium alginate (SA) is a well-known natural polymer that is extracted from cell walls of brown algae [16,17]. Recently, SA has received much attention in concrete applications due to self-healing behavior [18,19]. The influence of the SA on mechanical and flexural properties is still unclear and different studies achieved different results. Abbas and Mohsen [20] indicated that the addition of SA increased the fresh and mechanical properties of concrete. However, Heidari et al. [21] reported a decrease in mechanical properties by using SA in the mix design. Mignon et al. [22] indicated that the addition of 1% calcium alginate can result in a 15% reduction in compression strength of concrete while it was 28% for SA. SA also improves the temperature resistance of concrete and enhances flame-, fire- and heat-resistance of cementitious composites [23]. Moreover, it was stated that the properties of the produced alginate gel are greatly affected by the polymer concentration and type [16,19]. Mignon et al. [22] showed that alginate can improve the internal curing of concrete effectively. Ouwerx et al. [19] showed that the concentration of SA in concrete can limit the elasticity of beads. Pathak et al. [16] prepared and compared different metal alginates and alginic acid exploited from fresh algae using the extraction method. It was reported that decomposition of cobalt alginate takes place at a higher temperature compared to sodium and calcium alginate. The distribution and pore size were significantly influenced by the presence of metal ions. The type of metal alginates may lead to variation in thermal behavior of the compounds. Table 1 shows a summary of the studies on the effect of alginates on mechanical parameters of concrete.

Table 1. A summary of the studies on the effect of alginates on mechanical parameters of concrete.

Reference.	Alginate Type	Weight Fraction (% of Cement)	Remarks
Mohammadyan-Yasouj et al. [24]	NaAlg	0.1	• Alginate decreases the flexural, tensile, and compressive strengths of concrete.
Ouwerx et al. [19]	Alginate gel bead	-	• Properties of alginate significantly depend on polymer type and concentration.
Pathak et al. [16]	Alginic acid and metal alginates	-	• Presence of metal ions impacted on the pore size distribution of alginates. • Different thermal behavior was observed in different metal alginates due to structural differences.
Heidari et al. [21]	Alginic acid	0.5 and 1	• Alginate decreases the flexural, tensile, and compressive strengths of concrete. • Alginate diminished the fresh properties of SCC.
Mignon et al. [22]	NaAlg, CaAlg	0.5 and 1	• Alginate improves internal curing • CaAlg beads of 1% reduced 15% of the compressive strength. • NaAlg of 1% resulted in a 28% decrease in compressive strength due to increasing in the water uptake.

Polymeric concrete is a kind of concrete in which natural aggregates such as silica sand and gravel are bound together in a matrix with a polymer binder as a supplement or replacement of cement in concrete [25]. Polymeric concrete has higher mechanical strengths, chemical resistance, and ductility, compared with ordinary concrete (OC) [26,27]. Currently, three distinct types of polymeric concrete are studied that include polymer-Portland cement concrete (PPCC), polymer impregnated concrete (PIC), and polymer concrete (PC) [27].

According to American Concrete Institute (ACI 548.3R), in PC, the polymer is served as the sole binding material present in concrete [28]. However, filler materials such as silica fume and fly ash can be utilized along with aggregates to enhance mechanical properties and minimize building cost. PC can achieve about 80% of its 28 day compressive strength in one day, and compressive strength of 100 MPa can be attained [26,29]. Higher ductility after 60 °C [30] and no visible failure under compression for mixes containing epoxy or epoxy and filler of 30% of the total volume is also reported for PC [31]. An investigation by Golestaneh et al. [32] indicated an optimal amount of epoxy to reach the maximum compressive and flexural strength was 15% of the total volume, while Elalaoui et al. [33] suggested 13% to reach the highest physical and mechanical properties at the lowest cost. However, the higher value for the suggested optimal amount by Golestaneh et al. [32], even with 20% epoxy, may be due to the utilization of silica fume as filler to get the maximum tensile strength.

The results indicate that, compared to OC, polymeric concrete exhibited fewer cracks that are probably due to the bound effect between fiber and matrix [34]. PC has higher strengths than OC [34–36] and, similar to the OC, with the addition of fiber, reduction in its workability is unavoidable [34]. Acceptable interface adhesion between fiber and polymeric matrix for fiber loading of 15% of the total volume resulted in high tensile and flexural strengths [37]. Understanding the behavior of concrete exposed to various temperatures is considered an important factor in meeting the safety and service life objectives in which structures are intended and designed. Three different temperature ranges are generally used in concrete studies that include low temperature (<0 °C), medium temperature (0–50 °C), and high or elevated temperature (<50 °C). The thermal response of concrete to elevated temperature mainly depends on constituents' characteristics and the mix composition [38]. Based on the applications and intended exposure condition, previous researches have considered various temperature ranges to evaluate the thermal response of concrete which can be classified as temperatures below 200 °C [39–41], below 600 °C [42–44], and below 1000 °C [45–47]. The value of 600 °C is generally selected because the interior of the concrete members will not exceed 600 °C in a short time. Higher temperatures (e.g., 1000 °C) are considered for the peak gas temperature of a fire that may reach a higher value [48], while the temperature lower than 200 °C is generally considered for members exposed to indirect fire heat.

The duration of exposure and heating rate are two other important factors that have been investigated in many research studies. Different heating durations are generally based on the recommendation by different specifications for maximum fire-resistance rating. For example, the fire resistance for column members in China fire design specifications is defined as 180 min (3 h) [48]. Alharbi et al. [49] indicated that duration of exposure has an effect on degradation of the stiffness while prolonged exposures can significantly reduce the strength of concrete. The heating speed caused by exposure to real fire is generally specified by fire standards (e.g., ISO 834 standard fire).

Investigation on the behavior of PC with basalt fiber has revealed that BF >1% reduces concrete strength [50]. On the other hand, the studies on epoxy/basalt polymer concrete showed enhancement of mechanical properties and more ductility under increasing temperature up to 100 °C [36]. Reis [30] observed that the epoxy mortars had higher sensitivity to temperature variations due to the heat distortion temperature of the resins [19]. Niaki et al. [51] demonstrated that basalt fiber improved the mechanical properties and increased the thermal stability of the PC subjected to different temperatures (up to 250 °C). Several research studies have been conducted to improve the durability of polymer concrete exposed to elevated temperatures [9]. Elalaoui et al. [52] proposed ammonium polyphosphate to be used as a constituent of the PC to improve the temperature resistance of the concrete. Niaki et al. [36] reported that adding crushed basalt aggregates into PC led to decreases in the highest maximum stress rapidly, but increases the yield displacement significantly due to temperature increase. Gorninski et al. [53] produced PC composites using waste alumina and showed that the addition of alumina flame retardant waste can efficiently improve the temperature resistance of the PC.

The effect of using BF on concrete has been carried out by many researchers, and several experiments were conducted to study the influence of adding different proportions, diameter, and length of fibers in concrete. Jiang et al. [54] demonstrated that BF addition can considerably improve the tensile and flexural strength and toughness index of fiber reinforce concrete. It was indicated that adding BF had no obvious increase in compressive strength. Compared to other types of fibers such as polypropylene and glass fiber (GF) higher performance for splitting tensile, flexural strengths, crack resistance, ductility post cracking flexural response have been reported for BF [54–57]. Almost all previous researchers are agreed upon the fact that an increase in the fiber content and/or length decreases the workability of concrete and increases porosity [58]. Kabay [59] showed that increasing the length and/or volume of fibers reduces concrete workability. It was observed that void content has a higher impact on abrasion compared to compressive and flexural strength. The inclusion of fibers reduced compression strength and abrasive wear of concrete. The highest flexure strength was achieved in mixtures with 60% w/c. Dias and Thaumaturgo [34] studied the effect of BF in geopolymer concrete. It was indicated that BF in geopolymer concretes improved the flexural and splitting tensile strength compared to geopolymer concretes; however, the addition of 1.0% BF resulted in a 26.4% reduction in compressive strengths of cement concretes.

The length and weight fraction of BF are two interactive factors that influence on mechanical and fresh properties of cementitious composites. Khan and Cao [60] investigated the mechanical properties of basalt-fiber-reinforced cementitious composites with four different fiber lengths (3, 6, 12, and 20 mm) and also with a combination of various lengths and contents. The results indicated that the compressive strength of basalt-fiber-reinforced cementitious composites containing fiber with the length of 6 and 12 mm is higher than that with 3 and 20 mm length. It was observed that short fibers in the matrix play a bridging role to limit the expansion of microcracks while longer fibers provided additional capacity to restrict the development of macrocracks. Amuthakkannan et al. [61] studied the effect of basalt fiber length and content on the mechanical properties of basalt-fiber-reinforced polymer matrix composites of the fabricated composites. It was shown that basalt fiber with the length of 10 mm and 50 mm provided better tensile strength than 4 mm and 21 mm in polymer matrix composites. It was indicated that shorter fiber lengths will create more fiber ends that act as stress concentration points, resulting in a faster failure at these points.

Almost all studies conducted on properties of fiber-reinforced cementitious materials indicated that increasing the fiber contents and/or length harms the workability and porosity of the fresh mix [58]. Reduction in the workability due to an increase in the fiber content requires higher water-to-cement ratio, which leads to higher porosity in the hardened concrete. Accordingly, fiber content is also a main parameter considered by previous researchers to control the fiber effect on the concrete properties. However, selecting an appropriate amount of fiber content to reach proper workability with expected mechanical properties for concrete is necessary. As shown in Table 2, the length of BF is varied from 3 to 30 mm while the fiber content is ranged from 0.05% to 5% of the volume fraction in the mixes. As it can be seen in the table, 2% is the most frequently used weight fraction in studies related to fresh and hardened concrete properties. Chopped fibers with shorter length are characterized with a more uniform distribution while longer lengths can better contribute with crack control.

Table 2. A summary of the studies on the effect of basalt fiber (BF) on mechanical parameters of concrete.

Reference.	Fiber Type	Length (mm)	Weight Fraction (%)	Remarks
Jiang et al. [54]	Basalt Polypropylene	12 and 22 4–19	0.05, 0.1, 0.3, & 0.5	- Compressive strength ↑ - Toughness & splitting tensile strength ↑ - Flexural strength (0.3% BF) and (0.5% BF) - Tensile and flexure strength (22 mm length of BF)
Kabay [59]	Basalt	12 and 24	0.07 and 0.14	- Length and/or volume of BF ↑ ⟹ workability ↓ - Compression strength ↓ - Abrasive wear (in the range of 2–18%) ↓ - Flexure strength ↑
Ayoub et al. [62]	Basalt	25	1, 2, and 3	- BF contents ↑ ⟹ compressive strength ↓ - Tension strength ↑ - No correlation between BF and E-value
Kizilkanat et al. [57]	Basalt Glass	12 12	0.25, 0.5, 0.75, and 1	- BF contents ↑ ⟹ fracture energy ↑ - Compressive strength ↑ (>0.25% fiber content) - Crack avoidance, tensile strength, and ductility ↑ - GF ↑ ⟹ flexure strength
Fenu et al. [56]	Basalt Glass	12 12	3 and 5	- No significant impact on dynamic in-crease factor - Energy absorption ↑ - Static flexural strength and post-peak behavior ↑
Shafiqh et al. [55]	Basalt Polyvinyl Alcohol	25 30	1, 2, and 3	- Strain attaining capacity ↑ - PVA fibers ↑ ⟹ ductility, post-cracking flexural response, and toughness ↑ - BF does not correlate with post-peak flex-ural behavior
Girgin [63]	Basalt Glass	24 24	2	- Fibers ↑ ⟹ fracture energy ↑; workability ↓ wand E-value ↓ - Compressive strength ↑ (0.5% and 0.75% fiber content) - Crack avoidance ↑, tensile strength ↑, and ductility ↑
Afroz et al. [9]	Basalt (Chinese) Basalt (Russian)	3 25	0.5	- Stability in alkaline medium ↑ - Protection against alkaline ion - Mechanical properties ↓ - Long-term flexural strengths and splitting tensile ↑
Zhao et al. [64]	Basalt	18	1, 1.5, 2 & 2.5	- Anti-impact deformation characteristics ↑
Katkhuda and Shatarat [65]	Basalt	18	0.1, 0.3, 0.5, 1, and 1.5	- Flexural and splitting tensile compressive strength ↑
Sun et al. [66]	Basalt	6 and 12	1, 2, 3, 4, & 5	- Compressive and splitting tensile strengths ↑; bending strength increase ↓

Ayoub et al. [62] stated that an increase in BF contents of the concrete mix leads to reduced compressive strength. However, 0.5% and 0.75% of BF content can slightly improve the compressive strength. The addition of 10% silica and BF can result in a higher tensile strength in high-performance concrete. BF content does not correlate with E-value. Fenu et al. [56] reported that the addition of GF and BF increased dynamic energy absorption at a high strain rate. Furthermore, it enhanced the post-peak behavior and static flexural strength of concrete. Shafiqh et al. [55] indicated that the addition of GF and BF enhanced strain capacity attaining of the concrete. Significant improvement was achieved in flexural response, ductility, and toughness by the inclusion of PVA fibers. However, no relation was found between BF addition and post-peak flexural behavior of concrete. Girgin 2016 [63] stated that the addition of GF resulted in a 35% reduction in the average strain capacity of concrete compared to the control specimens. The flexural strain capacity of BF was influenced by cement hydration in the matrix–fiber interface. Afroz et al. [67] studied the influence of BF fibers for sulfate and chloride resistance in concrete for long-term durability applications. It was shown that modified BF had better stability in the alkaline medium compared to non-modified ones. However, a slight reduction in the mechanical properties was reported for concretes reinforced with treated fibers.

Since polymer binders in polymer concrete are made of organic materials, they have a very low heat and fire resistance compared to minerals. Hence improving the thermal performance of the polymer concretes is of utmost importance for the construction industry. The limited information that exists in the literature indicates that application of SA in the concrete mixture could associate with self-healing of cracks and improving the fire, flame, and heat resistance of concrete while the inclusion of BF could enhance the energy absorption and ductile behavior of concrete that can prevent brittle fracture of structures. Several pieces of research have been conducted to study the effect of using SA and BF in cement concrete; however, such studies are limited when it comes to their applications in PC. To the author's knowledge, this study is the first that investigated the strength characteristic of SA-based BF-reinforced PC subjected to elevated temperature. After an extensive literature review, two experimental phases, including the preliminary phase to set the appropriate mix design, and the main phase to investigate the compressive strength of samples after exposure to elevated temperatures of 100 °C, 150 °C, and 180 °C, were conducted. A summary of the research on PC/PPCC with and without fiber reinforcement is presented in Tables 3 and 4, respecrively.

Table 3. Polymeric concrete.

Remarks	Filler and Polymer			Codes & Sample Size (mm)	Test Age (Day)	Conducted Tests and Sample Monitoring	Ref.
	Amount (% of the Total Volume (Vol%) or the Total Weight (wt %))	Details	Name				
• 15% epoxy & 200% filler (15% fine silica, 25% medium-size silica, & 60% coarse silica powder) had maximum compressive & flexural strengths • Tensile strength was maximized with 20% resin & 200% filler • Mechanical strength of polymer concrete was 4–5-folds higher than cementitious concrete	100, 150, & 200 Vol%	50–60, 600, & 1100 µm Size	Silica Fume	➢ ASTM (C33-03, C579-01, C293-02, C496/C496/M, & C496-04) • 50 × 50 × 50 cube • 76.2 × 152.4 cylinder	-	• Uniaxial compressive test • Uniaxial tensile test • Flexural compressive test	Golestaneh et al. 2010 [32]
	10, 15, & 20 wt %	Epoxy, Bisphenol A	Epoxy Resin				
• Investigate the effect of temperature on the performance of epoxy and unsaturated polyester polymer mortars • Higher ductility after 60 °C • Epoxy more sensitive than polyester • From room temperature to 60 °C, flexural and compressive strength decreases drastically as temperature increases; a loss of more than 50% is reported • The epoxy mortars are more sensitive to temperature changes than the unsaturated polyester ones	88 Vol%	245 µm	Only Coarse Aggregate	➢ RILEM TC113/PC-2, RILEM TC113/PCM-8, ASTM (C39-05, C348-02) • 40 × 40 × 160 prism • 50 × 100 cylinder	7	• Uniaxial compressive test • Flexural compressive test	Reis 2012 [30]
	12 wt %	Diglycidyl ether bisphenol A & an aliphatic amineHardener, RR515	Epoxy Resin				
• Mechanical and physical properties of epoxy polymer concrete after exposure to temperatures up to 250 °C • Optimum polymer amount is 13% • 50% reduction in compressive strength after exposure to 250 °C • No change in flexure strength • The optimal polymer content is 13% which leads to obtain the highest physical and mechanical properties at the lowest cost	-	$(0–4) \times 10^3$ µm	Sand	➢ RILEM CPT (PCM 2, PCM 8), NF EN (1097-6, 197-1), EN (12390-3, 206-1, 934-2) • 50 × 50 × 305 prism • 70 × 70 × 280 prism • 50 × 100 cylinder • 150 × 300 cylinder • 50 × 150 cylinder	7 & 28	• Uniaxial compressive test • Flexural compressive test • Heating • Porosity • Scanning electron microscopy • E-value calculation	Elalaoui et al. 2012 [33]
	-	$(4–10) \times 10^3$ µm	Gravel				
	6, 9, 13, & 16 wt %	Bisphenol A diglycidyl ether resin, Eponal 371	Epoxy resin				
• Effect of fly ash on the behavior of polymer concrete with different types of resin was investigated • Improve in ductility & increase in E-value by decreasing in fly ash content for all the mixes of PC concrete • Compressive strength as high as 100 MPa can be achieved using resins in polymer concrete • About 80% of the 28-day compressive strength can be achieved in 7 days for polymer concrete • Split tensile and flexural strengths decreased with the increasing fly ash content for all the mixes	0, 3, 10, 13, 20, 21, & 23 Vol%	15 µm (Type F)	Fly Ash	➢ ASTM (C128, D695, D3967), ISO 178 • 9 × 16 × 160 prism • 50 × 100 cylinder	3, 7, 14, 21, & 28	• Uniaxial compressive test • Uniaxial tensile test • Flexural compressive test • E-value calculation	Lokuge & Aravinthan 2013 [26]
	20, 22, 30, 40, & 43 Vol%	Orthophthalic	Polyester Resin				
		Bisphenol	Vinylester Resin				
		Thixotropic	Epoxy Resin				
• Increase in density of polymer matrix by an increase in filler content which resulted in more & bigger voids • An increase in filler amount to 60% reduced the flexural strength by 70%. • No visible failure under compression was observed for the mixes with up to 30% filler. • An increase in filler amount leads to increased compressive modulus of elasticity. • Adding filler could help preserve structural performance through absorbing or blocking UV radiation before reaching chromophores on which the color of a polymer matrix is dependent • The mix with 30% filler has better mechanical properties while the mix with 50% filler would be the most economical choice. Both 30% and 50% filler mix have high durability for UV radiation	0, 10, 20, 30, 40, 50, & 60 Vol%	Fire Retardant, Hollow Microsphere, Fly Ash	light-weight Filler	➢ ASTM (D7028, D4065, C905, C580, & C579) • 60 × 14 × 4 prism • 80 × 10 × 10 prism • 25 × 25 cylinder		• Uniaxial compressive test • Uniaxial tensile test • Flexural compressive test • Porosity • Ultraviolet • Density • Heat Generation • Glass transition temperature	Ferdous et al. 2016 [31]

Table 4. Polymer concrete (PC)/polymer-Portland cement concrete (PPCC) with fiber.

Remarks	Basalt and Polymer					Codes & Sample Size (mm)	Test Age (Day)	Conducted Tests and Sample Monitoring	Ref.
	Amount (% of the Total Volume (Vol%) or the Total Weight (wt %))	Etra details	Diameter (μm)	Length (mm)	Name				
• Geopolymer concrete showed higher strengths than Portland cement concretes • BF of 1.0% resulted in 26.4% & 12% reductions in compressive and splitting tensile strengths for Portland cement concretes • BF in geopolymer concretes resulted in higher flexural & splitting tensile strength than geopolymer concretes without fibers • Addition of fibers to all concretes tested caused increases in the VeBe time • Geopolymer concretes exhibited less cracks that is probably due to the bond between fiber and matrix	(0, 0.5, 1) Vol%	-	9	45	Basalt Fibre (BF)	➢ NBR (5738/93, 5739/94, 7222/94, 7222/94), ASTM (1993), ESIS (1992), Rilem Draft Recommendations (1989) • 150 × 300 cylinder • 150 × 150 × 500 prism (with 30 mm depth and 3 mm thickness notch)	28	• Uniaxial compressive test • Uniaxial tensile test • Flexural compressive test • VeBe consistometer test	Dias & Thaumaturgo 2005 [34]
	A/B = 1 (13.85 wt %) & 47.7 wt %	A: SiO_2/Al_2O_3 ratio = 5.35, (Na_2O + K_2O)/SiO_2 = 0.209, B:SiO_2/Na_2O = 2.24, KOH = 14M	-	-	Geopolymer (Poly(Siloxo-Sialate))				
• Comparison between epoxy polymer concrete plain, reinforced with CF and GF • Increase in compressive strength of epoxy polymer (27.5–45.4% by GF & 36.1–55.1% by CF was observed • Slightly ductile failure of reinforced polymer, while unreinforced polymer showed a brittle failure • Comparing plain polymer concrete to ordinary concrete, compressive strength is 85% higher • When polymer concrete is reinforced, more than 100% increase in compression strength was observed • Epoxy polymer concrete (with and without fiber) proved to be an excellent alternative to concretes	1 & 2 Vol%	-	Chopped	6	Carbon Fiber (CF)	➢ RILEM, ASTM (C469-94, C617-98) • 50 × 100 cylinder	7	• Uniaxial compressive test	Reis 2005 [35]
				6	Glass Fiber (GF)				
	20% wt %	Eposil 551 (Silicem®), Based on a diglycidyl-ether of bisphenol A, Aliphatic amine hardener	-	-	Epoxy Polymer				
• Maximum tensile and flexural strengths of BF/polyester poly butylene succinate (BF/PBS) were achieved at a fiber loading of 15 vol% and a good interface adhesion between the fiber and matrix observed in the composites • Impact strength of BF/PBS decreased with fiber addition primarily and then increased by increasing fiber • Thermal deflection temperature (HDT) of BF/PBS composite was significantly higher than the HDT of PBS resin	(0.0–15) Vol%	-	10	continuous twistless roving	BF (coated by silane coupling agent)	➢ GB/T(1040-1992, 9341, 1843, 1633, 1634) • Dumbbell shape • 4 × 10 × 80 prism (with 2 mm depth notch)	-	• Uniaxial tensile test • Flexural compressive test • Impact test • Thermal stability • Scanning electron microscopy	Zhang et al. 2012 [37]
	20–30 wt %	Diglycidyl ether of bisphenol A resin (DGEBA), Low viscosity (CY 184), Polyaminehardener (Aradur ®2965)	-	-	Resin				
• BF was exposed to water, styrene butadiene rubber and superplasticizer that prevails in cementitious materials • BF >1% reduced concrete strength & basalt was degraded and degenerated by biochemical changes • In increased alkaline conditions, spalling of fibers was observed when exposed to the pH of 12 & further disintegration of fibers were noticed when exposed to polycarboxylate based superplasticizer and polymer matrix of styrene butadyene rubber at pH 12 • Further studies are required to enhance the structural stability of BF in the concrete matrix	(0.5, 1, 1.5, & 2) Vol%	-	13	24	BF	➢ - • 100 × 100 × 100 cube • 150 × 300 cylinder	14 & 28	• Compression • Uniaxial tensile test • X-ray diffraction test • Fourier transform infrared • Scanning electron microscopy • Energy dispersive X-ray	Sarayu et al. 2016 [50]
	97–85 vol%	Mp 114 °C, Vicat softening temperature 96 °C	-	-	Polymer/Styrene Butadiene Rubber (SBR)				
• Mechanical properties of an epoxy/basalt polymer concrete at 24, 50, 75, & 100 °C were investigated • Increase in the amount of epoxy resin to 25 wt % enhanced mechanical properties of this concrete • Increase in temperature resulted in more ductility, but mechanical properties deterioration and stiffness loss • Decrease in aggregate size resulted in higher flexural & splitting tensile & lower compressive strengths	(0, 70, 72.5, 75, 77.5, & 80) Vol%	-	1–5	-	Crushed Basalt (aggregate)	• ASTM (C39/C39M, C580, C496/C496M) • 50 × 100 cylinder • 25 × 25 × 54 prism	7 & 28	• Uniaxial compressive test • Uniaxial tensile test • Flexural compressive test Scanning electron microscopy	Niaki et al. 2017 [36]

2. Materials and Methods

2.1. Materials

Materials including aggregates, BF, SA, and two-part epoxy resin for this experiment were provided by a local supplier. Basalt fiber, SA, and epoxy resin were productions originally from the U.S., Iran, and Germany, respectively. Triplicate cubic concrete samples of 50 × 50 × 50 mm were tested for the compressive strength of each mix composition. According to ASTM C117 and E11, the aggregates for the mortar were sieved through sieve number 4 to provide relatively fine aggregates of size less than 4.75 mm. The fineness modulus of the used aggregates was 2.72. Size distribution curve for aggregate used in the present research is shown in Figure 1. The review of the literature presented in Table 2 showed that the length of the BF considered in the table for production of polymer and cementitious composites is ranged from 6 to 45 mm. Shorter chopped lengths fibers are more effective for appropriate fiber distribution while longer chopped lengths are more effective in crack bridging action [68].

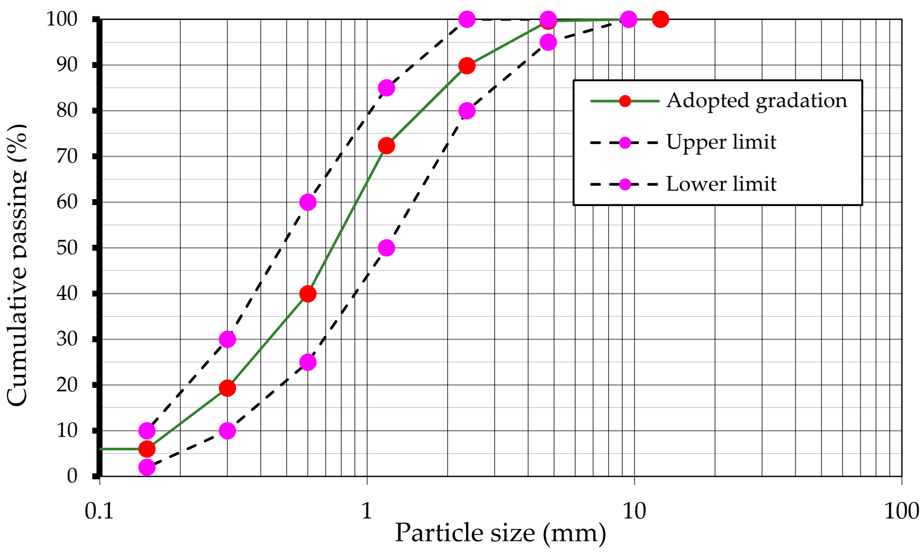


Figure 1. Size distribution curve for aggregate used in the present research.

In order to achieve the objectives of this study and in light of the findings reported in previous studies, together with the literature review discussed in the introduction section, the average length of the chopped BF in the mortar mixtures is considered 10 mm for this study. Moreover, the amount of investigated fiber content reported in previous studies and literature review is ranged between 0.15% and 2% of the total volume of the PC. In this study, the content of the chopped BF in the mortar mixtures was considered 2% of the total volume, which is consistent with the literature. BF is another admixture in the composite to improve the thermal resistance of the composite. Nonetheless, the addition of BF into the mixtures may improve the fresh properties of the composite, it reduces the compressive strength of the hardened mortar specimens. In order to restrict the adverse effect and take advantage of BF in improving thermal resistance and rhetorical properties, a lower proportion of SA compared to that used in literature was incorporated. BF amount used in this study occupied only 0.1% of the total mortar volume. The geometrical and mechanical properties of the BF used in the present study are shown in Table 5. The fine fraction of aggregates 0–150 µm were excluded.

Table 5. Properties of BF used in the experiment.

Cutting Length (mm)	10
Diameter (µm)	17
Density (gr/cm3)	2.65
Elastic modulus (GPa)	93–110
Tensile strength (MPa)	4100–4800
Elongation (%)	1.3–3.2
Softening point (°C)	1050
Water absorption (%)	<0.5

Two-part epoxy resin with a specific weight of 1.1 gr/cm^3 was used in the experiment. In this process, a low viscous epoxy, known as saturant resin (Part A) and hardener (Part B), was mixed to obtain a homogeneous mixture. Epoxy resins are the most widely used PC compounds [69]. Epoxy concrete is composed of two parts of the epoxy and aggregate blend. The curing of the epoxy resin systems is an exothermic reaction. The aggregates were checked to be dry and free of dirt, debris, and organic materials using sieving and oven drying. The mix proportion of the saturant resin and hardener with the trading name of Araks FK20 was as per the guidelines of the manufacturer. Generally, epoxy formulations are skin sensitizers, and handling precautions should be taken carefully [69]. In order to determine the general proportions of selected materials in the experimental study, two amounts of 13% and 15% of the total mortar volume were used for epoxy content in the mix design stage. SA occupied 0.1% of the total mortar volume.

The curing time and temperature for PC are affected by parameters such as the epoxy formulation, mix proportions of PC composition, and mass volume. Generally, PC mortar cures in hours after casting while complete curing of the cement-based materials takes days or weeks.

2.2. Mix Designs and Preparation of Specimens

The experimental study was conducted in two phases, one aimed to obtain appropriate proportions and the other is to investigate the main objective of this research. In the first phase of the experimental program, two epoxy concrete mixes made of aggregate and epoxy resin without the inclusion of BF and SA were tested. The results of the compressive strength for the epoxy resin contents of 13% and 15% were 41.9 MPa and 39.7 MPa. For the second phase, different mix designs of PC were determined to have aggregate, epoxy resin, FB, and SA in the composition of the mix. The resin amount, in the PC mix designs, was constant and equal to 13% of the total concrete volume. The mix design for SA-based BF-reinforced mortar subjected to 0 °C and elevated temperatures of 100 °C, 150 °C, and 180 °C is presented in Table 6. Zero temperature in these tables that is room-curing temperature without heating was a reference before heating of samples. The hardened mortar specimens were exposed to three elevated temperatures of 100 °C, 150 °C and 180 °C for a duration of three hours. Then, the compressive strength of samples was tested and compared for each mix design under raised temperature conditions. To test compressive strength, PC samples were placed in the oven for three hours under the intended temperature after 7 days of curing. In order to prevent cooling shock, samples were left at room temperature to cool down gradually before applying compressive load in the testing machine.

Table 6. Details of PC in the main study.

Name **	BF (%) *	SA (%) *	Evaluation Temperature (°C)
MPT_0	-	-	0
MPT_{100}	-	-	100
MPT_{150}	-	-	150
MPT_{180}	-	-	180
$MPBT_0$	0.2	-	0
$MPBT_{100}$	0.2	-	100
$MPBT_{150}$	0.2	-	150
$MPBT_{180}$	0.2	-	180
$MPAT_0$	-	0.1	0
$MPAT_{100}$	-	0.1	100
$MPAT_{150}$	-	0.1	150
$MPAT_{180}$	-	0.1	180
$MPBAT_0$	0.2	0.1	0
$MPBAT_{100}$	0.2	0.1	100
$MPBAT_{150}$	0.2	0.1	150
$MPBAT_{180}$	0.2	0.1	180

* of the total weight; ** MPT, MPBT, MPAT, MPBAT are PC with no SA and BF, with BF only, with SA only, and with SA and BF, respectively.

2.3. Compressive Strength Testing

The compressive strength tests of the specimens were carried out according to ASTM C109-08. For each mixture, three 50 × 50 × 50 mm cubic specimens of each mix were tested after 3 days. In order to determine the ultimate load-carrying capacity under pure compression, the axial compressive load was applied continuously with a rate of 2.4 kN/sec according to ASTM C31 by a compression machine with 2000 kN capacity. The load was applied until the rupture of the specimen which means that the failure of the specimen at the point, the reading of the load in kN, and stress in MPa were recorded from the dial gauge.

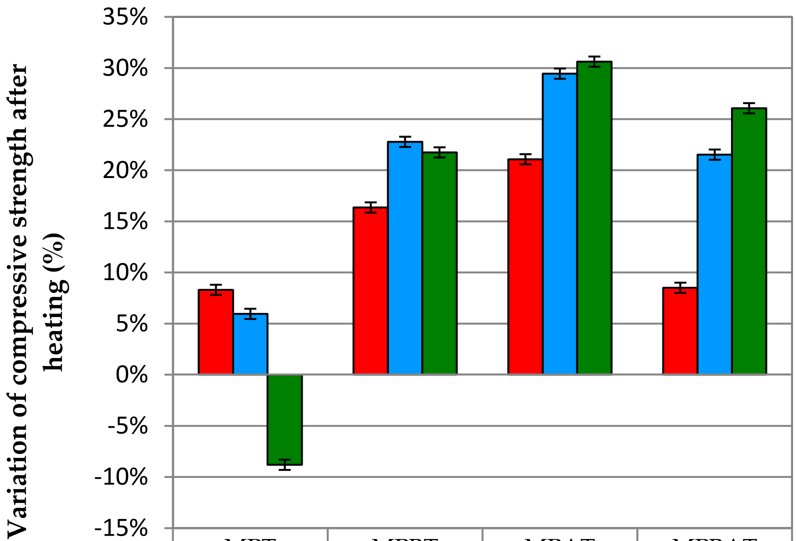
3. Result and Discussions

Compressive tests were performed to investigate the temperature resistance of PC mortar and the effect of the inclusion of chopped BF and SA on the mechanical strength of PC. The results of the ultimate load-carrying capacity of the mortar specimens for different mix designs are shown in Table 7. The result shows that incorporation of BF and/or SA into PC reduced the compressive strength to 33.8, 34.3, and 35.3, which is consistent with the observation published by Dias and Thaumaturgo [34] and Niaki et al. [36], that BF reduces the compressive strength of PC.

Table 7. Compressive strength for the PC with/without SA and BF.

Name	f'_c (MPa)	Variation to MPT_0 (%)	Variation after Heating (%)	
	7-Day			
MPT_0	43.7	-	-	Compared to MPT_0
MPT_{100}	47.33	+8.31	+8.31	
MPT_{150}	46.3	+5.95	+5.95	
MPT_{180}	39.85	−8.81	−8.81	
$MPBT_0$	33.8	−21.10	-	Compared to $MPBT_0$
$MPBT_{100}$	39.33	−10.00	+16.36	
$MPBT_{150}$	41.5	−5.03	+22.78	
$MPBT_{180}$	41.15	−5.83	+21.75	
$MPAT_0$	34.3	−21.51	-	Compared to $MPAT_0$
$MPAT_{100}$	41.53	−4.97	+21.08	
$MPAT_{150}$	44.4	+1.60	+29.45	
$MPAT_{180}$	44.8	+2.52	+30.61	
$MPBAT_0$	35.3	−19.22	-	Compared to $MPBAT_0$
$MPBAT_{100}$	38.3	−12.36	+8.50	
$MPBAT_{150}$	42.9	−1.83	+21.53	
$MPBAT_{180}$	44.5	+1.83	+26.06	

Figure 2 shows the variation in the compressive strength of different mix designs compared to the reference state. The analysis of the results obtained by the compressive strength test of the samples maintained at room temperature revealed that the addition of BF and SA to the reference mix design decreased compressive strength. A lower decrease in compressive strength was observed for the mortar mix containing sodium alginate (SA) compared to those with only alginate. The samples with sodium alginate pose lower compressive strength due to the amount and size of voids in the structure of the hardened composite compared to the control mortar [24]. This weakening of compressive strength may ascribe to forming voids by the addition of the fibers into the matrix, which is in agreement with test results by Reis [30], Kabay [59], and Sun et al. [66]. However, the observation during uniaxial compressive loading indicated that the inclusion of FB leads to the absorption of a large amount of plastic energy before failure that is indicated also in other research studies. He and Lu [70] and Donker and Obonyo [71]. The analysis of the results obtained by the compressive strength test for polymer mortar containing BF and SA revealed that the addition of BF and SA to the reference mix design enhanced compressive strength growth in elevated temperatures. The cure of an epoxy resin is an exothermic process; however, the observation of an experimental investigation on curing temperature of epoxy resin conducted by Lahouar et al. [72] reported absorption of energy between 20 °C and 80 °C representing an endothermic peak due to possible phase change in curing state of the resin. Variations in the compressive strength after heating of the PC containing either BF or SA alone or both together indicate improving the effectiveness of these additives. The obtained results are not in agreement with those of either two works of Reis et al. [35] and [30], indicating a sharp increase (up to 50%) or drastic drop of compressive strength due to temperature elevation.



	MPT	MPBT	MPAT	MPBAT
100°C	8%	16%	21%	8%
150°C	6%	23%	29%	22%
180°C	-9%	22%	31%	26%

Figure 2. Failure of samples under compression test (all tests were conducted in triplicate).

The negative percentage for variation of compressive strength of MPT specimens is in agreement with previous studies that indicated the adverse effect of elevated temperature on the hardened specimens. The increase in the variation of compressive strength in MPBT, MPAT, and MPBAT supports the finding of this research that the addition of BF and SA enhances the compressive strength of PC. The highest positive influence by raised temperature is corresponding to the mixture including SA alone that with an increase in the temperature from room temperature to 100 °C then 150 °C and finally to 180 °C, growth in the compressive strength became 21.08%, 29.45%, and 30.61%, respectively. A lower increase of the compressive strength of the BF-reinforced PC is due to the entrapped voids because of fiber addition. The obtained results about enhanced temperature resistance of SA-based mortar specimens also conform to the finding of DeBrouse [23].

Utilization of both BF and SA together in the PC has been with a lower increase from room temperature to 100 °C until 180 °C, compared to the individual application of these materials. However, it can be seen that heating of PC for 3 h under 180 °C resulted in strength reduction, while together or individual effectiveness of BF and SA in the PC is remarkable on the improvement in the compressive strength after heating for all the three temperatures. From Table 6, the highest compressive strength for samples of PC after 3 days of air curing was higher than the cement concrete samples. A comparison between the obtained compressive strength of polymer and cement concretes with BF and SA indicated that the elevated temperature had a greater influence on polymer concrete than that of cement concrete. The rate of increase was around 20% for polymer concrete, while it was around 5% for cement concrete for temperature rise from room temperature to 180 °C.

Polymer concrete samples after failure under compression test are shown in Figure 3. It should be demonstrated that PC samples exhibited no obvious crack on the surface when the applied load was released after failure under compression. The produced polymer concrete can be considered as a composition of two phases of polymer mortars and aggregates. Through applying the load displacement into the specimens, it was observed that the failure was initiated by the creation of interphase microcracks between polymer mortars and aggregates. By increasing the compressive load, longitudinal cracks were propagated along the jaws' direction, which was similar to those that happen in normal concrete. It was observed that the time between crack initiation and total failure of the specimens was lower than that of cementitious concrete specimens [24,73].

(**a**) PC (**b**) BF-reinforced PC (**c**) SA-based PC (**d**) SA-based BF-reforced PC

Figure 3. Failure of samples under compression test.

The compressive load was applied until the mortar specimens of each mix reached their ultimate load-bearing capacity and failure occurred. High plastic deformation of the polymer concrete was observed corresponding to the applied load.

4. Conclusions

In order to investigate the effectiveness of the addition of BF with the natural source and/or SA as a waste material to reduce the strength degradation of polymer concretes after exposure to raised temperatures of 100 °C, 150 °C, and 180 °C, an experimental program was conducted in two phases including primary study and main study. The addition of BF and/or SA decreases concrete compressive strength under room temperature, but the addition of BF and SA each alone leads to compressive strength increase during exposure to heat. An increase in the temperature to 180 °C showed an almost positive effect on the compressive strength. The highest positive influence by raised temperature is corresponding to the mixture including SA alone that, with an increase in the temperature from room temperature to 100 °C then 150 °C and finally to 180 °C, growth in the compressive strength became 21.08%, 29.45%, and 30.61%, respectively. The addition of BF and SA both together increases the rate of strength growth of polymer concrete under heat from 100 °C to 180 °C. In view of these conclusions, the addition of BF and SA results in a decrease of compressive strength of polymer concretes under room temperature, but it is obvious that these materials are positive to improve the resistance of PC. However, the most important outcome of this research may be a natural source of BF and waste material SA to prevent PC compressive strength degradation under elevated temperature. Increase of compressive strength up to 30%, that when noticed to the cement amount with the energy-wasting process to be produced, is a very valuable finding.

Author Contributions: Conceptualization, N.A.O., S.E.M.-Y. and H.A.A.; methodology, N.A.O., S.E.M.-Y. and H.A.A.; software, N.A.O.; validation, N.A.O., S.E.M.-Y. and H.A.A.; formal analysis, N.A.O., S.E.M.-Y. and H.A.A.; investigation, N.A.O., S.E.M.-Y. and H.A.A.; resources, N.A.O., S.E.M.-Y., H.A.A., H.S., S.S.R.K., and M.P.; data curation, N.A.O.; writing—original draft preparation, N.A.O., S.E.M.-Y., H.A.A. and H.S.; writing—review and editing, N.A.O., S.E.M.-Y., H.A.A., H.S., M.P. and S.S.R.K.; visualization, N.A.O., S.E.M.-Y., H.A.A., H.S., S.S.R.K., and M.P.; supervision, S.E.M.-Y., H.A.A.; project administration, N.A.O., S.E.M.-Y., H.A.A., H.S., S.S.R.K., and M.P. funding acquisition, N.A.O., S.E.M.-Y., H.A.A., H.S., S.S.R.K., and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by the Islamic Azad University, Najafabad Branch, and the Ministry of Education, Youth, and Sports of the Czech Republic and the European Union (European Structural and Investment Funds Operational Program Research, Development, and Education) in the framework of the project "Modular platform for autonomous chassis of specialized electric vehicles for freight and equipment transportation", Reg. No. CZ.02.1.01/0.0/0.0/16_025/0007293.

Conflicts of Interest: The authors declare no conflict of interest.

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