

RESEARCH ARTICLE

Improvement of Very-High Strength Heat-Resistant Concrete's Brittleness Index Incorporating Micro Polyether Ether Ketone Polymer under High Temperature

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ABSTRACT

Very-high strength heat-resistant concrete (VSHRC) can endure elevated temperatures without substantial deterioration of its properties. Nonetheless, the escalating brittleness remains a significant issue with this type of concrete, particularly when subjected to elevated temperatures. This issue results in a brittle failure mode when subjected to thermal stress. To rectify this deficiency, micro Polyether Ether Ketone (PEEK) polymer was included as a fraction of the overall aggregate content in VSHRC. This study involved the incorporation of micro PEEK with VSHRC at several ratios of 0.2%, 0.3%, 0.4%, and 0.5% by the wet mixing method. The compressive and split tensile strength were evaluated as part of the mechanical characteristics. The trials were performed under standard settings, as well as at several higher temperatures and durations of exposure. The findings indicated that the incorporation of 0.3% micro PEEK in VSHRC enhanced split tensile strength and reduced brittleness index (BI) under all heat exposure circumstances due to it is working as filler after this percentage. At 125°C, the split tensile strength rose by 3.88%. Moreover, heating at 175°C yielded the peak split tensile strength of 13.35 MPa and a 12.69% decrease in BI. These upgrades sought to mitigate microcracks and fortify the bond between aggregate and binder by the use of micro PEEK particles. Moreover, microstructural analyses demonstrated that the PEEK polymer contributed to a reduction in both the quantity and dimensions of microvoids and pores.

Keywords: Brittleness Index, Mechanical Properties, Polyether Ether Ketone, Very-high Strength Concrete, Heat-resistant Concrete

INTRODUCTION

Polymers are employed as a novel technology in the manufacture of concrete to improve its qualities [1-3]. In addition to granular or powder forms that can serve as fine aggregate in cementitious composites, such as rubber, polyethylene,

polyurethane, ethylenevinyl acetate copolymer (EVA), vinyl acetate-vinyl versatate (VVA), and polyacrylic ester (PAE), polymers encompass a broad range of materials as resins and emulsions that act as binder, such as polyacrylates [2, 4-7]. Compressive and tensile strengths are reduced when a particular polymer is used as an aggregate or binder [2, 8-10].

One of VSHRC's enduring drawbacks is that the concrete becomes more brittle because to its intrinsically high compressive strength and poor tensile strength. Particularly at high temperatures, the increased brittleness produces brittle fracture characteristics that result in limited micro-crack bridging [11-14].

The integrity and functionality of the concrete are compromised by the majority of traditional polymers' low heat resistance and propensity to break down at high temperatures [15,16]. Because of their remarkable viscoelastic behaviour at elevated temperatures, thermoplastic polymers must be used into VSHRC in order to close this gap and increase the brittleness index without significantly degrading the concrete's qualities. One of the organic high-performance thermoplastic polymers that can sustain high temperatures without deteriorating or losing its key characteristics is PEEK. It is renowned for its remarkable thermal stability and mechanical strength [17-19].

An indication of a material's brittle or ductile behaviour under load, the BI is a characteristic of a material expressed as the ratio of compressive strength to the equivalent split tensile strength. A high BI is distinguished by its strong compressive strength and comparatively low tensile strength, and it shows restricted flexibility. Due of its higher compressive strength compared to tensile strength and brittle mode of failure under load, VSHRC typically exhibits high BI [20-22].

Polymers, such as acrylics and vinyl acetate-versatate copolymers, are widely used as modifiers in concrete due to their ability to improve some of the properties of cementitious materials. Water-soluble polymers such as cellulose ether, starch ether, polyacrylamide, ethylene-vinyl acetate, polyvinyl alcohol, polystyrene, polyester, and styrene-butadiene copolymer have also been used in concrete [7,10,23-26].

Each polymer has unique properties that affect the performance of the cementitious matrix. Chemical interactions between polymers and cement lead to the formation of complex structures and changes in the shape, content, and quantity of hydrated cement [26,27]. Furthermore, the qualities of polymer concrete are influenced by a variety of elements, including concrete mixture content, aggregate size and type, polymer type and features, and curing circumstances.

COMPRESSIVE STRENGTH OF CUSTOMISED POLYMER CONCRETE

Idrees et al. [7] used styrene-butadiene rubber (SBR) as a partial cement replacement ratio of 3%, 5%, 7%, and 10% to examine the compressive strength

of normal strength concrete (NSC). According to the researchers, a maximum improvement in compressive strength of 22.67% was attained at 10% SBR, demonstrating SBR's compatibility with the cement matrix. Conversely, for steam-cured and air-cured samples, the compressive strength of very-high strength concrete (VHSC) dropped by around 12.05% and 30.12%, respectively, at 5% SBR. The compressive strength of VHSC was considerably decreased by using SBR as a binder at a high replacement ratio, which interfered with cement processes and decreased compressive strength [10].

Laqsum et al. [2] assessed the compressive strength of normal-strength concrete (NSC) by including epoxy polymer (EP) and polyacrylate emulsion (PA) as binders at addition ratios of 10%, 20%, and 30% by weight of cement in distinct mixtures. The findings indicated that EP decreased compressive strength by 2.83% at 10% EP, whereas PA enhanced compressive strength by 2.34% at 30% PA. The divergent behaviour was ascribed to variations in polymer-cement interaction, wherein PA increased matrix cohesiveness while EP disrupted cement hydration.

The impact of several vinyl-based polymer additions on the compressive strength of NSC was investigated by Dvorkin et al. [28]. The re-dispersed polymer powders comprised vinyl ester of versatile acid (VEOVA), vinyl acetate ethylene (VAE), and polymer of vinyl acetate (PVA). The polymers were included as emulsion binders in distinct mixtures at concentrations of 1% and 2% by weight of the dry mix. The incorporation of each polymer resulted in a reduction of compressive strength by 7.09%, 5.97%, and 4.85% for VEOVA, VAE, and PVA, respectively.

Pacheco et al. [9] examined the partial substitution of coarse and fine particles with polymer waste in normal-strength concrete (NSC). In the concrete mix, 5% of the fine aggregate was replaced with polyethylene terephthalate (PET) and 5% with a blend of polypropylene (PP) and polystyrene (PS), while 5% of the coarse aggregate was substituted with expanded polystyrene (EPS). The compressive strength improved by 3.46% as a result of optimised particle packing and the capacity of polymer particles to disperse stresses within the concrete matrix.

Assessments of the compressive strength of two classes of normal-strength concrete, C20 and C40, were conducted utilising polyethylene (PE) polymer as a partial substitute for fine aggregate at proportions of 2.5%, 5%, 7.5%, 10%, and 15%. The use of PE polymer led to a reduction in compressive strength of 7.23% for C20 concrete and 3.15% for C40 concrete, respectively. The diminished strength is due to the degradation of the link between the polymer and the cementitious matrix [8].

Kim and Park [16] assessed the compressive strength of polymer-modified cement mortar using four polymer types, including EVA, VVA, and PAE, as cement modifiers at concentrations of 1%, 2%, and 3% of cement, subjected to increased temperatures ranging from 200 to 800°C. At 200°C, the compressive strength decreased by 14.89%, 21.28%, and 4.26% for 2% EVA, VVA, and PAE, respectively. Exposure to elevated temperatures caused a gradual reduction

in the strength of polymer-modified cement mortar, attributed to the thermal degradation of the polymer and the rupture of polymeric chains, resulting in a loss of molecular integrity and degradation of the polymer film within the cementitious matrix. The deterioration compromises interfacial adhesion, induces micro-crack development, and diminishes compressive strength.

Figure 1 depicts the effect of polymer content on the compressive strength of Normal Strength Concrete (NSC) and Very High Strength Concrete (VHSC) based on prior studies. The incorporation of polymers up to 10% as a partial replacement for cement resulted in an improvement in the compressive strength of normal-strength concrete, attributable to the improved binding characteristics of the cementitious matrix. The inclusion of polymers as a binder in VHSC diminishes compressive strength by disrupting cement hydration and delaying the development of cementitious compounds. Furthermore, the use of polymers as aggregates in normal-strength concrete (NSC) diminished the compressive strength, particularly at elevated replacement ratios, hence compromising the link between the binder and aggregate as well as the load transfer capacity of the concrete.

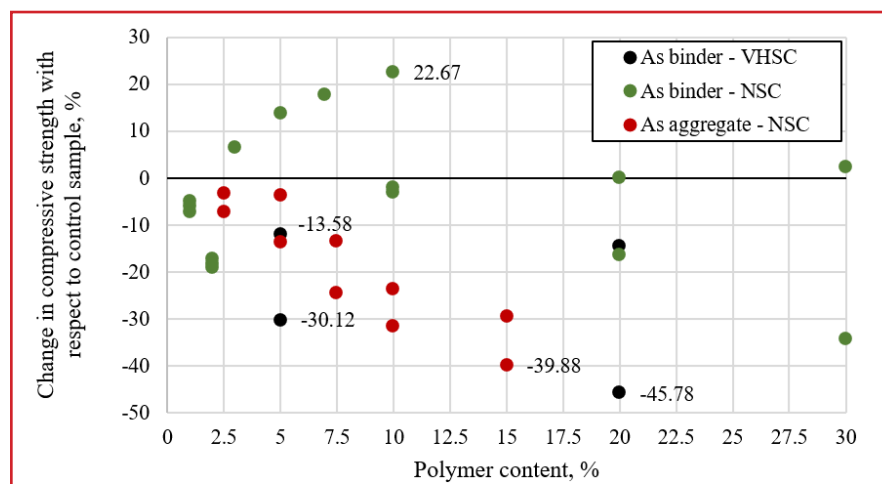


Figure 1. Effect of polymer content on the compressive strength of NSC and VHSC [2,7,8,10,28]

SPLIT TENSILE STRENGTH OF CONCRETE WITH POLYMER

Mayhoub et al. [10] examined the influence of SBR on the split tensile strength of VHSC with 5% and 20% cement substitution. The split tensile strength rose by around 45.83% for steam-cured samples with 20% SBR content, while a notable decrease of approximately 66.66% was recorded for air-cured samples with 5% SBR content. The research indicated that the decrease in split tensile strength was due to the curing procedure, with steam curing being more appropriate for polymer-modified VHSC.

Dvorkin et al. [28] assessed the split tensile strength of normal-strength concrete (NSC) using VEOVA, VAE, and PVA as re-dispersible polymer binders at 1% and 2% by weight of the dry mix in distinct mixtures. The split tensile strength enhanced by 60%, 66.66%, and 57.77% with 2% VEOVA, VAE, and PVA,

respectively. The improved split tensile strength is associated with the role of polymer binders in augmenting the adhesion strength of the cementitious matrix.

Pacheco et al. [9] studied the partial substitution of coarse and fine particles with polymer in normal-strength concrete (NSC). In the concrete mix, 5% of the fine aggregate was replaced with PET and 5% with a mixture of PP and PS, while 5% of the coarse aggregate was substituted with EPS. The split tensile strength diminished by 15.1% due to the substantial quantity of polymer material functioning as aggregate, which augmented the aggregate volume and diminished the concrete's efficacy under tensile loading, therefore lowering the split tensile strength.

Ahmad et al. [8] assessed the split tensile strength of normal-strength concrete (NSC) utilising two classes, C20 and C40, with polyethylene (PE) employed as a partial substitute for fine aggregate at proportions between 2.5% and 15%. The split tensile strength augmented by 2.86% for C20 and diminished by 10.45% for C40. The findings demonstrated that superior grades of concrete exhibit greater vulnerability to variations in aggregate properties, potentially undermining split tensile strength.

The split tensile strength of NSC and VHSC is influenced by the polymer content, as illustrated in Figure 2. The results indicated that the split tensile strength of both NSC and VHSC is enhanced by the use of polymers as a binder. This is attributed to the polymer's stronger bonding within the cementitious matrix and its improved crack-bridging ability. In contrast, the use of polymers as an aggregate results in a substantial decrease in split tensile strength. This phenomenon may be attributed to the degradation of the interfacial bond between the aggregate and the cement matrix by polymer particles.

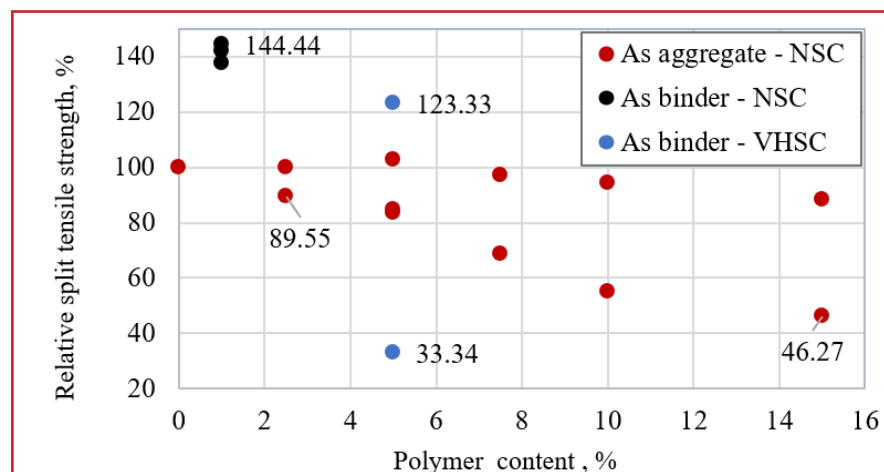


Figure 2. Effect of polymer content on the split tensile strength of NSC and VHSC [8-10,28]

BRITTLINESS INDEX OF VERY-HIGH STRENGTH HEAT-RESISTANT CONCRETE

Figure 3 demonstrates the influence of various polymers on the BI of NSC based on prior research. While replacing 10% of the entire aggregate with PET, PP, and PS in NSC enhanced BI by 21.88% [9]. However, employing PE polymer

as a partial replacement for fine aggregate in two distinct classes of NSC at 2.5%, 5%, 7.5%, 10%, and 15% resulted in differing BI values. For C20, utilising PE decreased the BI. In contrast, it enhanced the BI as PE was introduced into C40. As the polymer fraction climbed, so did the BI. The BI rose by 8.14% and 52.34% when 2.5% and 15% of PE were added, respectively.

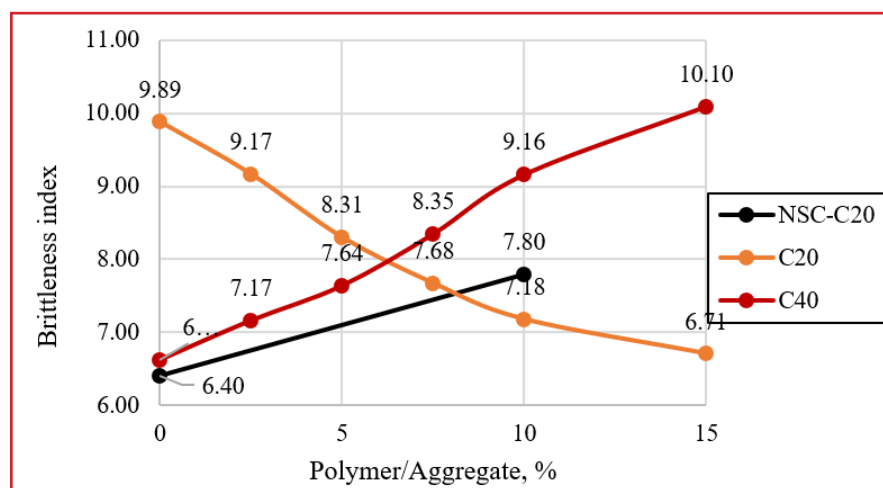


Figure 3. Effect of the amount of different types of polymers on the BI of NSC [8,9]

SIGNIFICANCE OF THIS RESEARCH

The inclusion of RAP aggregate in the VSHRC may reduce the tensile strength of the concrete because to the poor binding strength between fine aggregate and cement paste. Thus, integrating micro Polyether Ether Ketone Polymer can increase both the compressive and tensile strength of VSHRC, which may improve the brittleness index as a consequence, especially when this concrete is subjected to various heating and temperature cycles.

METHODOLOGY

The experimental program was divided into two major stages: the first was the design of the control mix, and the second was the addition of PEEK polymer to VSHRC with different addition ratios to evaluate the effect of PEEK polymer on the selected mechanical properties of VSHRC under both normal and elevated temperatures for varying durations. To determine the effect of micro PEEK on the brittleness index of VSHRC mixes, micro PEEK polymer was added to the concrete as a proportion of total sand content at addition ratios of 0.2%, 0.3%, 0.4%, and 0.5%. Preliminary cube compressive strength testing findings at 7 days instead of 28 days, due to slight increase of the strength after 7 days, showed that addition ratios more than 0.5% of micro PEEK polymer resulted in a significant strength loss.

SELECTION OF MATERIALS

This study used cement and fine aggregate as materials. The specifications and qualities of the cement, aggregate, and admixture components were taken from a previous work that is now in press [29]. Nonetheless, this study introduces a new micro PEEK polymer.

PORTLAND CEMENT

In this investigation, ordinary Portland cement (Type I) was used. Tables 1 and 2 show the physical qualities and chemical makeup of cement, respectively. The cement properties meet ASTM criteria [30,31].

Table 1. Physical properties of Portland cement [32]

Properties	Results	Allowable limit
Average cube compressive strength at the age of 7 days	23.6	19 MPa
Normal consistency, %	33.2	-
Initial setting time, minutes	130	>45
Final setting time, minutes	246	≤375
Specific gravity	3.1	-

Table 2. Chemical composition of cement [31]

Composition	Test results,%	Allowable limit
C ₂ S	7.67	-
C ₃ S	66.33	-
C ₃ A	2.19	8 (max)
C ₄ AF	15.5	-

FINE AGGREGATES

The VSHRC control mix was made up of three distinct types of fine aggregates: quartz sand, magnetite black sand, and RAP aggregate [29]. Figure 4 depicts the three types of sand used in the study, while Figure 5 displays the sieve analysis, and their attributes are summarised in Table 3. Quartz sand has more than 90% silicon dioxide, allowing it to tolerate high temperatures while maintaining concrete strength. As a result, it was chosen as a fine aggregate for VSHRC manufacture. Table 4 shows the chemical compositions of RAP aggregate and magnetite black sand. The source and processing of RAP aggregate were obtained from [29].

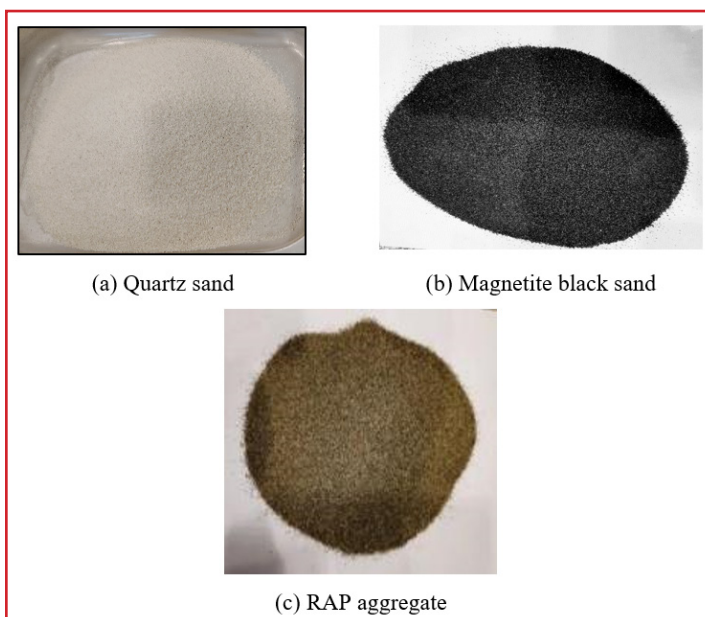


Figure 4. Fine aggregate utilized in the research

Table 3. Physical properties of fine aggregate

Physical properties	Quartz sand	Magnetite black sand	RAP aggregate
Appearance/color	Granular/light tan	Granular/black	Granular/brown
Water absorption, %	0.32	0.65	2.389
Bulk specific gravity	2.6	4.789	2.513
Density, g/cm ³	2.65	5.02	2.68
Average particle size, mm	0.499	0.204	0.267
Fineness modulus	4.29	1.05	2.52
Melting point, °C	1710	-	-

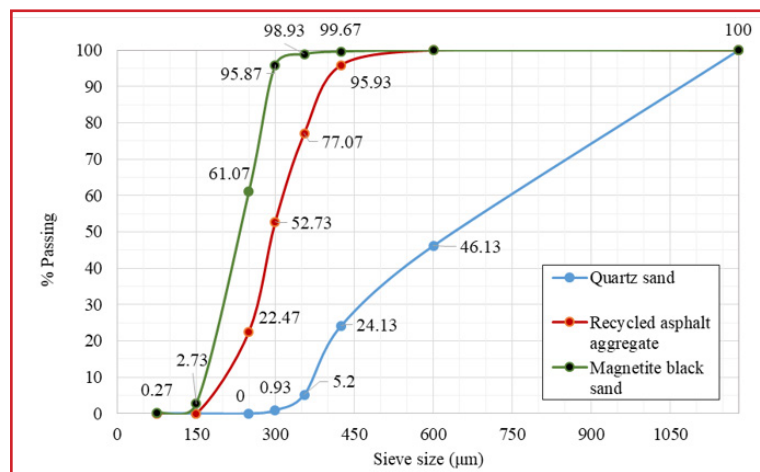


Figure 5. Sieve analysis of fine aggregates

Table 4. Chemical composition of RAP aggregate and magnetite black sand

Composition	Value, %	
	RAP aggregate	Magnetite black sand
SiO ₂	34.74	0.15
CaO	31.98	-
Fe ₂ O ₃	3.12	-
Fe ₃ O ₄	-	99.45
Al ₂ O ₃	4.634	0.27
LOI	22.41	-
Others	3.116	0.13

ADMIXTURE

In order to enhance the strength and workability of VSHRC mixtures, a polycarboxylate-based high range water-reducing admixture (Sika Viscocrete 1681) was used. According to [33], the Marsh cone test was used to evaluate the saturation dose of superplasticizer in concrete mix, which ranged between 1.2-1.6%. The saturation dosage of the admixture was determined, and the saturation percentage was 1.53%.

POLYETHER ETHER KETONE POLYMER (PEEK)

To improve the heat resistance of the VSHRC, micro-sized PEEK polymer was used as an addition depending on the weight of the overall fine aggregate, as illustrated in Figure 6. Table 5 summarises the features of PEEK polymers.



Figure 6. Polyether Ether Ketone polymer

Table 5. Properties of PEEK polymer

Properties	Value
Appearance and color	Ultra-fine Powder, white
Formula	(C ₁₉ H ₁₂ O ₃) _n
Melting point, °C	343
Glass transition, °C	143
Coefficient of thermal expansion, ppm/°C	55 (below glass transition)
	140 (above glass transition)
Thermal conductivity, W/m.°C	0.3
Density, g/cm ³	1.3
Specific gravity	1.31
Water absorption, %	0.3
Average particle size, D50, micron	13

MIXING POTABLE WATER

The VSHRC production water was heated tap water that was devoid of clay, contaminants, and organic compounds. The total dissolved solids were from 200-250 mg/L, and the electrical conductivity was 400-450 μ S/cm. Both are within acceptable limits for concrete manufacture, with total dissolved solids less than 1000 mg/L and electrical conductivity less than 1500 μ S/cm [34,35].

MIX PROPORTIONS

The VSHRC mix proportions were determined from previous studies that assessed the mechanical characteristics of concrete by using RAP aggregate. The leftover quartz sand was then partially replaced with RAP aggregate. The ratio of RAP aggregate to quartz sand was 5%. The control mix was chosen to have the highest RAP concentration possible in concrete. The final mix proportions for the control mix were water-to-cement around 0.21, and the cement to quartz sand-black sand- RAP fine aggregate in the ratio of 1:0.66: 0.21:0.04. Besides, using superplasticizer in dosage of 1.53% with respect to cement mass. The polymer was applied in various ratios of 0.2%, 0.3%, 0.4%, and 0.5% of the total fine aggregate.

MIXING PROCESS

Three distinct mixing processes were used to combine VSHRC mixes: mechanical mixer, mechanical homogeniser, and ultrasonic homogeniser. Figure 7a illustrates how the mechanical homogenizer’s high-shear mixing operation minimises agglomeration by promoting uniform dispersion and shear cutting of PEEK particles. Furthermore, the ultrasonic homogeniser alters the surface morphology of the PEEK particles via the ultrasonic cavitation effect, which increases surface roughness and improves interfacial interaction between the PEEK particles and the cementitious matrix, as seen in Figure 7b. Figure 8 depicts the mixing technique used to produce VSHRC.



Figure 7. Mixing PEEK additive with mixing potable water (a) Mixing PEEK additive with mixing potable water using a mechanical homogenizer (b) Mixing PEEK additive with mixing potable water using an ultrasonic homogenizer

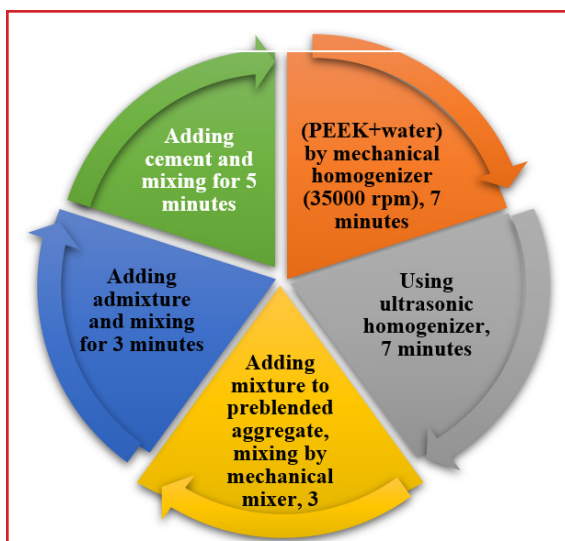


Figure 8. Schematic diagram for the mixing process of VSHRC

Following the mixing procedure, a flow table test and setting time in fresh conditions were performed to evaluate the workability and setting time of VSHRC. Furthermore, the proportion of PEEK polymer used depends on the desired strength and workability of the concrete mix. Initially, PEEK was added in amounts ranging from 0.1 to 5%, however the average compressive strength after 7 days of maturity dramatically decreased beyond 0.5% PEEK. As a result, the ultimate range for adding PEEK to the VSHRC mix was 0.2-0.5%. In the flow table test, micro PEEK polymer was added at the specified ratios, and for all addition percentages, the flow spread exceeded 105%, with a setup time of more than 45 minutes. Both test results met ASTM criteria [36,37].

HEATING PROCESS

The samples were placed in an electric oven at the age of 28 days and heated at a rate of approximately 1.5 °C/min until the targeted temperature was reached. Upon reaching the required temperature, the samples were maintained under the elevated temperature for the specified exposure duration. After finishing the heating period, the oven was switched off, and the specimens were left to cool gradually inside the closed oven for 24 hours. Following this controlled cooling system, the samples were taken out, and the tests were performed. The heating and cooling processes for VSHRC samples were exposed to 125°C, 150°C, and 175°C for the duration of two hours are shown in Figure 9, and a similar heating procedures were carried out for the 4-hour and 6-hour heat exposure durations.

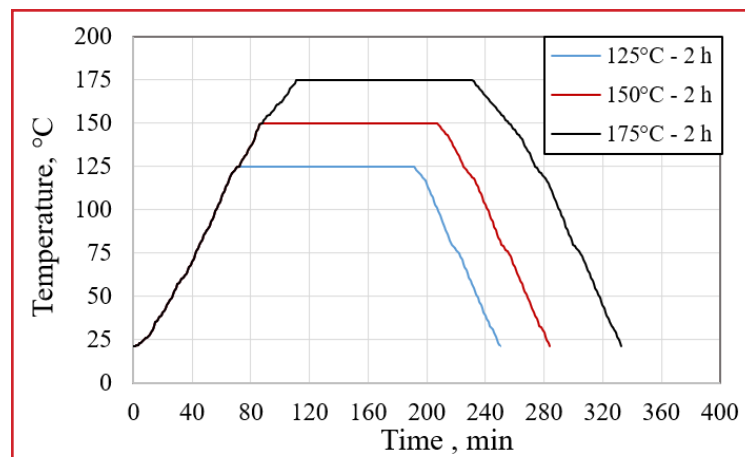


Figure 9. Heating and cooling regime of VSHRC at 125°C, 150°C, and 175°C

MECHANICAL PROPERTIES OF VERY-HIGH STRENGTH HEAT-RESISTANT CONCRETE

To determine the brittleness index of VSHRC in the hardened state, cube compressive strength and split tensile strength tests were performed at 28 days after curing by water bath method for both the control mix and mixes containing 0.2%, 0.3%, 0.4%, and 0.5% micro PEEK polymer as a fine aggregate. These assessments provide a full understanding of the influence of micro PEEK polymer on the performance of VHSC mixtures at both conventional and increased temperatures of 125°C, 150°C, and 175°C for exposure times of two, four, and six hours basing on the previous researches' results.

CUBE COMPRESSIVE STRENGTH TEST

Standard cube samples with side lengths of 50 mm were examined in accordance with ASTM C109 [38]. Six VSHSRC samples were tested without heating, while three concrete samples were examined with heating, and the average cube compressive strength values of the concrete were calculated.

SPLIT TENSILE STRENGTH TEST

Standard cylinder samples with a diameter of 50 mm and a height of 100 mm were used to conduct the split tensile strength test of VSHSRC according to ASTM C496 [39]. For each condition, three concrete samples were tested, and the average split tensile strength values of VSHSRC were calculated.

MICROSTRUCTURAL ANALYSES OF VSHSRC UNDER DIFFERENT ELEVATED TEMPERATURES

In this work, eight exemplary VSHSRC samples were chosen to undergo microstructural assessment using microstructural characterisation methods such as Field Emission Scanning Electron Microscopy (FESEM) and Energy-Dispersive Spectroscopy. The combined analytical tests evaluate the morphological aspects and elemental distribution of the microstructure of VSHSRC.

RESULTS AND DISCUSSION

MECHANICAL PROPERTIES OF VSHSRC

This section assesses the impact of micro PEEK polymer on the mechanical characteristics of VSHSRC, specifically focusing on compressive and split tensile strengths, as show in Table 6. Additionally, their interrelations regarding BI under ordinary conditions and various heat exposure scenarios are examined. The findings are analysed and juxtaposed with the mixture devoid of PEEK to assess the influence of micro PEEK polymer on enhancing the mechanical characteristics of concrete.

Table 6. Mechanical properties of VSHSRC with different quantity of PEEK polymer

PEEK, %	Compressive strength MPa									Split tensile strength Mpa										
	20 C	125 C			150 C			175 C			20 C	125 C			150 C			175 C		
		2 h	4 h	6 h	2 h	4 h	6 h	2 h	4 h	6 h		2 h	4 h	6 h	2 h	4 h	6 h			
0.0	110.7 ₁	89.40	90.57	91.48	98.56	106.3	118.1	106.7	111.0	131.3	12.22 ₂	10.98	10.21	10.71	9.936	10.95	11.67	10.06	10.53	13.20
0.2	94.76	82.95	87.68	91.60	87.83	92.30	97.38	95.88	95.94	99.97	10.51 ₁	9.722	9.759	11.03	9.245	10.49	10.53	9.552	11.42	12.08
0.3	111.0 ₂	88.11	93.70	92.29	90.93	102.4	105.2	105.3	106.7	115.9	11.37 ₈	10.74	10.75	11.13	11.42	11.43	11.67	10.32	11.53	13.35
0.4	92.37	84.64	85.42	86.40	85.21	87.15	101.2	92.62	104.1	108.7	10.42 ₈	10.38	10.43	10.50	9.011	10.95	11.58	10.20	11.26	11.50
0.5	90.14	83.32	84.14	85.26	84.51	86.22	88.64	89.17	103.34	107.97	10.276	9.986	10.140	10.445	8.769	9.882	10.317	10.193	11.123	11.170

Under typical conditions, the incorporation of PEEK generally reduces the BI, with the exception of a 7.71 BI increase seen at the inclusion of 0.3% PEEK, attributed to enhanced compressive strength and reduced tensile strength. Exposure of VSHRC to 125°C, along with the incorporation of PEEK polymer, results in a reduction of the BI across all addition ratios due to an enhancement in split tensile strength, hence imparting flexibility to VSHRC, as seen in Figure 10. Moreover, the use of PEEK polymer reduces the BI by enhancing split tensile strength when subjected to thermal exposure at 150°C and 175°C, as seen in Figures 11 and 12. The incorporation of 0.3% PEEK resulted in a reduction of the BI by 10.96% and 12.69% at heating temperatures of 150°C and 175°C, respectively, after 6 hours of thermal exposure, in comparison to concrete devoid of PEEK.

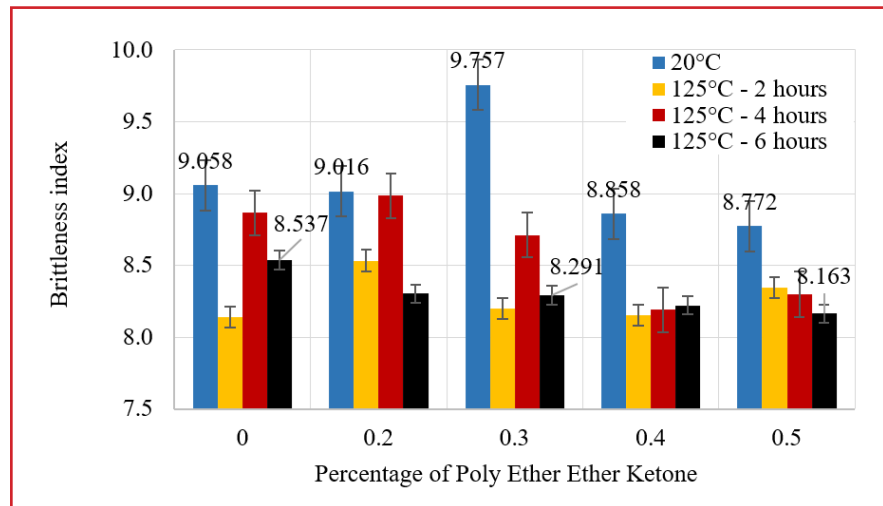


Figure 10. Influence of PEEK addition ratio on the BI of VSHRC at 125°C with different heating durations

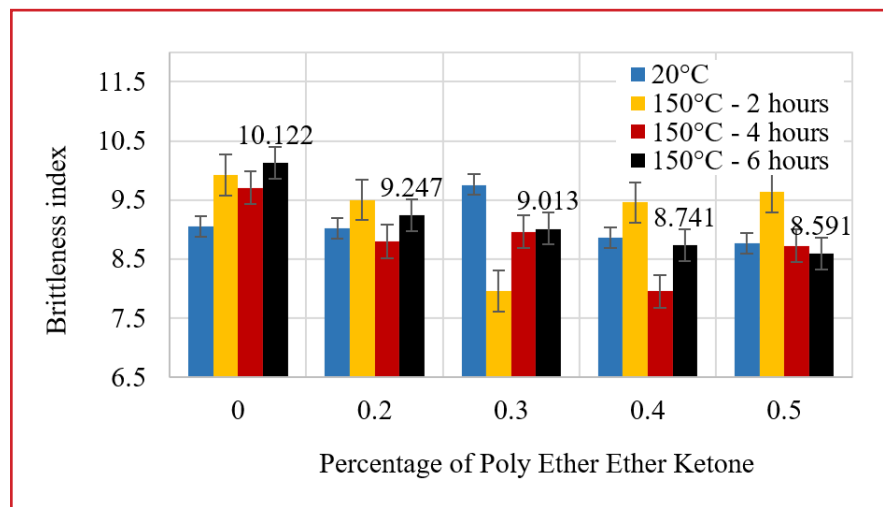


Figure 11. Influence of PEEK addition ratio on the BI of VSHRC at 150°C with different heating durations

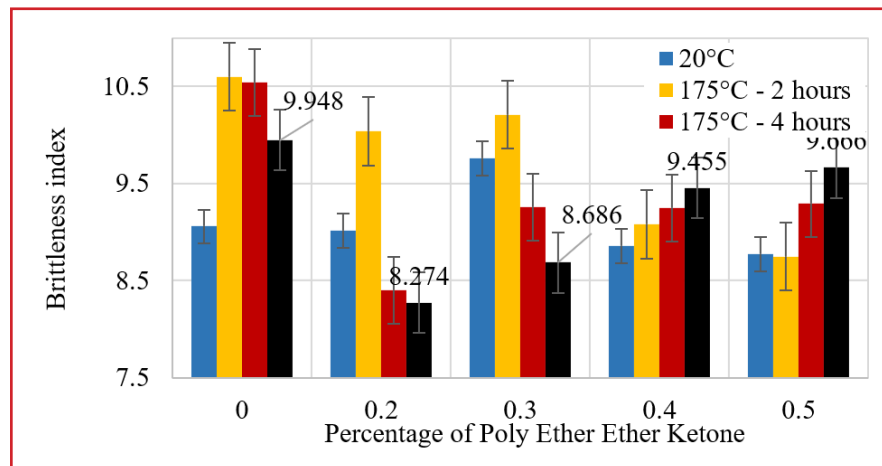


Figure 12. Influence of PEEK addition ratio on the BI of VSHRC at 175°C with different heating durations

UNDER VARYING ELEVATED TEMPERATURES, THE WATER ABSORPTION OF VSHRC THAT INCORPORATES PEEK

The inclusion of 0.3% PEEK to VSHRC results in a substantial reduction in water absorption, as demonstrated in Table 7, with a maximum reduction of 50.74% at the standard condition. PEEK’s ability to reduce water absorption is attributed to its ability to reduce water demand and the ability of micro PEEK particles to refine the microstructure by filling micro cavities, which in turn minimises capillary pathways and reduces water absorption.

Under all heat exposure conditions, the mix containing 0.3% PEEK exhibits the most substantial reduction in water absorption while the VSHRC is subjected to elevated temperature. In comparison to the mix without PEEK, the water absorption decreases by 47.54%, 30.72%, and 22.76% at the elevated temperatures of 125°C, 150°C, and 175°C for 6 hours, respectively. The reason for the reduction in water absorption of VSHRC is the role of micro PEEK particles in filling micro cavities, which minimises water demand, thereby reducing permeability and water absorption.

Table 7. Water absorption of VSHRC with different quantity of PEEK polymer

PEEK, %	Water absorption %									
	20 C	125 C			150 C			175 C		
		2 h	4 h	6 h	2 h	4 h	6 h	2 h	4 h	6 h
0.0	2.558	2.567	2.607	2.680	2.580	2.660	2.822	2.659	2.810	2.843
0.2	1.338	1.434	1.532	1.742	1.664	2.027	2.131	1.942	2.084	2.220
0.3	1.260	1.303	1.347	1.406	1.319	1.496	1.955	1.786	2.060	2.196
0.4	1.353	1.685	1.865	1.923	1.824	2.159	2.206	1.848	2.148	2.488
0.5	1.481	1.693	1.882	1.968	2.010	2.244	2.494	2.094	2.307	2.502

MICROSTRUCTURAL ANALYSES OF VSHRC UNDER DIFFERENT ELEVATED TEMPERATURES

The FESEM of the VSHRC control mix exhibits slight localised variability and few voids, as seen in Figure 13 a. At a heating temperature of 125°C, an increase in micro-cracks and micro-voids inside the concrete matrix is noticed, resulting from the evaporation of free and mixed water during the heating

process, as illustrated in Figure 13b. A significant decrease in Silicon from 24.05% to 18.08% and Calcium from 32.27% to 30.36% is noted in the EDS test presented in Table 8. At an increased temperature of 150°C, VSHSRC exhibits partial augmentation by the production of C-S-H, accompanied by a rise in silicon and calcium, as seen in Figure 13c. The microstructural enhancement of VSHSRC is accentuated with prolonged heating of the concrete samples to 175°C, attributable to the rise in Silicon and Calcium to 24.91% and 44.62%, respectively, resulting from secondary hydration promoted by the residual combined water and the softening of the asphalt binder enveloping the RAP aggregate particles, as illustrated in Figure 13d.

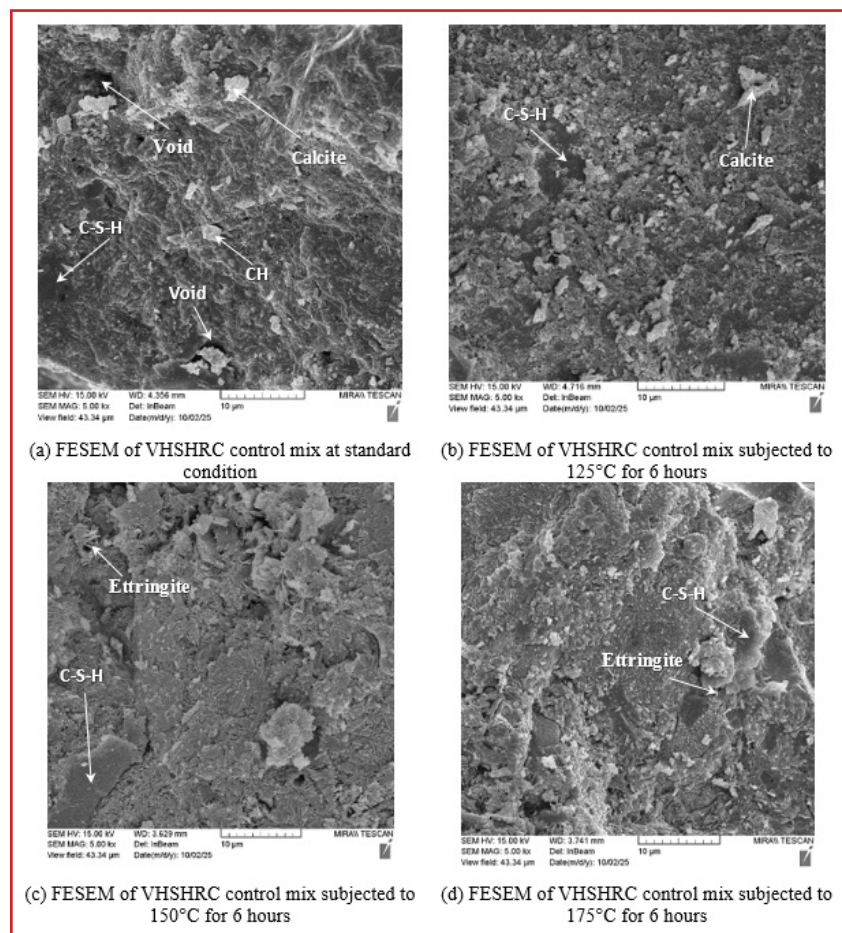


Figure 13. FESEM of VSHSRC control mix containing aggregate at different elevated temperatures

Table 8. Results of the EDS test showing the elemental weight-percentage of VSHSRC under different heat exposure conditions

Element	Weight percentage, %							
	VSHSRC control mix				VSHSRC containing 0.3% PEEK			
	Heating temperature, °C				Heating temperature, °C			
	20	125	150	175	20	125	150	175
Si	24.05	18.08	20.73	24.91	19.36	17.59	18.57	20.63
Ca	32.27	30.36	42.97	44.62	23.44	21.30	22.30	23.93
O	30.04	29.44	24.65	20.24	44.82	45.42	42.17	41.57
Al	4.25	3.55	3.21	3.61	3.56	4.28	4.60	3.91

Furthermore, the FESEM of the VSHSRC indicates that the surface of PEEK particles becomes rough as a result of the mixing process, which uses both mechanical and ultrasonic mixers to combine PEEK with VSHRC ingredients throughout manufacture. Figure 14 shows how roughening the surface of PEEK particles increases the connection between them and the cementitious matrix. The EDS test findings demonstrate a decrease in the proportion of silicon and calcium weight at temperatures of 125°C and 150°C, respectively. At a heating temperature of 175 °C, however, the microstructure refined due to PEEK's behaviour in bridging thermal microcracks. The rise in Silicon from 17.59% to 20.63% and Calcium from 21.3% to 23.93% corresponds to an increase in compressive strength at 175°C.

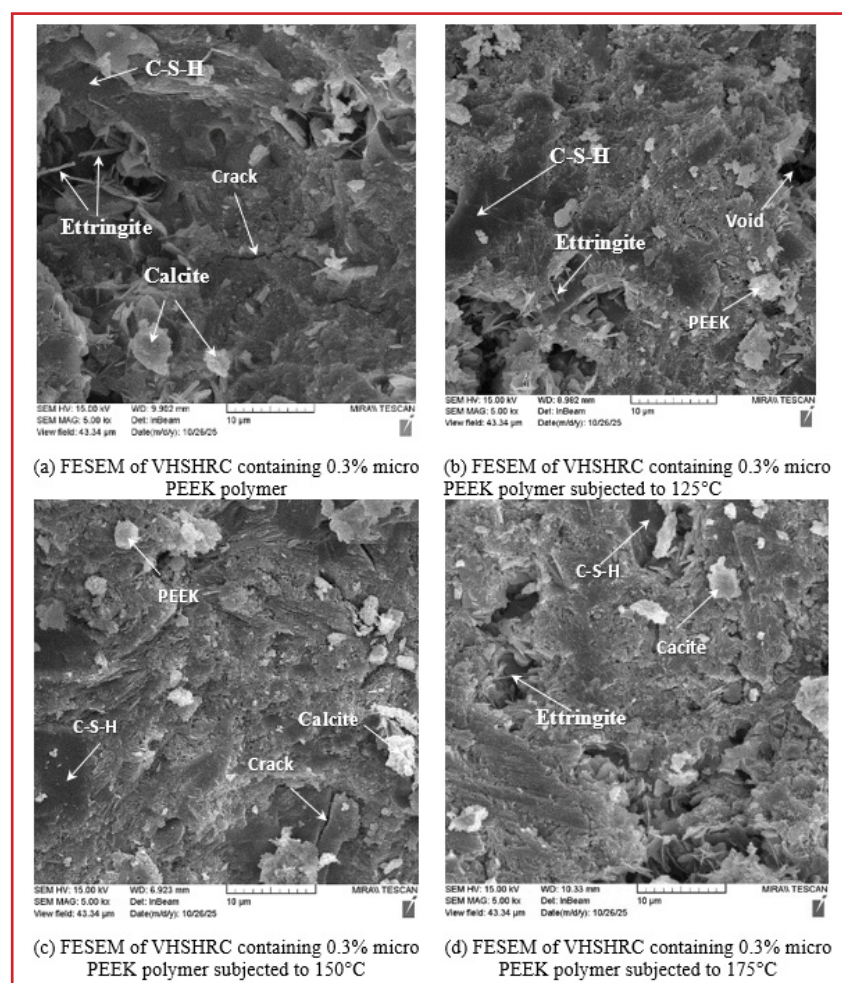


Figure 14. FESEM of the VSHRC containing 0.3% micro PEEK polymer at different elevated temperatures

CONCLUSION

The brittleness index is altered when road construction waste material, such RAP aggregate, is used to clean up the environment. This waste material weakens the binding between the cement paste and fine aggregate. As the concrete is heated for certain durations, this VSHSRC weakness becomes increasingly apparent. Hence, the following findings are produced by using PEEK polymer as a fine aggregate with VSHRC:

- In all thermal exposure conditions, the use of PEEK in VSHRC significantly improved the split tensile strength. At a heating temperature of 125°C, the split tensile strength increased by 3.88%. Additionally, at 175°C, the split tensile strength increased to a peak value of 13.35 MPa. These enhancements pertain to the efficacy of PEEK particles in bridging thermally produced micro-cracks and augmenting the adhesion between the binder and aggregate.
- The brittleness index values were decreased in all heating conditions as a result of the use of PEEK. The brittleness index decreased by 12.69% when exposed to heat at 175°C. This was primarily due to an increase in tensile strength, which was greater than an upsurge in compressive strength, as a result of the extra hydration of cementitious material from the steam produced at this heating temperature. This hydration allowed for flexibility under load due to an improvement in split tensile strengths.

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CONFLICTS OF INTEREST

The author has no conflicts of interest to declare.

AUTHOR CONTRIBUTIONS

Zhwan Anwar Noori: conceptualization, methodology, writing-original draft preparation. **Ferhad Rahim Karim:** supervision, writing-review & editing. **Hardy Kamal Karim:** supervision.

DATA AVAILABILITY STATEMENT

All the data is available in this article.

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