CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 5, ISSUE 2, 2025, 296 - 312
DOI: https://doi.org/10.15282/construction.v5i2.12758

RESEARCH ARTICLE

Influence of Recycled Asphalt Pavement Aggregate on the Mechanical Properties of Very-High Strength Heat-Resistant Concrete

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ABSTRACT - Very-High Strength Heat-Resistant Concrete (VHSHRC) endures elevated temperatures for extended durations without performance deterioration. Furthermore, it exhibits enhanced resistance to spalling, loss of strength, and diminished durability. The use of VHSHRC is particularly evident in scenarios involving prolonged exposure to elevated temperatures, such as power plants, industrial facilities, and areas susceptible to fires. The increasing need for resource-efficient building materials in concrete structures demands the assessment and performance implications of integrating Recycled Asphalt Pavement (RAP) aggregate into VHSHRC mixes. The use of RAP aggregate is an exemplary option for constructions aiming to reduce environmental impact, optimise resource efficiency, and conform to the increasing focus on sustainability. This research employed RAP aggregate as a partial substitute for quartz sand at rates of 4%, 5%, 6%, and 7%. Mechanical tests were performed on VHSHRC exposed to various high temperatures and exposure periods. The research findings revealed that the optimal ratio of RAP aggregate was 5%, resulting in increases in compressive strength and split tensile strength of 3.34% and 3.68%, respectively.

ARTICLE HISTORY

Received	:	10 July 2025
Revised	:	5 August 2025
Accepted	:	25 August 2025
Published	:	29 December 2025

KEYWORDS

Brittleness index
Magnetite black sand
Recycled asphalt pavement aggregate
Split tensile strength
Very-high strength heat-resistant concrete

1. INTRODUCTION

Concrete is essential in the building sector because to its exceptional mechanical qualities, cost-effectiveness, durability, and efficiency in structural and industrial operations. The features of the materials used in concrete manufacture considerably influence its overall characteristics, including strength, durability, and serviceability of concrete buildings.

1.1 Very-High Strength Concrete

Very-High Strength Concrete (VHS) generally denotes concrete exhibiting a compressive strength exceeding 70 MPa (10,000 psi) at 28 days for cylindrical specimens measuring 100 × 200 mm, with its tensile strength ranging from 8% to 12% of the corresponding compressive strength, rendering VHS brittle in the absence of steel reinforcement. Moreover, VHS has a modulus of elasticity of up to 60 GPa. VHS demonstrates reduced permeability and improved durability due to its higher microstructure density, achieved by a water-to-binder ratio of less than 0.35, together with the use of extra cementitious materials and superplasticizers [1]. Owing to the aforementioned qualities, VHS has been utilised in high-rise structures and various concrete applications [2, 4, 6-8].

1.2 Heat-Resistant Concrete

Heat-resistant concrete (HRC) is a type of concrete particularly engineered to endure elevated temperatures without substantial deterioration in its mechanical properties or durability. This concrete variant is utilised in specialised constructions, including furnaces, chimneys, fireplaces, kilns, incinerators, and other industrial edifices subjected to high temperatures. Very-High Strength Heat-Resistant Concrete (VHSHRC) is a distinctive kind of concrete that integrates the advantages of both exceptional strength and thermal resistance. This specialised concrete is utilised for constructions that endure significant mechanical and thermal loads. Defence structures, fire-prone high-rise buildings, tunnels, power plants, and industrial furnaces are subjected to increased temperatures. The essential criterion for this type of concrete is to maintain its residual mechanical and durability capabilities without degradation when exposed to extreme temperatures.

1.3 Recycled Asphalt Pavement Aggregate in Concrete

The recycled asphalt pavement aggregate is obtained by a milling process that involves the extraction of existing, aged, or defective asphalt layers, either in full-depth or partial-depth removal. Following the milling operation and collecting of Reclaimed Asphalt Pavement (RAP), it may be utilised in its current state or subsequent to the extraction of the asphalt binder that envelops the RAP. The incorporation of RAP aggregate in concrete entails the partial or complete substitution of coarse or fine particles. The use of RAP aggregates in concrete buildings has garnered significant attention owing to pressing environmental issues and the necessity for sustainable construction techniques. The use of RAP aggregate in concrete constructions not only offers environmental advantages but also adheres to the ideals of a circular economy. The integration of RAP aggregate in concrete buildings presents an effective approach to lowering construction

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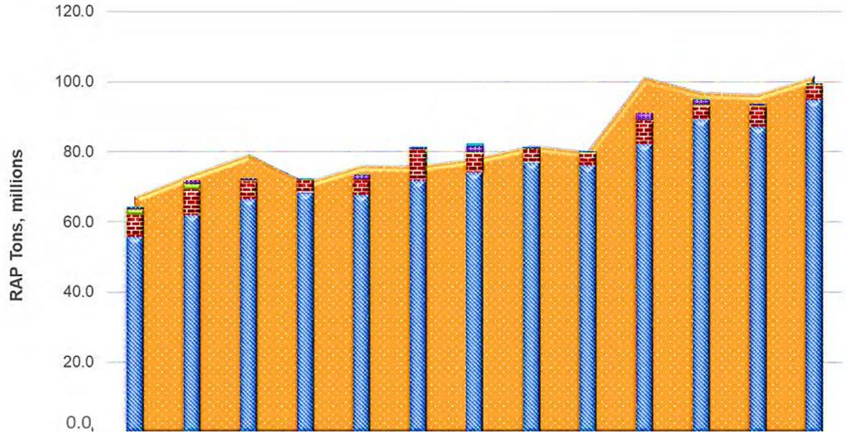
and demolition waste, conserving natural resources, and diminishing the carbon footprint of global infrastructure [17, 18]. Numerous studies have examined the mechanical and durability performance of concrete constructions utilising recycled asphalt pavement (RAP) aggregate. The incorporation of RAP aggregate typically results in diminished mechanical performance of concrete, attributable to the asphalt binder coating the aggregate particles, which compromises the interfacial transition zone (ITZ) of the concrete matrix, particularly at elevated replacement ratios exceeding 10% [17-22].

On the other hand, RAP aggregate can enhance the workability of concrete mix and the ductility of hardened concrete by virtue of the residual asphalt binder that coatings the aggregate particles, which functions as a lubricant within the concrete matrix and provides the hardened concrete with elasticity under stress [23]. However, the mechanical performance of concrete is significantly impacted by the selection and control of several key factors, including material characterisation, aggregate gradation and blending, and the method of preparation and treatment of the RAP aggregate, which are all essential for the successful implementation of RAP aggregates in concrete structures [20, 24]. The utilisation of RAP has garnered significant interest on a global scale, as examples: The total estimated quantity of RAP stockpiled in the United States at the end of 2021 was approximately 101.3 million tonnes. Figure 1 illustrates the utilisation of RAP in numerous sectors, such as landfilling, building construction projects, and the repurposing of RAP in cold-mix, hot-mix, and warm-mix bitumen mixtures. It was discovered that the annual demand for RAP employment increased beginning in 2009. The annual demand for RAP utilisation gradually increased from 2009 to 2021, with a cumulative increase from 67.2 to 101.3 million tonnes [25].



RAP	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Accepted	67.2	73.5	79.1	71.3	76.1	75.8	78.0	81.8	79.9	101.1	97.0	96.3	101.3
Landfilled	0.1	0.0	0.3	0.2	0.1	0.2	1.0	0.1	0.0	0.0	0.1	0.2	0.1
Used in Other	0.7	0.8	0.7	0.2	1.5	0.6	1.6	0.4	0.2	2.0	1.4	0.3	0.2
Used in Cold Mix	1.5	1.6	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.1
Used in Aggregate	6.2	7.3	4.9	3.6	4.0	8.5	5.5	3.7	3.4	6.4	3.8	5.8	4.2
Used in HMA/WMA	56.0	62.1	66.7	68.3	67.8	71.9	74.2	76.9	76.2	82.2	89.2	87.0	94.6

Figure 1. Utilization of RAP in United States[25]

2. SIGNIFICANCE OF THE RESEARCH

The incorporation of RAP aggregate into VHSHRC offers a sustainable solution for the preservation of natural resources. Conversely, the efficacy of RAP aggregate in enhancing the residual mechanical properties of VHSHRC at elevated temperatures continues to be a challenge. The objective of this investigation is to assess the mechanical performance of VHSHRC at a variety of elevated temperatures and for varying durations of heat exposure. Furthermore, to evaluate the impact of RAP aggregates on VHSHRC mixtures.

3. LITERATURE REVIEW

3.1 Concrete Exposed to Elevated Temperature

The physical properties of concrete are significantly altered when it is subjected to high temperatures, including the loss of mechanical strength, reduced durability, fracture, spalling, and deterioration [10, 26]. A study was conducted to evaluate the mechanical performance of VHSHRC under elevated temperatures, and numerous researchers investigated the impact of elevated temperatures on concrete [10, 14, 27]. The thermal performance of concrete under elevated temperatures is significantly influenced by the variety of material used in its production. Quartz sand and magnetite black sand, which are silicate-rich sands with a high melting point and thermal stability, exhibit superior performance in concrete at elevated temperatures. Sand's minimal thermal expansion mitigates internal stresses during heating, thereby improving its thermal resistance. In contrast, the concrete experiences thermal cracking and a decrease in strength when it is subjected to heat when other types of sediments with lower melting points are used [2].

3.2 Effect of Magnetite Black Sand on the Mechanical Properties of Very-High Strength Heat-Resistant Concrete

Magnetite black sand is a dense, weighty mineral-rich material that is distinguished from ordinary sand by its superior magnetic properties. Magnetite black sand is enriched with numerous radioactive minerals, such as zircon, thorium, hafnium, and uranium. Additionally, it contains heavy materials that are non-radioactive, including iron, ilmenite, rutile, granite, heavy silica, monazite, and titanium [28]. Black sand is extensively employed in the construction of buildings and a variety of industrial applications, such as the iron and steel industry and nuclear industries, as a result of its composition [29]. Furthermore, magnetite sand is essential for enhancing the thermal resistance and resilience of concrete mixtures [30, 31]. A study was conducted to compare the impact of magnetite black sand with standard aggregate. The investigators determined that the compressive strength of the reference concrete with normal aggregate decreased steadily as the temperature increased. Nevertheless, concrete mixtures that contain magnetite aggregate exhibited an increase in strength up to 300°C. Concrete mixtures that contain magnetite aggregate maintained 40% of their initial strength, in contrast to 30% for the reference concrete, even at 800°C [32].

A study was conducted to assess the impact of varying proportions of magnetite black sand (BS) and fly ash (FA) on concrete mixes. The concrete mixes were composed of BS with a replacement ratio of 0%, 15%, 30%, 45%, 60%, 75%, and 100%, and two percentages of FA, 10% and 15%. For a duration of three hours, the specimens were exposed to three distinct elevated temperatures: 250 °C, 500 °C, and 750 °C. The compressive strength of a concrete mixture that contained 15% BS and 10% FA was observed to be 132%, 134%, 135%, and 181% higher than the control mix at 180 days under laboratory conditions of 250°C, 500°C, and 750°C, respectively. Conversely, the compressive strength of mixtures containing BS with a content exceeding 60% demonstrated a significant decrease in comparison to the control mix [1]. In an effort to improve the heat resistance of the VHSHRC mixture in relation to compressive strength, the utilisation of BS was assessed. Five distinct VHSHRC formulations were prepared with a BS ratio of 0%, 15%, 30%, 45%, 60%, 75%, and 100%. The Silica Fume (SF) and FA proportions were consistent at 0%, 10%, and 15%. At 28 and 90 days of age, the compressive strength test was conducted before and after exposure to elevated temperatures of 250 °C, 500 °C, and 750 °C for 3 hours. The findings demonstrated that the compressive strength of VHSHRC was substantially improved at 250 °C and 500 °C as a result of the addition of BS. The compressive strength was significantly improved when BS proportions of 15-45% were combined with 10% FA. Nevertheless, compressive strength decreases as the BS proportion exceeds 45%. The results obtained suggested that the interfacial transition zone of the cement matrix was improved by BS in high-temperature conditions. The researchers determined that BS is a suitable material for structures, such as nuclear power plants, that necessitate superior fire resistance [28].

To evaluate the impact of incorporating three varieties of fine aggregates—namely, BS, magnetite, and ilmenite—alongside steel slag as the coarse aggregate in high-performance heavy-weight concrete, evaluations were conducted. The concrete specimens were subjected to a range of elevated temperatures, including 250°C, 550°C, and 750°C, for a duration of 2 hours, in order to conduct a variety of mechanical tests, including compressive strength and modulus of elasticity. The investigators determined that subjecting concrete with 100% substitution of BS, ilmenite, and magnetite to 250°C at the age of 28 days resulted in a 5.4%, 4.2%, and 6.0% increase in compressive strength, respectively, when compared to control concrete at 22°C. At 750°C, black sand, ilmenite, and magnetite experienced compressive strength losses of 57.8%, 68.1%, and 51.9%, respectively. By employing BS, ilmenite, and magnetite sand, the water absorption decreased from 5.1% to 4.5%, 2.9%, and 3.6%, respectively[3].

3.3 Effect of Natural Sand on the Mechanical Properties of Very-High Strength Heat-Resistant Concrete

The compressive strength and split tensile strength of the concrete samples were subsequently tested after being exposed to elevated temperatures of 90°C, 200°C, 300°C, and 400°C. This was implemented to investigate the mechanical properties of concrete. VHSHRC specimens were heated at 90°C for 28 days, and the compressive strength was minimally affected. After 7 days of heating, the split tensile strength increased by 29% in comparison to the control samples, but it decreased to 96% of the control after 28 days. The samples' compressive strength and split tensile strength increased by 16% and 3%, respectively, after being heated for 7 days at 200 °C. the compressive strength was 109% and the divided tensile strength was 98% of the control samples after 28 days of heating. There was a 13% and 36% decrease in compressive strength and split tensile strength, respectively, as a result of heating at 400°C for 7 days. The compressive strength and split tensile strength of the control samples were reduced to 69% and 57%, respectively, after 28 days [33]. A study was conducted to assess the impact of incorporating quartz grit into the concrete production process and subjected the concrete to a temperature of up to 400°C. The investigators determined that the compressive strength of concrete that was subjected to elevated temperatures was substantially improved by quartz grains. The cube strength was enhanced from 76.2 MPa to 90.2 MPa by incorporating 20% quartz sand into the total fine aggregate [34].

4. EXPERIMENTAL PROGRAMME

The experimental program was divided into two primary phases: the initial phase was concentrated on the design of the control mix, while the second phase was dedicated to the integration of RAP aggregate into the VHSHRC mixtures. In order to assess the impact of RAP aggregate addition on the mechanical performance of the concrete in both ambient and elevated temperatures, mechanical experiments were conducted under laboratory conditions and at varying elevated temperatures for varying exposure durations.

4.1 Selection of Materials

In order to preserve its rheological properties, the materials were chosen to withstand elevated temperatures. Conversely, the concrete must preserve its thermal resistance and mechanical efficacy.

4.1.1 Portland cement

The investigation employed ordinary Portland cement (Type I). Tables 1 and 2 illustrate the chemical composition and physical characteristics of the cement, respectively. The cement should adhere to the ASTM specifications [35, 36].

Table 1. Physical properties of Portland cement and their limits of ASTM [35]

Test name	Results	Allowable limit
Average cube compressive strength, (N/mm2) 7-days	23.645	19 MPa, lower limit
Normal consistency (%)	33.2	-
Initial setting time(minute)	130	Not less than 45
Final setting time(minute)	246	Not more than 375
Specific gravity	3.1	-

Table 2. Chemical composition of cement and limits [36]

Composition	Test results (%)	Allowable limit
Calcium oxide (CaO)	63.90	-
Silicon dioxide (SiO2)	20.10	-
Aluminum oxide (Al2O3)	4.08	6 (max)
Ferric oxide (Fe2O3)	5.10	6 (max)
Magnesium oxide (MgO)	1.48	6 (max)
Sulfur trioxide (SO3)	2.20	3 (max)
Loss on ignition	3.41	
C2S	7.67	
C3S	66.33	
C3A	2.19	8 (max)
C4AF	15.50	

4.1.2 Fine aggregates

Throughout the investigation, three types of fine aggregates were used to produce VHSHRC: quartz sand and magnetite black sand for the control mix, and RAP aggregates as a partial substitute for quartz sand. The high silica content, hardness, and angular form of quartz sand contribute to better particle packing, increased strength, and longevity of the concrete mix. Furthermore, quartz sand has good thermal stability, making it ideal for high-temperature applications [2]. Figure 2.a depicts the quartz sand used in this investigation, which had a silicon dioxide level more than 90%. Previous research on magnetite BS for the manufacture of VHSHRC mixes has shown that it is a great material that can tolerate high temperatures without significantly degrading the mechanical characteristics of concrete. In this study, BS was utilised to partially replace quartz sand, as indicated in Figure 2.b. The chemical makeup of BS is shown in Table 3. The top layer of roads that have experienced early distress and degradation of road surfaces such as cracking, deformation, and disintegration is removed to a specified depth using specialised equipment known as the milling process, as shown in Figure 3(a) [37]. The milling procedure is carried out by the Municipality of Sulaimania. Figure 3(b) depicts how RAP is collected and kept in stockpiles following grinding. Random samples were obtained from the stocks.


(a) (b)

Figure 2. Fine aggregate utilized in the same single size (a. feature of quartz sand, b. feature of magnetite black sand)

Table 3. Chemical composition of magnetite black sand

Composition	Test results (%)
Ferrosoferric oxide (Fe_3O_4)	99.45
SiO_2	0.15
Al_2O_3	0.27
CaO	0.04
P	0.007
S	0.008
Mn	0.02
Pb	<0.003
K_2O	0.0084
Na_2O	<0.0067
TiO_2	0.067
Ca	0.029
Zn	<0.001


(a) (b)

Figure 3. Source of recycled asphalt pavement aggregate (a) milling process of pavement, and (b) RAP stockpile)

Separation methods removing asphalt binder from the RAP

a. Centrifugal extraction method

Following the collection of random RAP samples from the stockpiles, the asphalt binder was extracted from the RAP using a centrifuge binder extractor equipment. To separate the asphalt binder from the mixture, benzene was employed as the solvent. The binder extraction from RAP was carried out using the standard approach of method A of both ASTM D2172 / D2172M and AASHTO T 164 standards [38]. Figure 4 depicts the extraction of asphalt binder from RAP.

(a) (b)

Figure 4. The process of removing asphalt binder from RAP (a) asphalt binder centrifugal device, (b) separation of asphalt binder)

b. Ignition method

The asphalt binder was extracted from the RAP using an asphalt binder analyser, as shown in Figure 5.a. During this procedure, the RAP samples were heated under regulated conditions in a furnace, causing the asphalt binder to burn off and leaving behind recycled aggregates. This approach accurately determines binder content using the standard process (ASTM D6307 or AASHTO T 308) [39, 40]. Figure 5.b shows the recycled asphalt pavement aggregate following the ignition technique operation. RAP aggregate was employed in the study as a partial substitute for quartz sand after it was pulverised and sieved to the required particle size. Figure 6 depicts the sieve analysis of fine aggregates employed in this research, while Table 4 presents the physical parameters of fine aggregates.


(a) (b)

Figure 5. Process of preparing recycled asphalt pavement aggregate by ignition method (a) asphalt binder analyzer device, (b) recycled asphalt pavement aggregate)

4.1.3 Admixture

Polycarboxylate-based high range water reduction additive (Sika Viscocrete 1681) was utilised as a hardening accelerator and to improve the workability and strength of VHSHRC. Table 5 shows the physical parameters of the water-reducing admixture. The mash cone test, which evaluates the influence of admixture on the rheological behaviour of cement, was used to establish the optimal admixture dose for obtaining the desired workability and strength of concrete [41, 42]. A total of six experiments were conducted, with superplasticizer doses ranging from 1.2% to 1.6% of the weight of cement. The best superplasticizer dosage to cement was 1.53%, as shown in Figure 7.

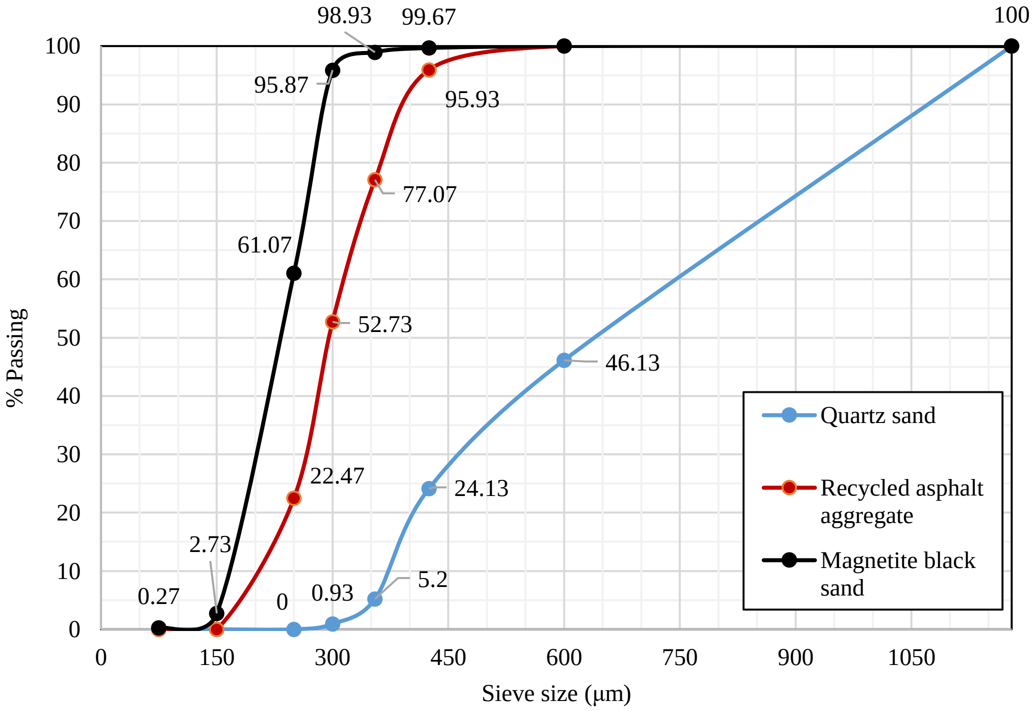


Figure 6. Screen analysis of fine aggregates (quartz sand, recycled asphalt pavement aggregate, magnetite black sand)

Table 4. Physical properties of fine aggregate

Physical properties	Quartz sand	Magnetite black sand	Recycled asphalt pavement aggregate
Appearance/color	Granular / light tan	Granular / black	Granular / brown
Absorption, %	0.32	0.65	2.389
Bulk specific gravity	2.6	4.789	2.513
Apparent specific gravity	2.609	4.953	2.674
Effective specific gravity	2.6045	4.866	2.594
Density, g/cm3	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	-	-

4.1.4 Mixing water

All concrete combinations were mixed with ordinary warm tap water, which was devoid of organic compounds, pollutants, and clay. The water used to make VHSHRC had a TDS of 211 mg/L and an EC of 422 µS/cm, both below acceptable limits for use in concrete manufacture [43].

4.2 Mix Proportions

The mix proportions for the control mix for VHSHRC were determined by earlier researchers, and concrete components were optimised to reach a desired strength and workability [44]. The mix percentage is shown in Table 6.

Table 5. Physical properties of water reducing admixture

Physical properties	Results
Composition	Aqueous solution of modified polycarboxylates
Appearance and color	Light brownish
Specific gravity, g/cm3	1.070
PH value	4.5-6.5

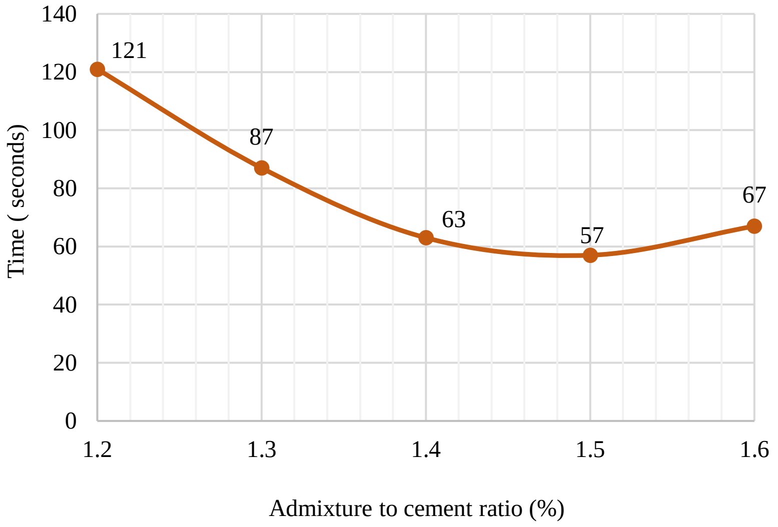


Figure7. Marsh cone test for the selected admixture and Portland cement

Table 6. Mix proportions for control mix of VHSHRC

Materials	Quantity
Cement/Sand	1.097
Water/cement	0.21
Quartz sand	76.5% of total sand
Black sand	23.5 % of total sand
Admixture/binder	0.015

5. TESTS OF VERY_HIGH STRENGTH HEAT-RESISTANT CONCRETE

In this work, mechanical tests were performed to assess the performance of hardened VHSHRC in laboratory conditions and high temperatures of 125 °C, 150 °C, and 175 °C in different time variations, as shown in Figure 8. The tests include cube compressive strength and split tensile strength testing. The experiments were done on concrete specimens cured in water and tested at 28 days of age for both the control mix and concrete mixes containing 4%, 5%, 6%, and 7% RAP aggregate content, respectively. Table 7 shows the number of samples that correspond to their respective tests.

5.1 Mechanical Properties of Very-High Strength Heat-Resistant Concrete

5.1.1 Cube compression test

Figure 9 illustrates the preparation and testing of standard cube specimens measuring 50 × 50 mm. Six samples of control mix and non-heated specimens were made, casted, and tested according to ASTM C109/C109M-20 with a loading rate of 0.2-1.0 MPa/s and a head movement rate of 1.3 mm/min ± 0.5 mm/min.

Figure 8. Very-high strength heat-resistant concrete samples in oven

Table 7. Number of samples tests for the research program

Temperature	Heat exposure duration (hours)	Number of samples									
		Control mix		Concrete with RAP aggregate content							
				4%		5%		6%		7%	
		Compression test	Split tensile test	Compression test	Split tensile test	Compression test	Split tensile test	Compression test	Split tensile test	Compression test	Split tensile test
20°C	0	6	3	6	3	6	3	6	3	6	3
125°C	2	3	3	3	3	3	3	3	3	3	3
	4	3	3	3	3	3	3	3	3	3	3
	6	3	3	3	3	3	3	3	3	3	3
150°C	2	3	3	3	3	3	3	3	3	3	3
	4	3	3	3	3	3	3	3	3	3	3
	5	3	3	3	3	3	3	3	3	3	3
175°C	2	3	3	3	3	3	3	3	3	3	3
	4	3	3	3	3	3	3	3	3	3	3
	6	3	3	3	3	3	3	3	3	3	3

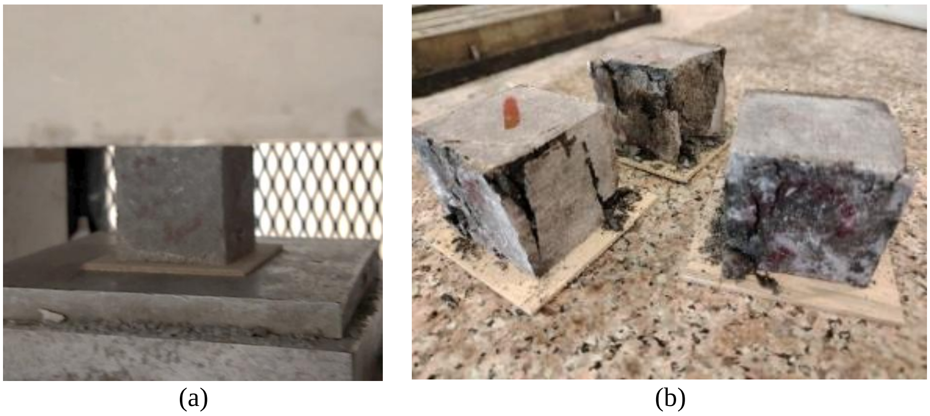

(a) (b)

Figure 9. Concrete samples before and after compressive strength test (a) Concrete samples before testing, (b) Concrete samples after testing

5.1.2 Split tensile test

Standard cylinders with a diameter of 50 mm and a height of 100 mm were prepared and examined at 28 days, as illustrated in Figure 10. The test was done as per ASTM C496/C496M-20, with a loading rate of 0.017-0.023 MPa/s.

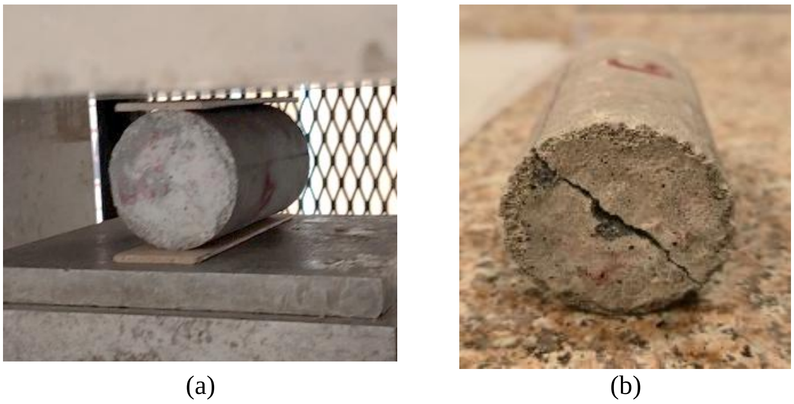

(a) (b)

Figure 10. Concrete samples after split tensile strength test (a) Concrete samples before testing, (b) Concrete samples after splitting

6. RESULTS AND DISCUSSION

6.1 Cube compressive strength

Figure 11 illustrates the compressive strength of a VHSHRC mix under laboratory conditions at 28 days. The control mix had the maximum compressive strength, 128.15 MPa. Compressive strength decreased overall as RAP aggregate concentration increased. However, an exception was found at a 5% RAP replacement ratio, when compressive strength improved when compared to other RAP content levels. At 5% RAP aggregate concentration, compressive strength dropped by 13.6%. Furthermore, the 7% RAP aggregate ratio resulted in the lowest compressive strength, which decreased by 29%.

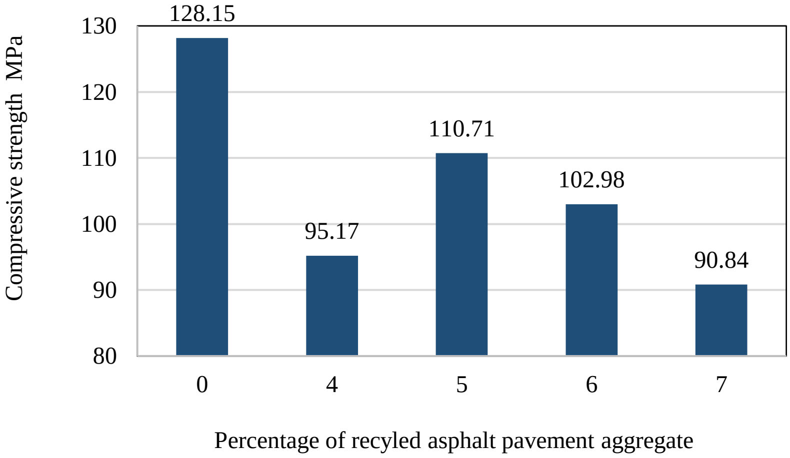


Figure 11. Variation of percentage of RAP aggregate with compressive strength at standard conditions

When VHSHRC samples were subjected to an increased temperature of 125°C, as shown in Figure 12, compressive strength decreased consistently for all RAP aggregate ratios relative to the control mix. After two hours of heat exposure, the inclusion of 5% RAP aggregate resulted in the least decline in strength, with a 9.81% decrease relative to the control mix. In comparison, the mix containing 4% RAP aggregate showed the greatest reduction in compressive strength, 13.8%. Interestingly, when the exposure length rose to 4 and 6 hours, the compressive strength of all mixtures improved when compared to the findings of two hours of heat exposure. Furthermore, the concrete mix exposed for 6 hours outperformed the four-hour heat exposure, demonstrating that VHSHRC is thermally enhanced. After six hours of heat exposure, the control mix lost 21.1% of its strength compared to the standard condition, whereas the 5% RAP mix lost 17.37%. Furthermore, when the 5% RAP mix was compared to the control mix exposed for the same 6-hour period, it showed just a 9.52% strength deficiency.

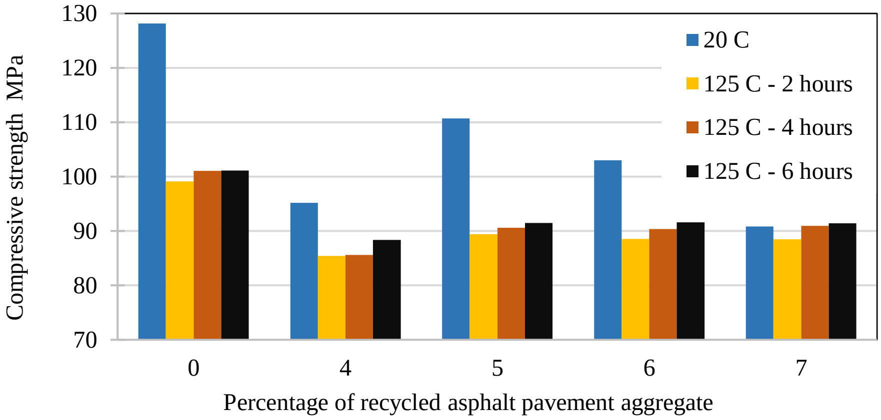


Figure 12. Variation of percentage of RAP aggregate and compressive strength at 125°C

Figure 13 shows that after exposing the VHSHRC mixes to 150°C for 2 and 4 hours, a decrease in compressive strength was seen for all mixes compared to their laboratory state. In contrast, when concrete samples were subjected to heat for 6 hours, compressive strength increased for samples with 4%, 5%, and 7% RAP aggregate ratios, with compressive strengths exceeding their equivalent values under laboratory settings. Furthermore, the highest compressive strengths at 150°C for 2, 4, and 6 hours were 98.56 MPa, 106.34 MPa, and 118.14 MPa, representing increases of 1.17%, 5.93%, and 8.72% above the control mixture at the same thermal conditions. At 6 hours, the 5% RAP aggregate concentration had the maximum compressive strength, measuring 118.14 MPa, which was 6.71% higher than the laboratory strength. As a result, it was determined that 5% RAP aggregate content was the optimal amount for enhancing compressive strength performance at 150°C for all three periods.

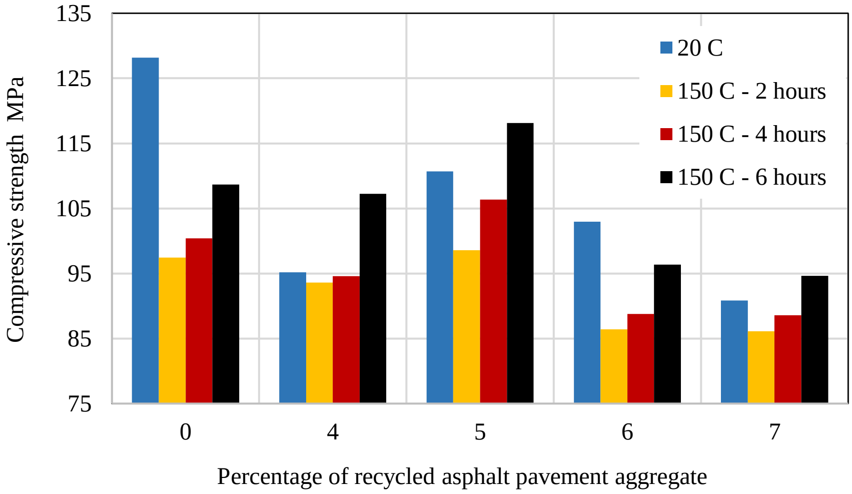
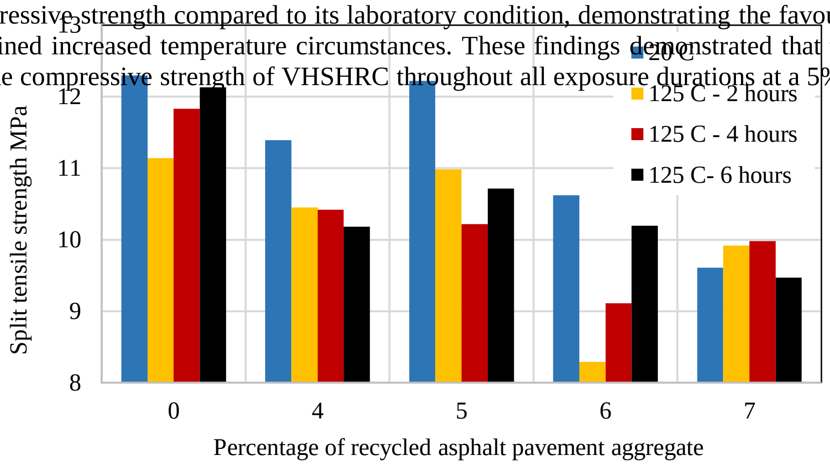


Figure 13. Variation of percentage of RAP aggregate and compressive strength at 150°C

Figure 14 exhibits the exposure of high-strength, heat-resistant concrete to 175 °C. After 2 hours of exposure, all concrete mixes including RAP aggregate showed a decrease in compressive strength compared to the control mix, indicating an early loss in thermal properties. However, at longer exposure durations of 4 and 6 hours, although the compressive strength of the control samples continued to decline, concrete mixes including RAP aggregate demonstrated a significant increase in compressive strength relative to laboratory settings. At 4 hours, the greatest compressive strength reported was 111.08 MPa, surpassing the compressive strength of the control mix under similar temperature conditions. After 6 hours of exposure, the greatest compressive strength of 131.33 MPa was observed, representing a 3.34% increase over the control mix under the same heat exposure. The concrete mix with 5% RAP aggregate material showed an 18.63%

improvement in compressive strength compared to its laboratory condition, demonstrating the favourable effect of RAP aggregate under sustained increased temperature circumstances. These findings demonstrated that the addition of RAP aggregate increased the compressive strength of VHSHRC throughout all exposure durations at a 5% ratio.



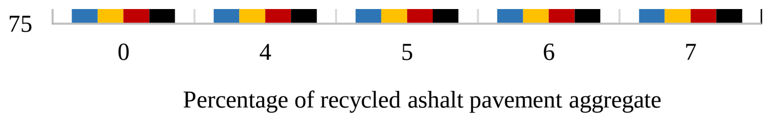


Figure 14. Variation of percentage of RAP aggregate and compressive strength at 175°C

6.2 Split tensile strength

The split tensile strength of the VHSHRC mix was measured at 12.296 MPa in a laboratory setting. The inclusion of RAP aggregates altered the split tensile strength of the VHSHRC mixes. At 4% RAP aggregate concentration, split tensile strength was reduced. At 5% RAP aggregate ratio, tensile strength improved to 12.222 MPa, comparable to the VHSHRC control mix. In contrast, greater RAP aggregate levels of 6% and 7% resulted in considerable reductions in split tensile strength, with falls of 13.61% and 21.88%, respectively, compared to the control mixture. According to the data shown in Figure 15, the ideal RAP aggregate concentration is 5% for sustaining the split tensile strength of the VHSHRC.

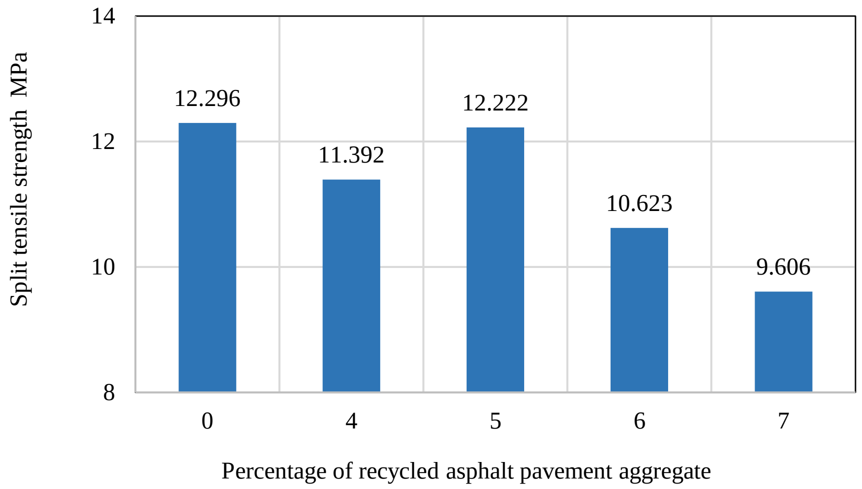


Figure 15. Variation of percentage of RAP aggregate and split tensile strength at 20°C

Under 125 °C thermal exposure for VHSHRC, all concrete mixes' split tensile strength decreased compared to laboratory settings (Figure 16). The mix with 5% RAP aggregates performed the best of the RAP aggregate ratios, obtaining equivalent strength to the control at 2 hours and then declining somewhat during extended exposures. In contrast, larger RAP aggregate levels of 6% and 7% resulted in a considerable and constant decrease in split tensile strength throughout all heat exposure times, showing the deleterious impact of excessive RAP aggregate. These findings shown that 5% RAP aggregate is the best ratio for preserving split tensile strength performance under both ambient and increased temperature situations. At 150°C, the split tensile strength of VHSHRC control mixes was 12.296 MPa in the lab. After 2 hours of heat exposure, it decreased to 11.407 MPa. After 4 and 6 hours, it climbed to 12.232 MPa and 12.095 MPa. VHSHRC concrete samples with 5% RAP aggregate had the best performance, increasing split tensile strength from 9.936 MPa to 11.671 MPa after 4–6 hours of heat exposure.

Figure 16. Variation of percentage of RAP aggregate and split tensile strength at 125°C

Higher RAP aggregate levels of more than 5%, on the other hand, consistently resulted in poorer split tensile strengths throughout all exposure periods, despite some improvements over longer durations. These findings led to the conclusion that utilising 5% RAP aggregate improved split tensile strength at increased temperatures, however using an excessive quantity of RAP aggregate content had a negative impact on the split tensile strength test results, as shown in Figure 17.

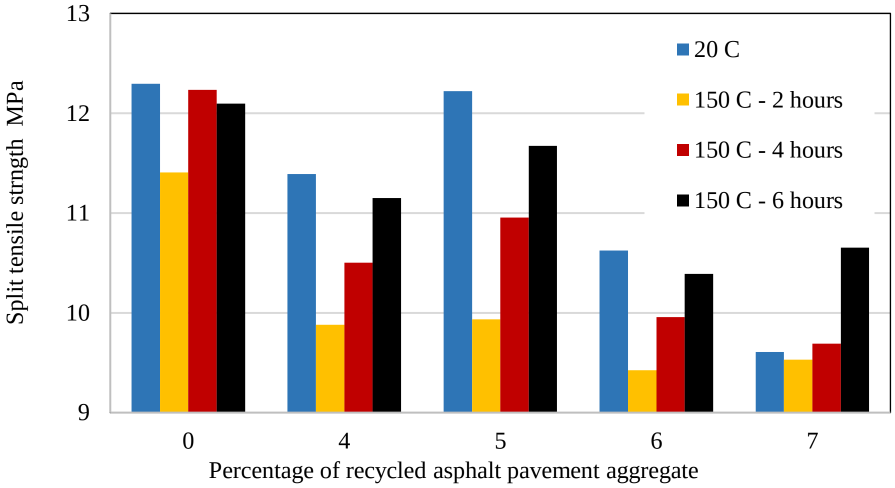


Figure 17. Variation of percentage of RAP aggregate and split tensile strength at 150°C

At ambient laboratory conditions, the VHSHRC control mix had the maximum split tensile strength of 12.296 MPa. The control mix's split tensile strength decreased to 10.934 MPa after 2 hours of heat exposure but increased to 12.734 MPa after 4 hours and beyond after 6 hours, as shown in Figure 18. Similar results were obtained in concretes including RAP aggregate blends. Concrete mixes with 5% RAP aggregate showed significant improvement in split tensile strength, reaching 10.066 MPa and 13.202 MPa after 4 and 6 hours of heat exposure, respectively. At 6 hours of heat exposure, the value of split tensile strength exceeded all other concrete mixes. After 6 hours of heat exposure, concrete mixes using 6% and 7% RAP aggregates rose in strength to 12.005 MPa and 11.451 MPa, respectively. In contrast, concrete with 4% RAP aggregate concentration performed consistently worse than the control, but strength increased with time. Exposing concrete to 175 °C for lengthy durations enhances split tensile strength, notably at 5% RAP aggregate concentration, yielding the greatest value under all conditions. The softening of the thin coat of asphalt binder that binds the fine aggregates is responsible for the increase in split tensile strength. The bonding activity that happens between the binder and concrete components results in a better matrix and less heat cracking.

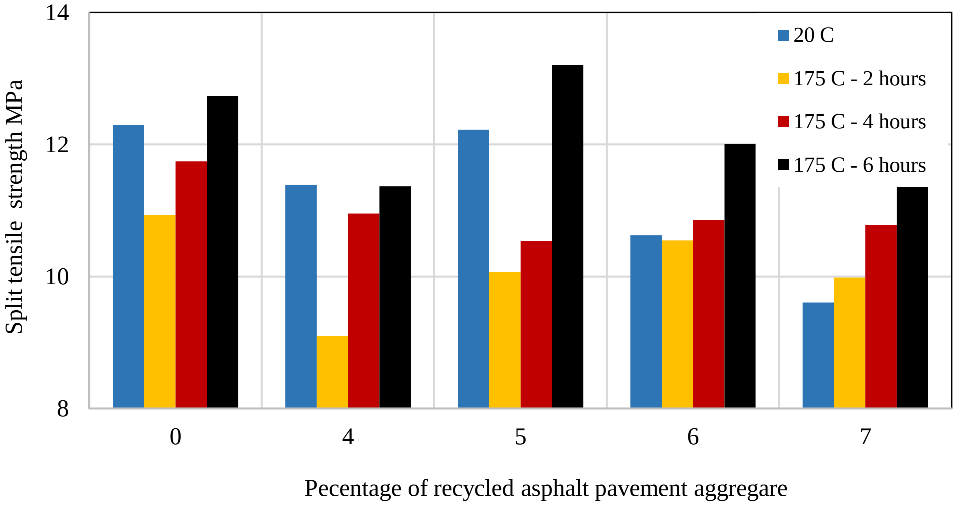


Figure 18. Variation of percentage of RAP aggregate and split tensile strength at 175°C

6.3 Brittleness index

The brittleness index of concrete is the ratio of compressive strength to the equivalent split tensile strength. A higher Brittleness Index (BI) value increases the brittleness of concrete [44–48]. Figures 20-23 show the BI of VHSHRC based on the results of compressive and split tensile strength tests. At ambient laboratory circumstances, the BI of the control mix was 10.42; however, by incorporating RAP aggregates, the BI was dramatically reduced to 8.354, indicating an improvement in ductility over the control. This might be attributable to the changing viscoelastic characteristics of the binder when combined with the RAP aggregate. However, beyond 4% of the RAP aggregate, an increase in BI was detected, as illustrated in Figure 19.

Figure 20 depicts how heating at 125°C affects all RAP aggregate ratios. Heating the control mix for 6 hours consistently lowered the BI from 10.422 to 8.336, suggesting toughening or decreased brittleness. A comparable decrease in BI with increased heating period was found for 4% and 5% RAP aggregate content. As a consequence, 5% RAP aggregates had the lowest BI value, indicating an ideal ratio. Under an enhanced temperature of 150°C, the BI of the control mix dropped with increasing heating duration. Whereas for mixtures containing RAP aggregates ranging from 4% to 7%, heating at 150°C often resulted in a higher BI than the control mix. Notably, the BI for 5% RAP aggregate reached its peak of 10.122 after 6 hours of heating, as shown in Figure 21.

Figure 22 depicts substantial changes in BI after exposing VHSHRC to 175°C. Heating initially lowered BI in the control mix, but prolonged heating resulted in a 9.979 rise in BI after six hours. Heating enhanced the BI in concrete mixtures using RAP aggregates. Notably, concretes containing 4% and 5% RAP aggregate showed a significant increase in BI following heating, with the BI for 5% RAP reaching 10.601 after 2 hours of heating, which exceeded the BI of the control mix. Higher RAP aggregate ratios of 6% and 7%, on the other hand, showed a more nuanced reaction to heating, with the BI fluctuating or even decreasing with prolonged heating, as seen with 7% RAP content.

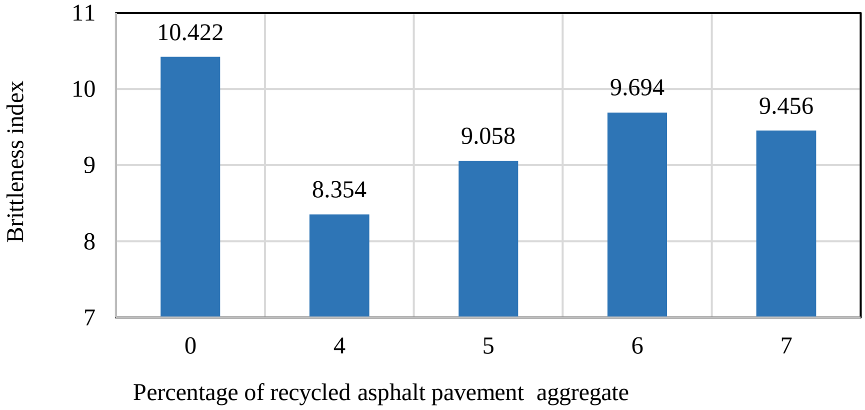


Figure 19. Variation of BI with percentage of RAP aggregate at laboratory condition

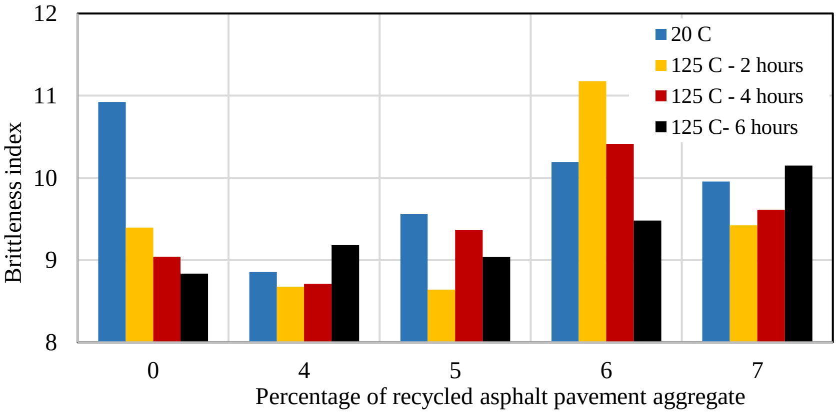


Figure 20. Variation of BI with percentage of RAP aggregate at 125°C

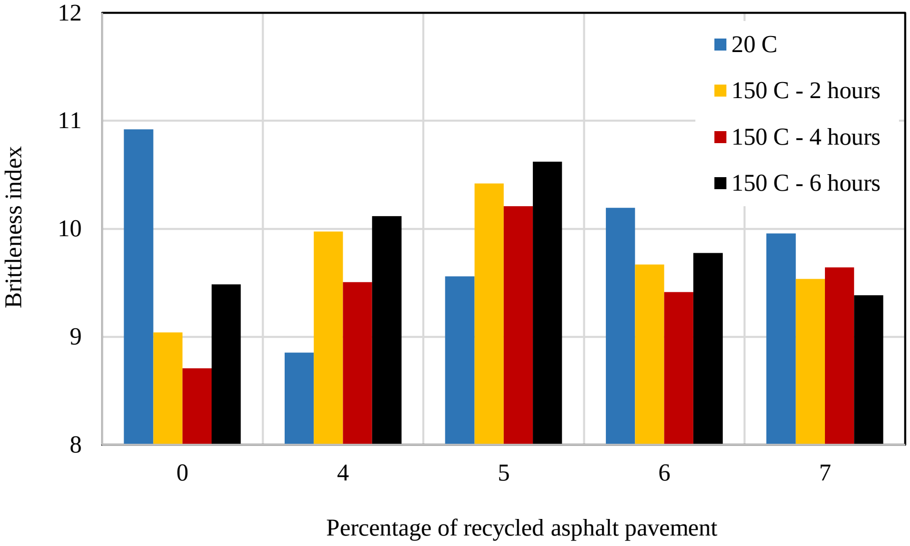


Figure 21. Variation of BI with percentage of RAP aggregate at 150°C

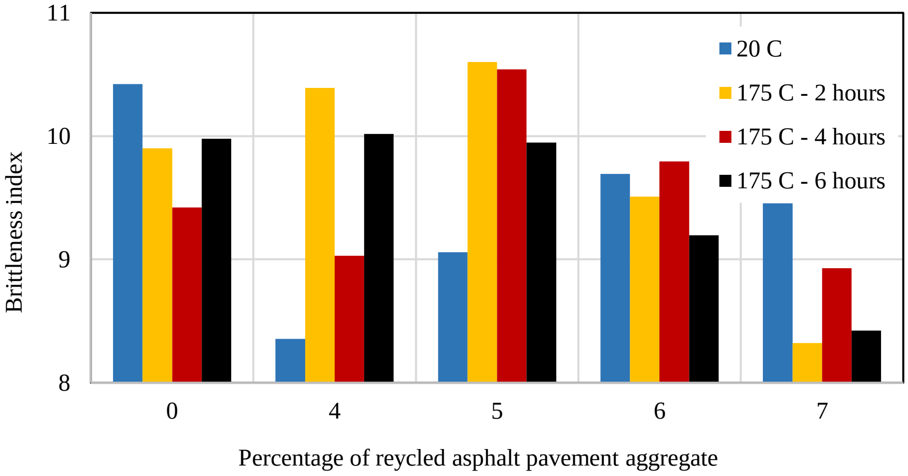


Figure 22. Variation of BI with percentage of RAP aggregate at 175°C

7. CONCLUSION

The mission of this study was to look at the influence of RAP aggregate on the mechanical performance of VHSHRC as a partial substitute for quartz sand at ambient laboratory settings as well as at increased temperatures for varying periods of time. Laboratory studies were conducted to assess compressive strength and split tensile strength at standard and increased temperatures of 125 °C, 150 °C, and 175 °C for 2, 4, and 6 hours, respectively. The results gave useful information about how these factors affect the mechanical characteristics and brittleness index of VHSHRC. In light of the experimental data and analysis, the following conclusions are drawn:

- Concrete with 5% RAP aggregate replacement ratio reached the greatest compressive strength of 118.14 MPa and 131.33 MPa at 150°C and 175°C, respectively. The improved compressive strength is due to the asphalt binder covering the RAP aggregate particles, which melted and filled the produced thermal micro fractures, bridging the fissures and decreasing the internal thermal stresses of the concrete. Furthermore, heat exposure increased the loss of free and bound water surrounding cement particles, resulting in the end of the hydration process.
- At 150°C and 175°C, the mix with 5% RAP aggregate showed the highest improvement (11.671 and 13.202 MPa, respectively). The increased split tensile strength is due to the better link between fine aggregate and cement matrix created by the asphalt binder that covers the RAP aggregate. In addition, thermally caused cracks were filled and bridged with asphalt binder.
- Incorporating RAP aggregates reduced the BI value at typical laboratory circumstances, especially at 4 and 5% replacement ratios, indicating better concrete ductility. However, at greater temperatures of 150°C and 175°C, the BI index rose with increasing heating time as the asphalt binder coated RAP aggregate degraded and lost its binding effect.

ACKNOWLEGMENTS

The authors have special appreciation to University of Sulaimani /College of engineering/ Civil engineering department for providing the academic environment, access to laboratory facilities to perform this research.

FUNDING

This study was not supported by any grants from funding bodies in the public, private, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

Zhwan Anwar Noori: Conceptualization, Methodology, and writing
Hardy Kamal Karim: Supervision
Ferhad Rahim Karim: Supervision, Writing- Reviewing and Editing

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author

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LIST OF ABREVIATTION

Symbols	Description
VHSHRC	very-high strength heat-resistant concrete
RAP	recycled asphalt pavement
BI	brittleness index
VHS	very-high strength concrete
HRC	heat-resistant concrete
BS	back sand
FA	fly ash
SF	silica fume
CaO	calcium oxide
SiO_2	silicon dioxide
Al_2O_3	aluminum oxide
Fe_2O_3	ferric oxide
MgO	magnesium oxide
SO3	sulfur trioxide
CaO	calcium oxide
SiO_2	silicon dioxide
Al_2O_3	aluminum oxide
Fe_3O_4	ferrosoferric oxide
TDS	total dissolved solids
EC	electrical conductivity