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Development and performance evaluation of heat-resistant concrete under varying temperature conditions

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Abstract:
In industries where thermal endurance is critical, such as metallurgy, power generation, and construction, heat-resistant concrete (HRC) represents a specialised form of concrete engineered for high-temperature applications and thermal cycling. Traditional concrete, when exposed to elevated temperatures, undergoes significant morphological and chemical transformations that lead to disintegration and a reduction in mechanical strength, as the thermal, mechanical, and deformation properties of concrete govern the response of structural elements to fire exposure. In this investigation, three distinct concrete mix designs were prepared and subjected to controlled heating, and their compressive strengths were evaluated against those of the control concrete to assess performance under thermal stress. The study also examined the composition, characteristics, and potential applications of HRC by exploring the use of various binders, additives, and aggregates aimed at enhancing thermal stability. Basalt aggregates, combined with high-temperature-resistant binders such as Portland slag cement, were employed as primary constituents. The results demonstrated that concrete containing basalt aggregates exhibited superior thermal performance compared with natural aggregates, with a binder content of 420 kg/m³ showing optimal strength retention across all curing and heating conditions. Consequently, the investigation confirmed the applicability of HRC for industrial construction environments exposed to high temperatures of 105, 350, and 700 °C.

Keywords:
elevated temperature; properties; basalt aggregate; Portland slag cement; compressive strength

1 Introduction

To meet the growing need for infrastructure, the global demand for concrete continues to increase. Ordinary Portland cement (OPC) is a typical binder used for concrete. Building fires have a peak temperature of approximately 1000 °C, which can reach 850 °C in less than 30 min. A petrochemical fire can peak at approximately 1100 °C and can reach 900 °C during the first 5 min. Exposure to elevated temperatures during fires is among the most severe hazards affecting reinforced concrete structures. To protect people and property, characterisation of the fire resistance of construction materials, in addition to other structural behaviours, is essential [1]. Despite being a noncombustible substance, concrete properties change when exposed to high temperatures. Concrete is used intermittently as a key structural element in construction owing to its various advantages over other building materials. When applied to structures, the concrete in structural members must comply with the fire safety standards specified in building codes. Fire represents one of the most extreme hazards to buildings. Therefore, ensuring adequate fire safety for structural components is essential in architectural design [2].

Since the 20th century, researchers have examined the effects of elevated temperatures on the mechanical properties of concrete [3]. The ability of concrete to withstand fire is extremely complicated because it is a composite material composed of components with various thermal properties and has attributes that rely on moisture and porosity [4]. When concrete is exposed to elevated temperatures, the macro-level characteristics of its strength and Young's modulus decline, and its internal structure deteriorates. Concrete exposed to high temperatures alters its mechanical properties depending on both environmental and material parameters, such as its constituents, initial strength before exposure to elevated temperatures, and moisture content [5]. The mechanical properties of concrete under high temperatures can be influenced by several factors, including the chemical and physical attributes of its constituents, intensity of heat exposure, dimensions of the concrete structure, external loads applied, and cooling conditions experienced by the structural member [6]. In addition, the chemical content and physical composition of concrete are typically altered at elevated temperatures. Upon exposure to approximately 110 °C, dehydration processes, such as the release of chemically bound water from calcium silicate hydrate (C–S–H), are observed [7].

Research has revealed that concrete shrinks as a result of the dissociation of caustic lime, a primary component of cement paste, at a temperature of approximately 530 °C. The compressive strength of concrete decreased dramatically at 600 °C, and concrete deteriorated overall due to the dissolution of $Ca(OH)_2$ and C–S–H gel, notably at 800 °C [8]. High temperatures caused by fire are known to reduce the strength and longevity of concrete constructions. The classification of cement and aggregates used in the configuration of concrete and the temperature and length of the structural component affect the ability of the material to resist fire. Aggregates generally exhibit high fire resistance. However, the internal pressure in the aggregates can be increased by the non-uniformity of high temperatures or by cooling the heated aggregates with a water spray. Consequently, the resulting strain can cause the aggregates to fracture [9]. A study by Chan et al. [10] found that high-strength concrete (HSC) performs poorly when exposed to fire because of its dense microstructure. The findings of the fire tests demonstrated that after exposure to elevated temperatures, the characteristics of HSC and controlled concrete differed significantly.

The incompatibility between cement pastes and aggregates on a thermal scale, the development of internal pressure due to water dissipation during heating, and chemical changes in these materials contribute to the loss of concrete strength at elevated temperatures. In addition, according to studies on the effect of high temperatures on the physical characteristics of concrete, normal-strength concrete performs differently from HSC at the same higher temperatures [11]. According to the authors [12], the compressive strength of HSC decreases more rapidly with temperature than that of normal-strength concrete in both stressed and unstressed conditions, with the difference most evident between 25 °C and 400 °C. Similar tendencies were observed in terms of the modulus of elasticity, where both concrete types exhibited a decremental plot. Moreover, in a paper on recycled coarse aggregates (RCAs), Silva [13] stated that most aggregates display thermal expansion up to 600 °C; consequently, internal tensions result in cracks that mostly form on the bonding surfaces. Thus, the mechanical capabilities of regular concrete mixtures are impaired. Because RCAs comprise two different components, that is, old natural aggregates and attached mortars, the quantity and variety of interfaces increase, increasing the likelihood of concrete degradation under exposure to high temperatures.

The interface transition zone (ITZ) has the greatest impact on the characteristics of natural concrete. RCAs have lower mechanical qualities than natural aggregates because they have larger ITZs [14]. Additionally, experimental studies have demonstrated that under high-temperature conditions, the hot superficial face tends to split and fall out from the cooler interior. Concrete may also exhibit cracking and spalling along with a loss of adhesion between the aggregates and cement paste [15]. A significant influence factor on the achievement of fibre-reinforced concrete (FRC) at elevated temperature is the addition of replacement materials, including silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBFS), and metakaolin (MK). These substitutes typically yield concrete with a denser microstructure. Even if the strength increases at room temperature, heating hinders the release of the internal vapour pressure, which can cause spalling damage [16]. Because of basalt's high density, low porosity, and thermal stability—all of which prevent weight loss and damage—the experimental investigation demonstrates that basalt aggregates mixed with Portland blast furnace slag cement help concrete maintain compressive strength up to 700 °C. By bridging gaps and enabling vapour to escape, FRC demonstrates how adding fibres such as steel and polypropylene lowers strength loss and spalling at high temperatures. Both FRC and heat-resistant concrete (HRC) fabricated with basalt aggregate highlight the importance of carefully choosing the materials. When comparing the experimental work with FRC, the parameters considered are the type of fibre, dosage, and hybrid used, which can further improve the strength and spalling resistance. The experimental work focused on aggregates and binders. Mixing appropriate fibres with long-lasting aggregates may result in concrete that performs better in industrial heat or fire [16].

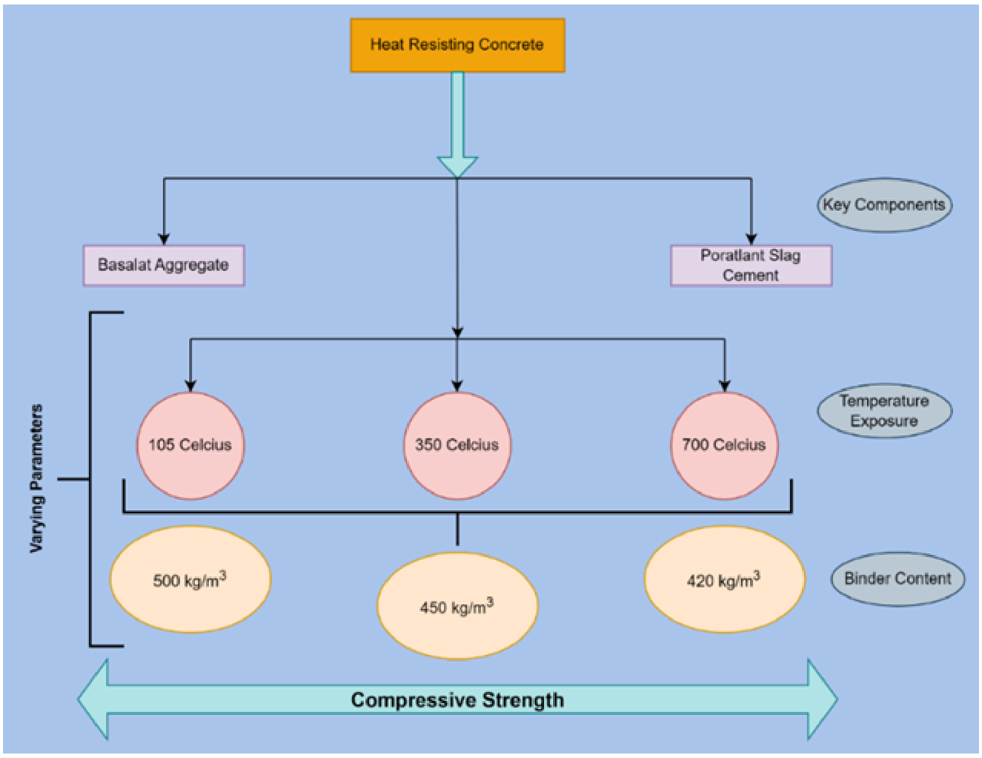


Figure 1. Flow Diagram of HRC in the present investigation

Another investigation was conducted using GGBFS as a supplementary cementitious material. According to previous reports, the temperature-dependent nature of GGBFS results in faster concrete strength development when cured at higher temperatures. Therefore, GGBFS can be used to prepare concrete using a high-temperature curing process [17]. The effect of enhanced curing temperature on the crystal structure and mechanical characteristics of slag-based cement concrete when exposed to high temperatures remains unclear [18].
For this experimental investigation, HRC was prepared using Portland blast furnace slag cement, basalt coarse aggregate, and basalt sand of Mix 30. Concrete cubes of 100 × 100 × 100 mm were cast using mix designs with cement contents of 500, 450, and 420 kg/m³. The results indicated that HRC enhances the thermal performance and safety of structures exposed to high temperatures. Further research is required to optimise HRC formulations for modern industrial and construction applications. Figure 1 depicts the process flow of HRC using various parameters.

2 Experimental program

2.1 Materials

OPC is the most widely used cement worldwide. It is a basic blend of clinker and gypsum and is commonly used in the construction of buildings, bridges, roads, and other infrastructures. OPC is acknowledged for its high-strength characteristics and quick-setting properties, which make it a popular choice for concrete production. The relative density of the OPC cement is 3,15 according to IS 4031 (Part-11) [19].
Natural aggregates are a broad category of construction materials that include crushed rock, sand, gravel, and other geological materials extracted from natural sources. These materials are used in various construction applications, including the production of concrete, asphalt, and roadbase materials. Natural aggregates are known for their durability, strength, and low cost, which make them essential components in modern construction. They are abundant in many regions and readily available for use in construction projects. Crushed basalt rock pieces are used as aggregates in the construction.
Basalt is a volcanic rock formed when lava cools rapidly near the Earth's surface. It is valued for its hardness and resilience to weathering. Because of these qualities, basalt aggregates are ideal for various construction applications. Basalt aggregates are responsible for the high compressive strength of concrete because of their higher density compared with other aggregates. They are also suitable for HRC owing to their outstanding thermal stability, which enables them to tolerate high temperatures without any noticeable deterioration. They are also suitable for use in asphalt roadways and highway bases, owing to their exceptional durability and resilience. Furthermore, the angularity and toughness of basalt pebbles make them more useful as railway ballast. Owing to their low porosity, high specific gravity, and excellent thermal stability, basalt aggregates are ideal for HRC because they improve strength retention at high temperatures. Compared to granite or limestone, their mineral compositions (olivine, pyroxene, and plagioclase) offer higher melting points and resistance to heat degradation. According to previous studies, basalt deforms and loses very little weight when heated, unlike other aggregates that are more likely to split or spall. Although substitutes, such as lightweight clays or recycled aggregates, provide heat resistance, their poor ITZ and high porosity degrade their performance. Yıldrıim demonstrated the low thermal expansion and exceptional toughness of basalt, confirming its viability for high-temperature structural applications [20].
Table 1 shows the properties of the basalt aggregates and other aggregates. Structures such as buildings, bridges, and other construction endeavours that require extraordinary strength and longevity frequently use structural concrete. Portland blast furnace slag cement is a type of blended cement produced by intergrinding Portland cement clinker and granulated blast furnace slag (a waste product from iron production). This type of cement provides improved durability, reduced permeability, and increased resistance to chemical attacks compared with traditional Portland cement. They are commonly used in the construction of bridges, marine structures, and other infrastructure projects where high durability is required. The specific

gravity of slag cement is 2,89. Chemical Admixture: Naphtha-based admixture was used. Naphtha-based admixtures are chemical additives used in the construction industry, typically in concrete and mortar mixtures. They are made from petroleum derivatives and mixed in minute proportions to improve mixing characteristics.

Table 1. Properties of different aggregates

Property	Basalt aggregate	Granite aggregate	Quartzite aggregate	Limestone aggregate	References
Thermal stability	excellent – retains structure up to ~ 1000 °C	good – stable up to ~ 600 °C	moderate – can crack due to thermal stress	poor – begins decomposing around 800 °C	[21-24]
Melting point (°C)	~ 1200-1300	~ 1215	~ 1670	~ 825 (starts decomposing)	
Thermal conductivity (W/m·K)	low – good insulator	moderate	high – leads to thermal stress	moderate	
Water Absorption (%)	low (0,2-0,6)	moderate (0,5-1,0)	moderate (0,6-1,2)	high (up to 2)	
Compressive strength retention at 700 °C	high (minimal strength loss)	moderate	low	poor	
Thermal expansion coefficient	low (reduces cracking risk)	moderate	high (prone to cracking)	moderate to high	
Suitability for HRC	highly suitable	moderately suitable	less suitable	unsuitable	

As evident from the above table, basalt aggregates outperform other conventional aggregates in terms of thermal stability, strength retention, and resistance to thermal degradation. This is primarily attributed to the igneous origin of basalt, its dense microstructure, and low thermal expansion, which help it resist cracking and preserve its mechanical integrity under thermal loading.

2.2 Properties of aggregates

Aggregates are crucial components of construction materials, such as asphalt and concrete. Their characteristics significantly affect how well and for how long these materials function. The ability of concrete to withstand compressive stress is essential for structural applications. For aggregates, this is less crucial; however, it is still significant for the overall strength of concrete. A crucial characteristic of aggregates used in construction is their specific gravity, which expresses the ratio of the density of the material to the density of water. The weight of a specified volume of aggregate divided by the weight of an equivalent volume of water is known as the specific gravity of the aggregate.

$$S.G = \frac{Weight\ of\ aggregate\ in\ air}{Weight\ of\ Equal\ volume\ of\ water} \tag{1}$$

One crucial characteristic of the aggregates used in construction is their ability to absorb water. This metric is measured as a percentage of the aggregate's dry weight and indicates the amount of water that an aggregate can absorb. The porosity and quality of the aggregate can be understood using the water absorption value, which in turn influences the durability and design of the concrete mix.

$$Water\ absorption\ (\%) = \frac{W_{saturated} - W_{ovendry}}{W_{ovendry}} \cdot 100 \tag{2}$$

The resistance of the aggregate to an abrupt shock or impact was measured using the aggregate impact value (AIV). This number indicates the toughness of the aggregate, which is crucial for determining whether it can be used for construction, particularly for roads.

$$AIV\ (\%) = \frac{Weight\ of\ oven - dried\ sample}{Weight\ of\ fraction\ passing\ 2{,}36\ mm\ sieve} \cdot 100 \quad (3)$$

The relative resistance of the aggregate to crushing under gradually applied compressive stress was measured using the aggregate crushing value (ACV). This number is crucial for determining whether the aggregates are suitable for use in various building applications, particularly in pavements and other structures that are subjected to strong compressive loads.

$$ACV\ (\%) = \frac{Weight\ of\ oven - dried\ sample}{Weight\ of\ fraction\ passing\ 2{,}36\ mm\ sieve\ after\ crushing} \cdot 100 \quad (4)$$

2.3 Mixture design

Natural coarse aggregates, fine and coarse basalt aggregates, and natural fine aggregates were blended for approximately 3-4 min during casting. To create a homogeneous dry mix, binder ingredients, such as OPC and Portland slag cement, were added and mixed for another 3 min. Water and the admixture were added to the dry mix after preparation to improve the uniformity, flow, and workability. Subsequently, the concrete was poured into moulds and allowed to rest for an entire day. Subsequently, the concrete cubes were sufficiently strong to be removed from the moulds and cured in water. After 7 and 28 days, the specimens were subjected to a compression strength test. Three 100 × 100 × 100 mm cube specimens were cast for each temperature level. The specimens were subjected to various curing and exposure conditions, namely normal water curing, natural air curing (humidity), and thermal exposure at 105 °C, 350 °C, and 700 °C. Following IS 10262:2019 [25], three distinct mixes were fabricated, with binder constituents of 500, 450, and 420 kg/m^3, as listed in Table 2. The concrete mixture was compacted inside the moulds using a vibrating table. After mixing, the concrete was placed and vibrated for less than 25 min, with the vibration period being less than 1,5 min. The moulds were covered with a damp cloth for 48 h following the casting process. Figure 2 shows the various post-curing conditions for the HRC cubes.

Table 2. Mix design of HRC

Sr. No.	Materials	Mix 1 (kg/m^3)	Mix 2 (kg/m^3)	Mix 3 (kg/m^3)
1	Portland Blast Furnace Slag Cement	500	450	420
2	Basalt Sand	700	722	746
3	Basalt Coarse Aggregate	900	1096	1105
4	Water-Cement ratio	0,450	0,368	0,399
5	Chemical admixture	0,70 %	0,80 %	0,80 %

Three cube-shaped test samples were prepared and exposed to different temperatures. The cubes were cured under standard conditions during the initial testing. In the second experiment, curing was performed in a naturally humid environment. The samples were put to the test at higher temperatures in the third, fourth, and fifth trials—105, 350, and 700 °C, respectively, as shown in Figure 3.

2.4 Curing condition

“Curing conditions” refer to the environmental conditions maintained during the curing process. This can include factors such as temperature, humidity, and pressure, as well as the duration of the curing process. The curing conditions can have a significant impact on the final properties of a material, such as its strength, durability, and resistance to moisture or other environmental factors. The different temperature conditions defined in Table 3 were used in the present investigation as follows:

Normal-condition cubes: after 48 h, six cubes (100 × 100 × 100 mm) processed under normal conditions were removed from the mould and kept covered with a moist cloth for 7 and 28 days. They were then tested in a compression testing machine to determine their strength at each age.

Figure 2. Various mixes of HRC

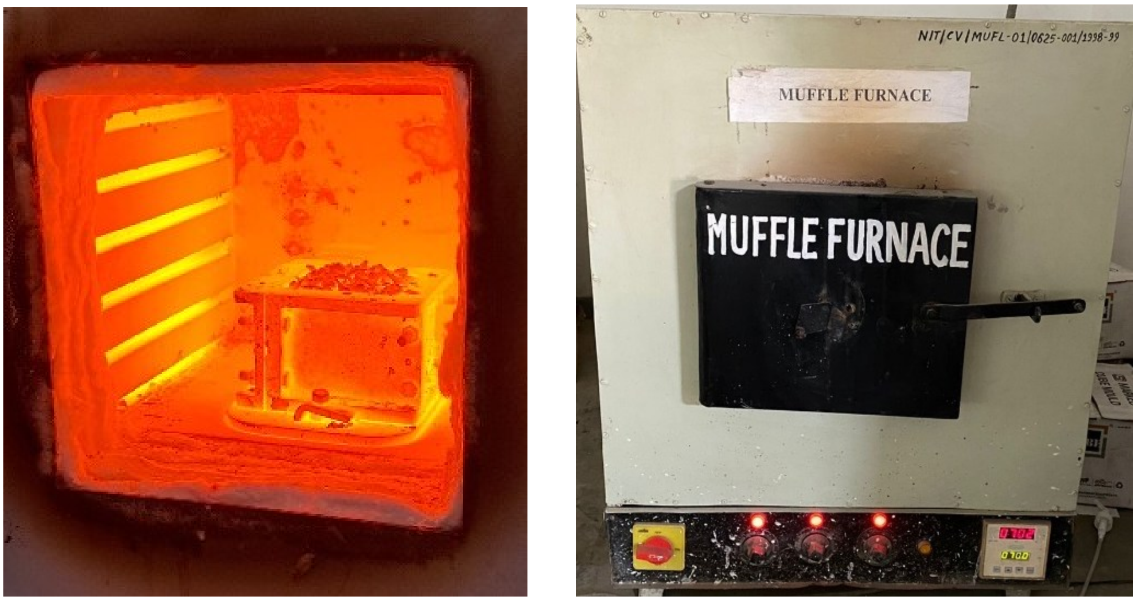


Figure 3. Cubes exposed to elevated temperatures

Natural Humidity: after 48 h, three cubes (dimensions: 100 × 100 × 100 mm) were unmoulded and placed in a humidity chamber maintained at 90 % relative humidity and a temperature of

20 °C + 2 °C for 7 days after casting. After removing the cubes from the chamber, they were kept for 1 h under ambient conditions and then placed in the compression testing equipment to determine their compressive capacity.

Temperature of 105 °C: after 48 h, three cubes with dimensions of 100 × 100 × 100 mm were unmoulded and placed in a humidity chamber maintained at 90 % relative humidity and a temperature of 20 °C ± 2 °C for 7 days after casting. Following this curing period, the cubes were removed from the humidity chamber and kept in a hot-air oven at a temperature of 105 °C for 32 h. After heat exposure, the cubes were gradually cooled to 25 °C. The cooled specimens were then placed in the compression testing machine to determine their compressive capacity.

Temperature of 350 °C: after 48 h, three cubes with dimensions of 100 × 100 × 100 mm were unmoulded and placed in a humidity chamber maintained at 90% relative humidity and a temperature of 20 °C ± 2 °C for 7 days after casting. After removal from the humidity chamber, the cubes were placed in a hot-air oven at 105 °C for 32 h, followed by heating in a muffle furnace at 350 °C for an additional 8 h. After removal from the furnace, the cubes were gradually cooled to 25 °C. The cooled specimens were then placed in the compression testing equipment to determine their compressive capacity.

Temperature of 700 °C: after 48 h, three cubes of 100 × 100 × 100 mm were unmoulded and placed in a humidity chamber maintained at 90% relative humidity and a temperature of 20 °C ± 2 °C for 7 days after casting. After removal from the chamber, the cubes were placed in a hot-air oven at 105 °C for 32 h, followed by heating in a muffle furnace at 700 °C for 8 h. After removal from the furnace, the cubes were gradually cooled to 25 °C. The cooled specimens were then tested in the compression testing equipment to determine their compressive capacity.

Table 3. Testing samples for HRC

Sr. No.	Cube size	Temperature condition	Number of cubes
1	100 × 100 × 100 mm	normal condition	6
2		natural humidity	3
3		temperature 105 °C	
4		temperature 350 °C	
5		temperature 700 °C	

2.5 Compressive strength test of concrete

The compressive strength of the concrete mixtures was evaluated using a 3000 kN capacity hydraulic compression testing machine. Cube specimens with a size of 100 mm were cast, and the compressive strength was measured following IS 516-2021 [26] at 7 and 28 days. An average of three cubes was used in the compressive strength testing machine. The compressive strength of the cubes was evaluated using the following equation:

$$Compressive\ strength = \frac{P}{A} \tag{5}$$

where P is the applied load in N and A is the cross-sectional area in mm^2. The cubes were tested in a compression testing machine at a loading rate of 2-3 kg/cm^2/s. Table 4 lists the permissible compression capacity criteria according to the EN 206 standard [27]. Standard cube sizes are frequently used in tests to determine the compressive strengths of the cube specimens. A correction factor is applicable for determining the strengths of various cube sizes because the size of the specimen can affect the results.

A commonly used factor is used to convert a 100 mm cube's compressive strength to an equivalent 150 mm cube strength. Empirical evidence and research show that a 100 mm cube typically has a higher compressive strength than a 150 mm cube. This is because smaller cubes have smaller surface areas for stress distribution and are less prone to defects. Given that the typical conversion factor is approximately 0,95, the strength of a 100 mm cube is equivalent to 95 % of that of a 150 mm cube.

Table 4. Permissible compression capacity criteria

Grade of Concrete	M30	M30	M30
Temperature	105 °C	350 °C	700 °C
28 days strength M30 without heating	30 N/mm^2	30 N/mm^2	30 N/mm^2
Permissible strength percentage after heating	96 %	80 %	40 %
Permissible strength after heating	28,8 N/mm^2	24 N/mm^2	12 N/mm^2
Calculation for the compressive strength		load in N/area of cube in mm^2	
Equivalent (150 × 150 × 150) cube strength calculation		0,9 × strength of (100 × 100 × 100 mm) cube	

3 Results and discussion

3.1 Physical characteristics of basalt aggregates

The specific gravity test results of the basalt aggregate were higher than those of the natural aggregates, indicating greater density, better packing efficiency, and lower porosity, as listed in Table 5. The water absorption values of both the 10 and 20 mm aggregates followed trends similar to those of natural aggregates. The specific gravity of the natural aggregate was 2,74, and that of the basalt aggregates was 2,86. Specific gravity tests were also conducted. The water absorption tests for the 10 mm downsized natural and basalt aggregates were 0,81 and 0,80, respectively. However, a difference was observed between the 20 mm downsized aggregates, where the water absorption value for the natural aggregates was 0,82 %, while that of the basalt aggregates was 0,93 %. The high crushing strength of basalt aggregates indicates that they can support heavy weights without fragmentation, which is essential for the resilience and endurance of concrete constructions. High-crushing-strength aggregates are often more durable because of their resistance to weathering, wear, and other environmental variables. The crushing value of the 10 mm downsized basalt aggregates was 18,6%, whereas that of the natural aggregates was 7,6 %, which was nearly 60 % lower. However, the 20 mm downsized aggregates showed no significant difference in the crushing value. For the natural aggregates, the crushing value was 9,5 %; for the basalt aggregates, this value was 10,2 %. The impact value for the 10 mm downsized sample showed similar trends to those of the crushing value. The impact value of the 10 mm downsized natural aggregates was 5,7%, while that of the basalt aggregates was 11,3 %. For the 20 mm downsized sample, the impact value of the basalt aggregates was 8,6 %, and that of the natural aggregates was 6,8 %. Impact and crushing tests were also conducted. These aggregates exhibited negligible deformation when subjected to loads, thereby augmenting the structural stability of concrete. High impact values generally indicate that aggregates are less durable and more prone to fragmentation under repeated and dynamic stresses. The long-term robustness of concrete constructions can be compromised by this property. When subjected to impact loads, the structural integrity of concrete with high impact value aggregates may deteriorate, thereby reducing both performance and safety. Additionally, these aggregates exhibit less resistance to climatic elements, including thermal stresses and freeze–thaw cycles, which could hasten the eventual disintegration of concrete over time.

The fresh properties of HRC containing basalt aggregates and supplementary materials were found to be suitable for practical applications. In this study, the fresh performance of HRC was adjusted using varying binder contents of 500, 450, and 420 kg/m^3, combined with basalt sand and coarse aggregates. The hardened densities of these mixes, in decreasing binder order, were measured at 2442, 2435, and 2328 kg/m^3, respectively. Workability, indicated by the retention time, varied between 45 and 53 min, whereas the placement technique remained consistent. Because of its larger paste volume, Mix 1, which had the highest binder content and water-to-cement ratio, probably had the largest slump, measuring between 100 and 130 mm, according to the mix proportions. Mix 2, which had the lowest water–cement ratio and moderate binder concentration, most likely had a smaller slump of 60–100 mm because it was firmer. Because the additional water somewhat compensated for the lower paste content, Mix 3, which had the lowest binder concentration but a slightly higher water-to-cement ratio than Mix 2, most likely displayed a slump in the 70-110 mm range. Overall, the slump values show how the admixture, water, and binder work together.

Table 5. Properties of natural aggregates and basalt aggregates

Sr. No	Properties of aggregates	Natural aggregates (below 10 mm)	Basalt aggregates (below 10 mm)	Natural aggregates (10-20 mm)	Basalt aggregates (10-20 mm)	Reference standard
1	specific gravity	2,74	2,87	2,74	2,86	IS: 2386 (Part III) – 2021 [28]
2	water absorption	0,81	0,80	0,82	0,93	
3	crushing value	7,65 %	18,67 %	9,54 %	10,25 %	IS: 2386 (Part IV) – 2021 [29]
4	impact value	5,79 %	11,35 %	6,88 %	8,65 %	

The addition of a naphtha-based chemical admixture enhanced the flowability and mix consistency, making it well-suited for high-temperature environments. Owing to the inherently higher density of basalt aggregates compared to conventional aggregates, the fresh density of the HRC mixes was also higher, contributing to better compaction and minimising the internal voids that typically worsen under thermal stress.

3.2 Effect of temperature on basalt aggregates

To design strong, long-lasting concrete and asphalt constructions, the influence of temperature on aggregates must be characterised. The longevity and performance of construction materials can be enhanced by mitigating the negative impacts of temperature changes through careful selection of aggregates, consideration of their thermal qualities, and suitable adjustments to the mix design. Similar to other materials, aggregates expand when heated and shrink when cooled. This heat transfer has the potential to cause strain in asphalt or concrete, which can result in deterioration, such as cracking or spalling. The moisture content of the aggregates can also be affected by changes in temperature. In contrast, low temperatures can enhance the moisture absorption if the aggregates are exposed to water. High temperatures have the potential to dry aggregates and reduce their moisture content. The water-to-cement ratio in concrete mixes is influenced by the moisture present in the particles, which in turn affects the strength and longevity of the concrete. High temperatures have the potential to accelerate the cement hydration process, shorten the time until workability, and increase the possibility of premature setting. This calls for modifications to the mix design before mixing, such as the use of retarding admixtures or chilling aggregates. On the other hand, low temperatures have the potential to slow hydration, which could impair the early strength development of concrete and lengthen the setting period. Furthermore, the type of aggregate utilised can affect the thermal conductivity of asphalt or concrete. Aggregates with higher thermal conductivity can dissipate heat more efficiently, thereby mitigating thermal stresses. This is especially crucial for buildings, such as pavements and bridges, that are subject to large temperature fluctuations. Table 6 lists the weight loss of the aggregates after exposure to heat. The initial weights of both the natural and basalt aggregates were 300 g. They were kept in containers in a muffle furnace for 0, 1, 2, 3, and 4 h, and the weight was measured using a weighing balance. The percentage weight loss between the basalt aggregates and the natural aggregates was calculated. Moreover, the reduction in the weight of the basalt aggregates was not significantly higher than that of the natural aggregates. At 105 °C, the natural aggregates exhibited a weight loss of 1,6% from the initial condition, whereas the basalt aggregates showed a loss of 1,9 %.

Similarly, at 350 °C, the weight loss of the natural aggregates was 2,0 %, while that of the basalt aggregates was 2,4 %.

Table 6. Effect of temperature on the weight loss of basalt aggregates (4,75-10 mm)

Temperature	**Duration** (hr)	**Natural aggregates** (gm)	**Basalt aggregate** (gm)	**Weight loss** (%)
105 °C	0	300	300,0	0,0
	1	298	296,0	0,6
	2	297	295,0	0,6
	3	296	294,8	0,4
	4	295	294,2	0,2
350 °C	0	300	300,0	0,0
	1	296	294,0	0,6
	2	295	293,0	0,6
	3	294	292,8	0,4
	4	294	292,6	0,4
700 °C	0	300	300,0	0,0
	1	294	293,0	0,3
	2	293	292,1	0,3
	3	292	291,4	0,2
	4	291	290,4	0,2

At 700 °C, the weight loss of the natural aggregate was 3,0 %, while that for the basalt aggregate was 3,2 %. Table 7 lists the percentage weight loss of the 20 mm downsized aggregates.

Table 7. Effect of temperature on the weight loss of basalt coarse aggregates (10-20 mm)

Temperature	**Duration** (hr)	**Natural aggregates** (gm)	**Basalt aggregate** (gm)	**Weight loss** (%)
105 °C	0	300	300,0	0,00
	1	298	298,0	0,00
	2	297	296,0	0,30
	3	296	295,0	0,30
	4	295	295,0	0,00
350 °C	0	300	300,0	0,00
	1	296	294,8	0,40
	2	295	294,2	0,20
	3	294	294,0	0,00
	4	294	293,8	0,06
700 °C	0	300	300,0	0,00
	1	294	293,5	0,10
	2	293	292,8	0,06
	3	292	292,2	0,06
	4	291	291,1	0,03

The results listed in the above table for the 20 mm aggregates indicate that the weight loss of natural and basalt aggregates at 105 °C was 1,6 %. Similarly, at 350 °C, the weight loss for both natural and basalt aggregates was identical, remaining at 2 % after 4 h of exposure. At 700 °C, the weight loss for both types of aggregates was 3 %. Hence, both natural and basalt aggregates exhibited a similar trend following heat exposure. The weight loss is a measure of the thermal endurance of an aggregate at high temperatures. Significant weight loss indicates deterioration, which may lower the overall durability and efficiency of concrete at extreme temperatures. The physical and chemical alterations that the aggregates undergo in response to heat exposure are reflected in this weight loss. Assessing the appropriateness and long-term durability of aggregates in HRC requires awareness of these alterations. The minerals that constitute basalt are mostly plagioclase, pyroxene, and olivine, which have higher thermal stabilities than those typically found in natural aggregates, such as quartz and feldspar. The minerals in basalt are resistant to melting and shattering at elevated temperatures. Elements found in basalt are less susceptible to expansion, breaking, or deterioration at high temperatures because of their higher melting points and lower thermal expansion coefficients [20].

3.3 Heat effect on compression capacity

Compression strength tests were performed for the cubes after 28 days. As mentioned previously, five exposure conditions were considered. Under all exposure conditions, the concrete with a binding content of 500 kg/m3 exhibited higher strength than the other mixes. The compressive strength data for all exposure conditions with a binder of 500 kg/m^3 are shown in Figure 4. The strength under normal curing conditions was 46 MPa after a 28-day test, whereas a decrease in the strength value was observed for all other curing regimes. With exposure to natural humidity, the strength value was found to be 31,2 MPa. After exposure to heat, the strength increased under low-temperature conditions (105 °C); however, the strength decreased with increasing heat conditions (39,9; 32,5; and 19.9 MPa at 105, 350, and 700 °C). This trend can be attributed to ITZ formation and the acceleration of the cement hydration process at elevated temperatures, causing concrete to rapidly set. The compressive strength is typically reduced because of this rapid hydration, which produces a less homogeneous and denser microstructure.

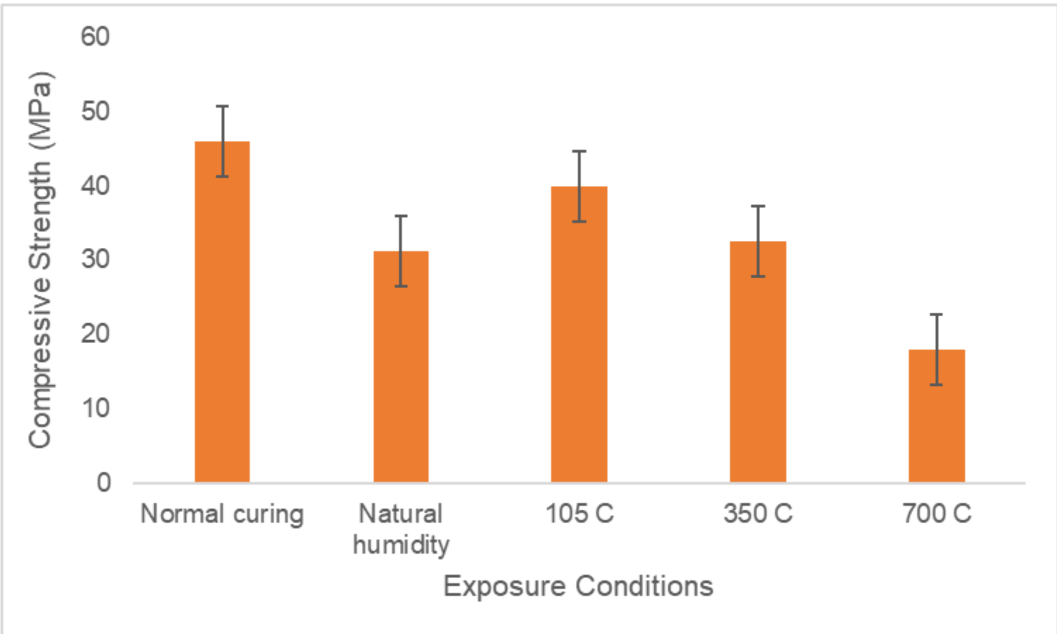


Figure 4. Compressive strength of cubes at all exposure conditions (500 kg/m^3)

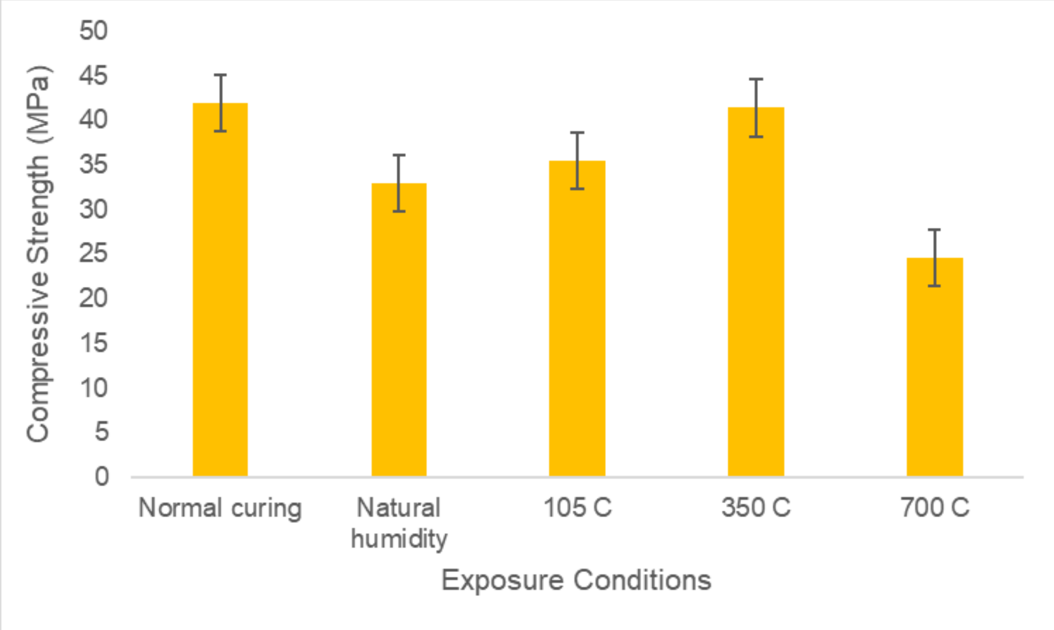


Figure 5. Compressive strength of cubes at all exposure conditions (450 kg/m^3)

Figure 5 shows the compressive strengths of the cube samples subjected to different curing regimes for 28 days with a binder content of 450 kg/m^3. The strength under compressive loading was lower than that of the strength having a binder content of 500 kg/m^3 at normal curing. Overall, the compressive strength value was found to be greater at 350 and 700 °C. However, cubes with a binder content of 500 kg/m^3 outperformed those with a binder content of 450 kg/m^3.

The rate at which moisture evaporates from concrete increases dramatically at high temperatures. A weaker matrix and decreased compressive strength may arise from moisture loss during the curing process, which can prevent the cement particles from fully hydrating. Figure 6 shows the compression values of the concrete cubes with a binder proportion of 420 kg/m^3. The strength under compression under normal conditions was 38 MPa, which was lower than that of the higher binder mixes. The compressive strength under natural humidity conditions was also found to be lower. The mix with a binder content of 420 kg/m^3 exhibited comparable compressive strength values of 39,8 and 39,4 MPa at 105 and 350 °C, respectively. However, the lowest strength was recorded at 700 °C, consistent with the results observed for the other binder contents.

High temperatures have the potential to degrade the C–S–H gel, which is essential for maintaining the strength of concrete. The binding qualities of cement paste are weakened by this breakdown, endangering the building as a whole. High temperatures can also result in the formation of microcracks, which change the pore matrix of the concrete. These alterations weaken the engineering characteristics of concrete, particularly its strength under compressive loading. The water-to-cement ratio frequently needs to be adjusted to preserve workability at higher temperatures. However, erroneous changes may result in either excessive water content, which can impair adequate hydration, or inadequate water content, which can increase porosity and decrease strength.

In contrast, FRC exhibits unique performance characteristics when subjected to elevated temperatures, with outcomes largely influenced by the fibre type, content, and thermal stability. At lower temperatures (up to approximately 200 °C), synthetic fibres such as polypropylene melt, forming microchannels that facilitate the release of steam pressure and reduce the risk of explosive spalling—this phenomenon is well-documented and is considered a key fire-resistance mechanism in FRC [30]. As temperatures rise further (above 400-600 °C), the cement matrix begins to deteriorate owing to the breakdown of the C–S–H matrix and dehydration of hydrated compounds, weakening the overall matrix [31]. Although steel fibres may maintain structural integrity, oxidation and degradation at the steel–concrete interface reduce their efficiency at very high temperatures. Nevertheless, the inclusion of thermally stable fibres enhances the thermal shock resistance, crack control, and residual strength of FRC under fire exposure. The hybrid use of fibres, such as combining polypropylene with steel, has also shown synergistic effects in improving both fire resistance and post-heating mechanical performance [32]. Thus, strategic fibre selection and optimised fibre dosage are crucial for improving the thermal resilience of FRC in fire-prone applications.

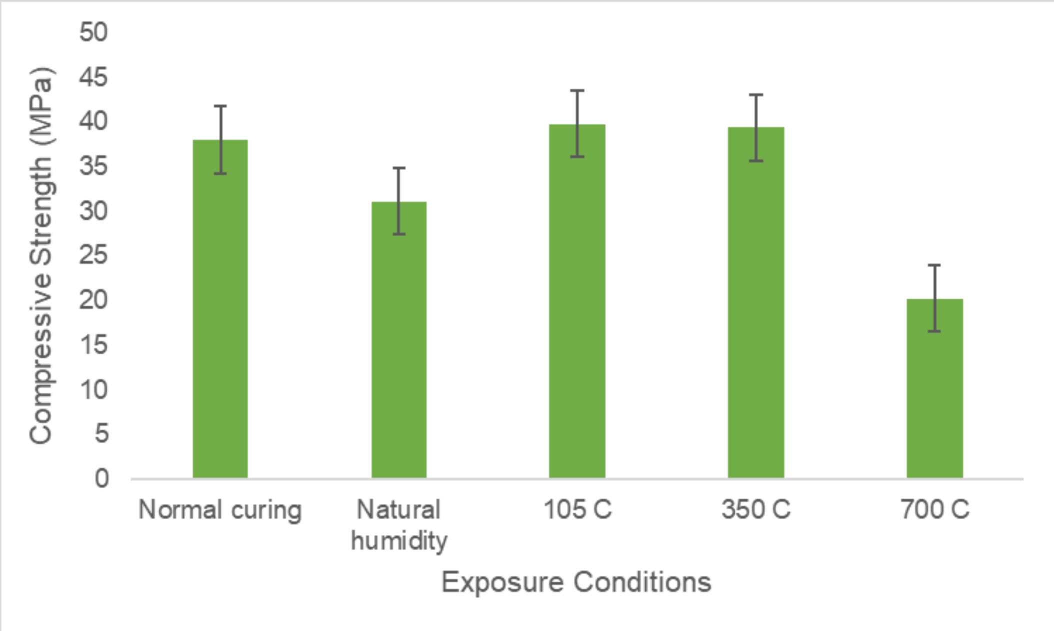


Figure 6. Compressive strength of cubes at all exposure conditions (420 kg/m^3)

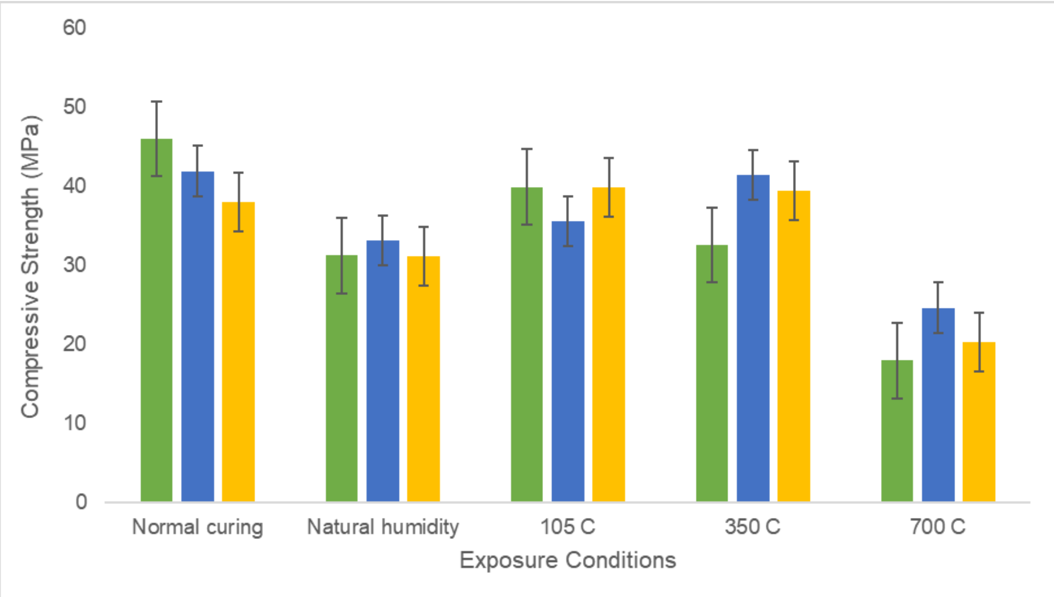


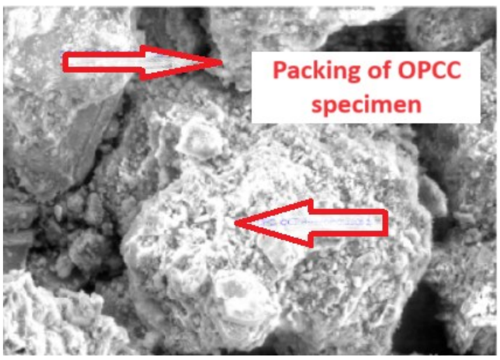
Figure 7. Compressive strength of cubes at all exposure conditions (all mixes)

Figure 7 lists all the curing regimes and the respective compressive strength values for varying binder parameters. The reduced compressive strength of concrete is caused by a lower binder content, particularly when subjected to high temperatures. This is because the hydration process that creates the binding matrix in concrete depends on the type of binder, which is typically cement. The production of C–S–H gel, essential for maintaining the strength of concrete, was reduced with the use of a lower binder content. A small amount of binder exacerbates the problem when heated to high temperatures because it accelerates the hydration process, resulting in a weaker and less homogeneous matrix. A further reduction in the compressive strength is attributed to the lower binder concentration, which leaves less material to compensate for microcracks and thermal stresses that occur at high temperatures.

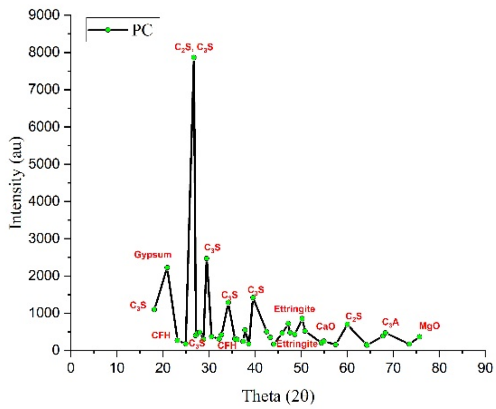
4 SEM and XRD

Microstructural investigations using scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis revealed that the OPC concrete underwent significant degradation when exposed to elevated temperatures. The XRD patterns of the control specimens showed dominant phases such as portlandite, calcite, quartz, C–S–H, and residual clinker minerals. When phase-change aggregates are incorporated, new crystalline phases such as mullite, gypsum, and ettringite emerge, indicating chemical interactions that can compromise the encapsulation layer and lead to the formation of expansive hydration products. SEM analysis illustrated the development of a porous interfacial transition zone (ITZ) characterised by needle-shaped ettringite and petal-like AFm phases, which contribute to increased porosity and microcracking. In contrast, mixes containing FA demonstrated a denser ITZ owing to the generation of additional C–A–S–H gel through its pozzolanic reaction with portlandite, thereby enhancing matrix cohesion and minimising C–S–H gel degradation under heat. Further observations confirmed that elevated temperatures significantly altered the microstructure of OPCC. XRD analyses indicated progressive transformation of key phases, such as the decomposition of C–S–H above 400 °C, portlandite dehydroxylation into CaO, and calcite decarbonation at temperatures exceeding 600-800 °C. The SEM images supported these findings, revealing increased porosity and extensive cracking, particularly within the ITZ, owing to thermal mismatch and vapour pressure effects [33; 34].

In concrete containing basalt aggregates, the microstructure initially appeared dense and well-formed, with the C–S–H gel predominating. As the temperature increased, the thermal strain led to visible cracking. The inclusion of slag enhanced resistance by reducing the $Ca(OH)_2$ levels and refining the pore structure. Microcracking became prominent from 350 °C onwards, accompanied by partial dehydration of C–S–H and the breakdown of hydration products. At 700 °C, the material exhibited widespread disintegration due to the collapse of binding phases and elevated porosity.



(a)



(b)

Figure 8. Microstructure of HRC with a binder content of 420 kg/m³: a) SEM of HRC after 28 days of curing; b) XRD of HRC after 28 days of curing

A few studies have been conducted at higher temperatures with different materials using basalt aggregates, which are listed in Table 8.

Table 8. Effect of various supplementary materials on elevated temperatures using basalt aggregate

Temperature	Microstructural changes	Effect of basalt aggregate	Effect of supplementary materials (metakaolin, boron carbide, silica fume)	References
20-150 °C	Minimal microcracks; intact C-S-H structure	Maintains dense ITZ and good aggregate–matrix bond	Refines pore structure; enhances gel compaction; delays microcrack initiation	[35-38]
300 °C	Slight microcracking; start of C-S-H gel shrinkage	Good resistance to thermal stress, minimal damage	Improves gel stability; SEM shows denser matrix with fewer voids	
500 °C	Increased cracking, C-S-H degradation, and widening of pores	Basalt resists expansion, limiting aggregate-paste debonding	Metakaolin and boron carbide limit C-S-H breakdown, reduce porosity, and crack width	
800 °C	Severe C-S-H breakdown, major microcracking and porosity	Basalt is still intact, better than magnetite or quartz	Additives reduce the extent of spalling; preserve internal cohesion to some extent	

In pure OPC concrete, the C–S–H phases formed from the hydration of C_2S and C_3S dominated the initial microstructure. Exposure to high temperatures transformed these dense gel structures into loose networks containing fissures and crystalline residues. This degradation was attributed to the breakdown of hydration products and thermal expansion of unhydrated clinker particles, which induced localised stress and promoted microcrack formation. The decomposition of portlandite into CaO during heating further weakened the matrix, particularly during cooling cycles, where moisture exposure can intensify the damage [39-40].

5 Conclusions

Concrete produced with basalt aggregate was exposed to fire at 105, 350 and 700 °C. Furthermore, the concrete produced using natural aggregates was exposed to the same fire pattern and was checked for compression. The following conclusions were drawn from this study:

- The specific gravity of both the 10 and 20 mm downsized basalt aggregates was nearly 4,1 % higher than that of the aggregates procured from natural resources. The water absorption of the 10 mm downsized aggregates was similar for both types of aggregates; however, for the 20 mm downsized aggregates, the water absorption of basalt aggregates was 3,7 % greater than that of natural aggregates. The impact and crushing strength values of both natural and basalt aggregates were almost identical, suggesting that basalt aggregates can replace natural aggregates.
- The percentage of weight loss was nearly the same for all mixes of both natural and basalt aggregates.
- The graphs show that under normal conditions, the compressive strengths were the highest, measuring 46,0; 41,9; and 38,0 MPa for the 500, 450, and 420 kg/m³ mixes, respectively. When subjected to natural humidity, a significant reduction in strength was

observed: that of the 500 kg/m^3 mix dropped by approximately 32,2 %, that of the 450 kg/m^3 mix by 25,6 %, and that of the 420 kg/m^3 mix by 18,2 %. In particular, at 105 °C, the strength recovered compared to the natural humidity condition. The strength of the 500 kg/m^3 mix increased by 27,9 %, that of the 450 kg/m^3 by 7,2 %, and that of the 420 kg/m^3 by 28 %, indicating potential continued hydration or internal curing effects at this temperature.

- At 350 °C, the compressive strength exhibited a mixed trend. The 500 kg/m^3 mix experienced a 29,3 % drop from its normal strength, whereas the 450 kg/m^3 mix exhibited a minimal decrease of 1,2 %. Notably, the 420 kg/m^3 mix exhibited a slight increase in strength of 3,2% compared to that under normal conditions, suggesting that lower binder content may better withstand moderate thermal exposure due to possible densification or pozzolanic activity.
- However, at 700 °C, all mixes suffered significant strength degradation. The strength of the 500 kg/m^3 mix dropped drastically by 61,1%, while the strengths of the 450 kg/m^3 and 420 kg/m^3 mixes decreased by 41,3 % and 46,8 %, respectively. These results indicated that at elevated temperatures beyond 350 °C, the thermal degradation of binder phases and microstructural damage become dominant, overshadowing any benefits of higher binder content. Notably, the mixes with 450 and 420 kg/m^3 binder content performed better than the 500 kg/m^3 mix at 700 °C, suggesting that optimal binder content and thermal compatibility may offer better resistance to high-temperature exposure.
- The occurrence of surface cracks was unrelated to the strength performance. When concrete was exposed to heat, the outer layers heated rapidly and expanded, while the inner layers remained cooler. This temperature gradient generated considerable thermal stress, resulting in the formation of surface cracks.
- For industrial applications requiring fire resistance, a binding content of 450 kg/m^3 was identified as the optimal mix for resisting heat up to 700 °C.
- Hence, from the above observations, it is concluded that basalt aggregates can replace natural aggregates when exposed to high-temperature conditions.

A more thorough investigation is required in several areas, including mechanical characteristics, durability, and microstructural behaviour, to prove that basalt aggregates are a competitive substitute for traditional natural aggregates. To verify the potential of aggregates as sustainable building materials, in-depth research into their internal interfaces, ITZ, and molecular-level interactions is required. To improve the performance and environmental sustainability, future research should also examine substitute aggregates that can withstand high temperatures, such as recycled materials and industrial wastes.

Evaluating the long-term behaviour of HRC in practical service settings is an important avenue for future research. This includes assessing the reaction of the material to actual fire exposure, spalling threats, and cyclic thermal stress. The long-term performance and dependability can be predicted using heat cycle simulations and accelerated ageing tests. Although the current research indicates encouraging mechanical strength retention up to 700 °C, further research is required to fully comprehend durability concerns. Future research should also use thorough XRD and SEM analyses to track peak shifts, new phases, and decompositions to better understand mineralogical changes under normal and enhanced curing settings (105, 350, and 700 °C) in HRC. Thermogravimetric analysis for every curing regime will also aid in quantifying the mass loss and thermal stability, confirming the microstructural results, and improving our understanding of durability and thermal resistance.

Furthermore, opportunities exist to further improve thermal performance and reduce environmental impact by incorporating additional cementitious materials such as fly ash, GGBFS, or recycled concrete aggregates. These substitutes may also improve the resource efficiency and thermal compatibility.

Optimising the ITZ, assessing the stability of minerals and molecules under extended heat stress, and conducting accelerated degradation studies should be the top priorities for future studies. Additionally, exploring improvements in microstructural integrity through the inclusion of microfibres could enhance overall thermal stability and offer higher resistance to cracking. Future advancements may expand the application and effectiveness of HRC in hot climates by focusing on key aspects such as enhancing material sustainability and longevity.

Abbreviations

ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
$Ca(OH)_2$	Calcium hydroxide
C–S–H	Calcium Silicate Hydrate
FRC	Fibre-Reinforced Concrete
FA	Fly ash
GGBFS	Ground Granulated Blast Furnace Slag
HRC	Heat-resistant concrete
HSC	High-strength concrete
IS	Indian Standard
ITZ	Interface transition zone
MK	Metakaolin
OPC	Ordinary Portland Cement
RCAs	Recycled Coarse Aggregates
SEM	Scanning Electron Microscopy
SF	Silica Fume (SF)
XRD	X-Ray Diffraction

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