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PERFORMANCE OF RECYCLED BRICK AGGREGATE CONCRETE (RBAC) CONTAINING HOOKED-END STEEL FIBERS AT ELEVATED TEMPERATURES

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Abstract: In response to the depleting natural stone reserves resulting from their extensive use as concrete aggregates, this research investigates the viability of integrating recycled brick aggregate (RBA) as a substitute for 50% of conventionally employed natural stone aggregates. Hooked-end steel fibers are added to it by 1% steel fibers. A comparative analysis is conducted against two reference concrete mixes comprising 100% natural aggregates (NA); and 50% each of RBA and NA. Workability assessments are performed using the slump test as per IS: 1199-1959 in the fresh state, while the mechanical properties, including compressive and split-tensile strength, are evaluated both at ambient conditions and under elevated temperatures up to 800 °C. The study reveals that recycled brick aggregate concrete (RBAC) exhibits significantly inferior properties when compared to natural aggregate concrete (NAC). However, its properties are improved significantly when hooked-end steel fibers are incorporated. These findings provide valuable insights into the sustainable use of recycled brick aggregates in concrete, offering a nuanced perspective on their performance across a range of temperature conditions, while addressing the pressing issue of depleting natural stone reserves in construction.

***Index Terms* - Recycled brick aggregate (RBA); recycled aggregate (RA); elevated temperature; waste; sustainable concrete development; steel fibers.**

I. INTRODUCTION

The utilization of concrete as a construction material is ubiquitous on a global scale, primarily attributable to its exceptional structural strength [1]. The concrete industry sustains an annual consumption rate that approaches a staggering 9 billion tons of rock and sand. Alarmingly, if this trend persists, it is projected that the annual demand for these vital resources will double, reaching an unprecedented 18 billion tons by the year 2050 [2]. However, this substantial consumption of natural aggregates has detrimental environmental implications, exacerbating the production of construction waste, thereby underscoring the urgent need for sustainable practices in construction. Recycling construction waste, particularly in the form of recycled aggregate (RA), has garnered sustained interest over several decades [3].

Nevertheless, the integration of recycled aggregates into concrete is challenged by their inherent deficiencies, including notably low compressive and tensile strength properties [4–7]. Consequently, the dosage of recycled aggregates in concrete mixtures is generally limited to approximately 25-35%, with further reductions enforced in structural applications [8]. The underperformance of recycled aggregate concrete can be attributed to the presence of aged mortar remnants adhering to the aggregates. These remnants, often porous and riddled with microcracks, negatively impact the concrete's overall properties [9,10]. Moreover, the crushing process during aggregate production accumulates internal damages within the recycled aggregates, further influencing the concrete's properties [11,12].

However, some promising studies suggest that the unhydrated portions of old mortar continue to undergo hydration and exert a beneficial influence [13,14]. The hydration of these previously unreacted mortar fractions not only fosters a stronger bond between the aggregate and old mortar but also effectively fills microcracks, thereby enhancing the overall properties of the concrete [12,15,16].

Steel fiber-reinforced concrete is a commonly employed construction material [17]. Structures constructed using concrete containing fibers benefit from increased ductility, which reduces the likelihood of crack formation [18]. These steel fibers serve a passive confinement role, enhancing the concrete's bond strength and hardness. Typically, damage becomes apparent in the form of spalling or cracking at the peripheries of concrete elements due to the inherent brittleness of the material [19]. The addition of steel fibers to concrete results in the enhancement of its mechanical properties [20].

Introduction to fire poses a significant challenge to the safety and integrity of concrete structures [21]. Concrete's mechanical properties experience severe degradation when exposed to elevated temperatures, necessitating a comprehensive examination of its behavior under thermal loading conditions [22]. A substantial loss in residual mechanical strength becomes evident when concrete is subjected to temperatures of up to 800 °C within the first hour of exposure [23,24]. While previous research efforts have concentrated on evaluating the performance of recycled aggregate concrete in various contexts, a detailed assessment of concrete made from recycled brick aggregates under elevated temperature conditions remain conspicuously underexplored.

Therefore, this present study seeks to address this gap in knowledge by comprehensively investigating the properties of recycled brick aggregate concrete containing hooked-end steel fibers when subjected to both ambient and elevated temperatures. In doing so, it aims to contribute valuable insights into the feasibility and performance of recycled brick aggregate concrete in high-temperature environments, advancing our understanding of its potential applicability in sustainable construction practices.

II. MATERIALS

The concrete preparation involved the use of various materials, which include ordinary Portland cement (OPC) of 43 grade, natural coarse aggregates, recycled brick aggregate (RBA), natural river sand as the fine aggregate, hooked-end steel fibers, and water. The hooked-end steel fibers employed in the mixture have dimensions of 0.75 mm in diameter and 60 mm in length. A visual representation of the RBA and steel fiber can be observed in Figure 1. Detailed properties of both fine and coarse aggregates are provided in Table 1, while the specific quantities of these constituents are outlined in Table 2.

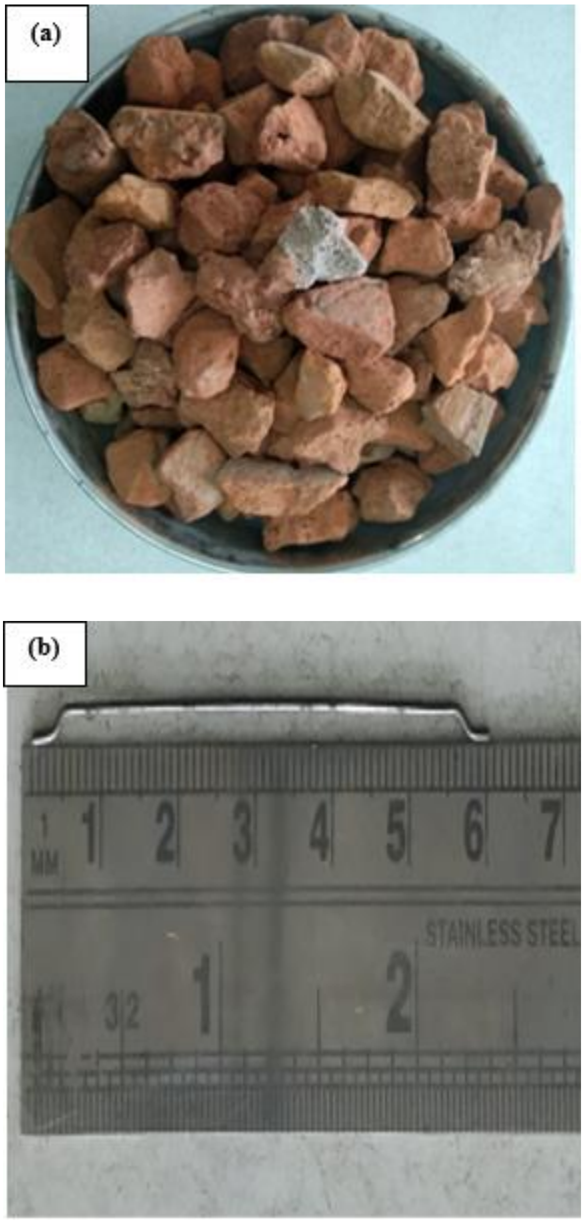


Figure 1 (a) RBA, and (b) hooked-end steel fiber

Table 1 Properties of fine and coarse aggregates

Properties	Fine aggregate	Coarse aggregates	
		NA	RBA
Fineness modulus	3.456	-	-
Silt content	1.3%	-	-
Specific gravity	2.627	2.72	1.78
Water absorption	-	0.5%	14.62%

Table 2 Concrete mix details

Mix	Cement (kg/m^3)	Sand (kg/m^3)	NA (kg/m^3)	RBA (kg/m^3)	Water (kg/m^3)	Steel Fibers (kg/m^3)	W/Cm ratio
NA100	450	627	1026	0	192	0	0.426
RB50-F0	450	627	513	513	192	0	0.426
RB50-F1	450	627	513	513	192	78.5	0.426

NA100= 100% natural aggregate; RB50= 50% recycled brick aggregate; F0= 0% steel fibers; F1= 1% steel fibers; and W/Cm= water to cementitious materials ratio.

III. CONCRETE MIX DETAILS

The quantities of each constituent material were determined through adherence to the mix design procedure outlined in IS 10262: 2019 [25]. This study focuses on evaluating the properties of M30 grade concrete mixes, which comprise 50% recycled brick aggregate (RBA) and 50% natural aggregate (NA), along with an additional 1% inclusion of hooked-end steel fibers based on the concrete's volume. These assessments are conducted under elevated temperature conditions. Additionally, two reference mixes are prepared for comparative purposes: the first reference mix exclusively contains 100% NA, while the second reference mix is composed of an equal 50% combination of RBA and NA. The differences in the mechanical properties among these mixtures are examined and discussed in detail.

IV. METHODS

The study encompasses an examination of workability and mechanical properties, including compressive and split-tensile strength, following 7 and 28 days of the curing period. Workability assessment of each concrete mix in its fresh state is conducted using the slump test, in accordance with the specifications outlined in IS: 1199-1959 [26]. Compressive strength testing involves the creation of cubical specimens measuring 150 mm in size, and the tests are executed following the guidelines stipulated in IS 516:1959 [27]. For split-tensile strength evaluation, cylindrical specimens with dimensions of 150 mm in diameter and 300 mm in length are cast and subsequently tested, adhering to the procedure detailed in IS 5816:1999 [28].

In total, 30 specimens are prepared for each concrete mix to investigate a single mechanical property. These specimens are exposed to a range of temperatures, namely 20, 200, 400, 600, and 800 °C, prior to testing. The assessment of mechanical properties is carried out subsequent to the natural cooling of the heated specimens through air exposure.

V. RESULTS AND DISCUSSIONS

This section presents the outcomes derived from a series of tests conducted on the distinct concrete mixtures. Furthermore, the potential factors contributing to the observed results are thoroughly examined and discussed.

Workability

The results of the slump test are depicted in Figure 2. It is noteworthy that the concrete mix denoted as RB50-F1 exhibited the lowest slump value, indicative of reduced workability, while conversely, the NA100 mix displayed the highest level of workability, characterized by a slump value of 78 mm. The slump value of the RB50-F0 mix falls between the values obtained for RB50-F1 and NA100. The diminished workability observed in the mixes incorporating recycled brick aggregate (RBA) can be attributed to the inherently porous internal structure of RBA, stemming from the presence of a substantial quantity of aged cement mortar. This property leads to heightened water absorption from the concrete mix, resulting in a lower slump value. Furthermore, the inclusion of hooked-end steel fibers in the RB50-F1 mixture further diminishes the slump value due to interlocking between and increased cohesion fibers, a phenomenon consistent with the findings reported by Yu et al. [29].

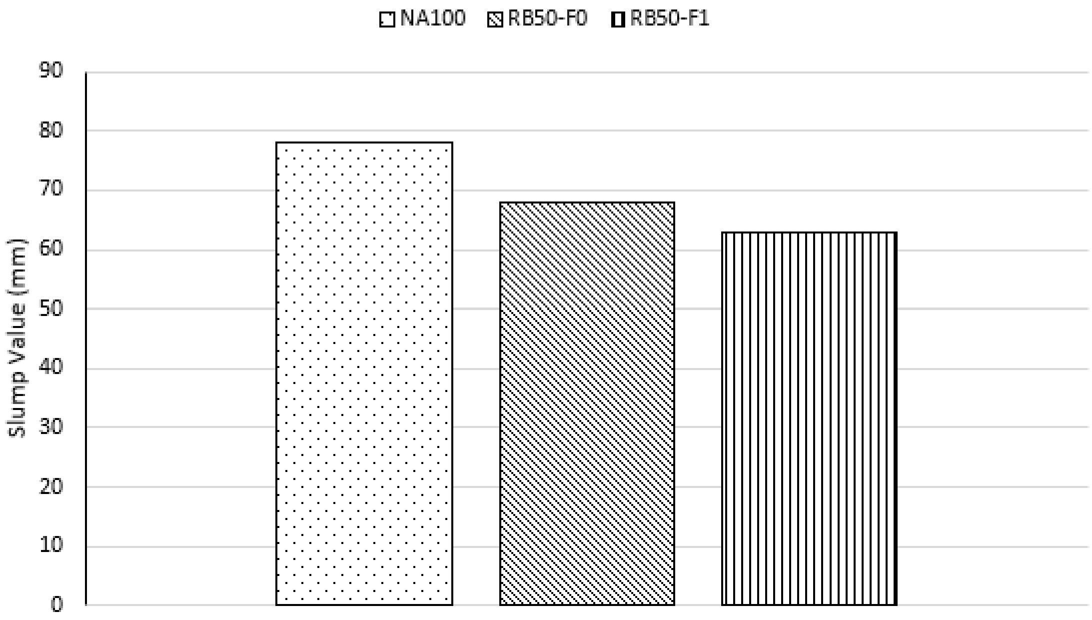


Figure 2 Slump test results

Compressive strength

The results of compressive strength testing are graphically represented in Figure 3, and a detailed presentation of the test outcomes is provided in Figure 4. The percentage reduction in strength is illustrated in Figure 5.

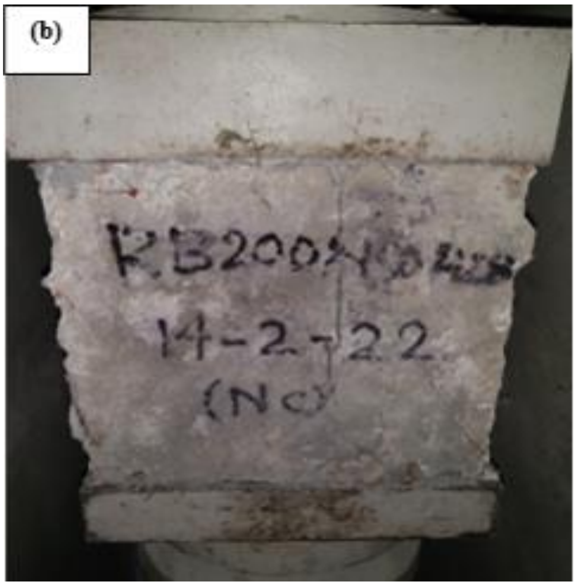
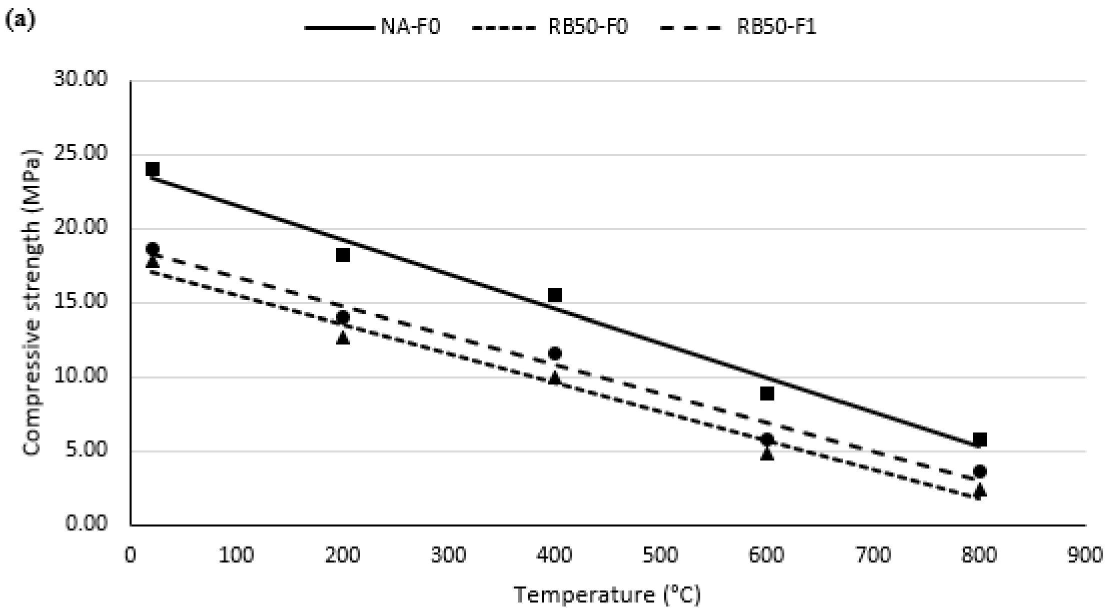


Figure 3 compressive strength test- (a) specimen heated in furnace, and (b) specimen under compression test



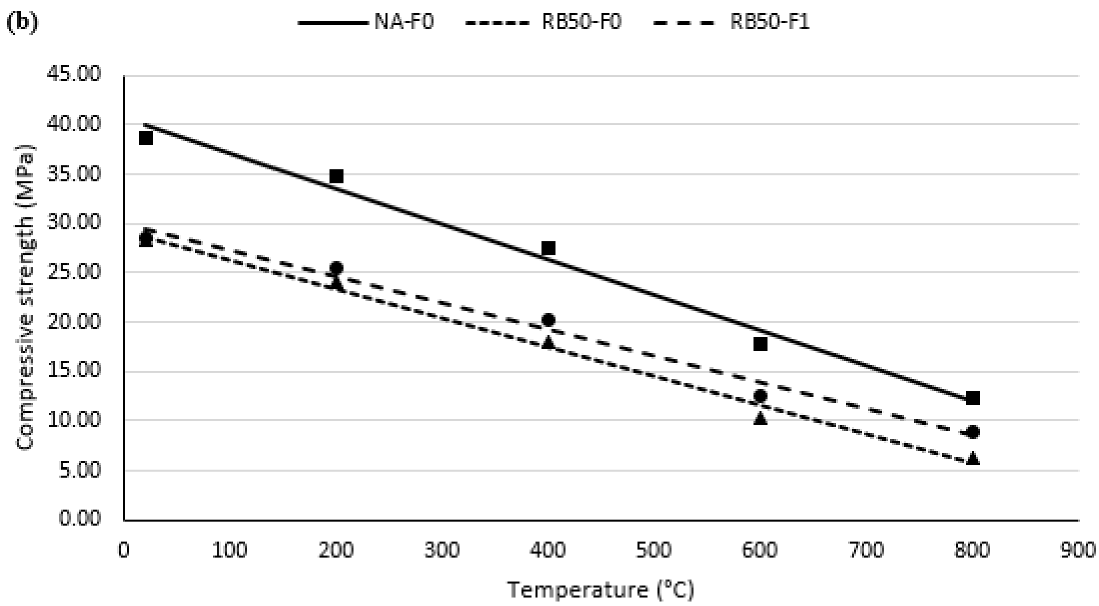


Figure 4 Compressive strength test results at- (a) 7 days, & (b) 28 days

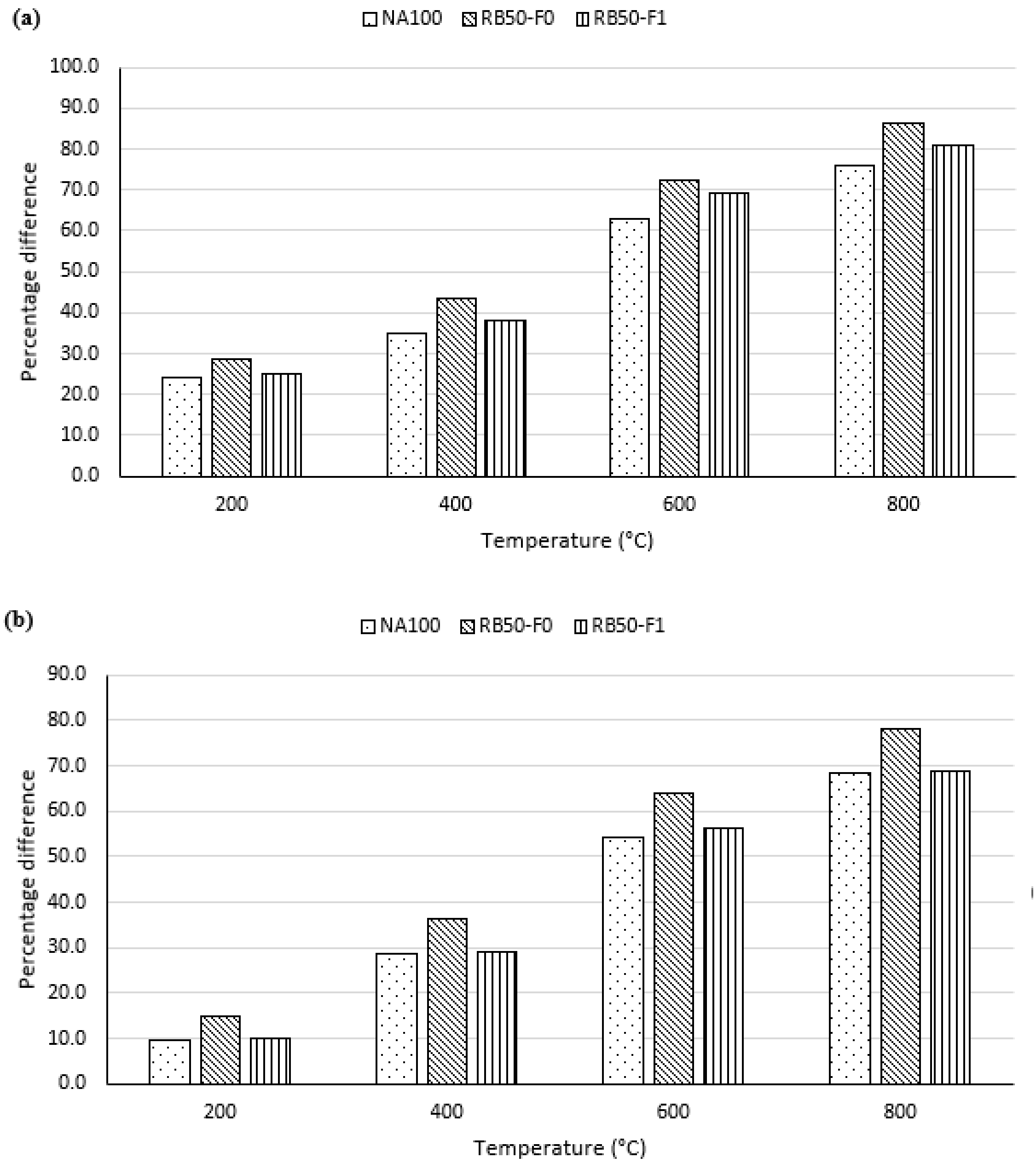


Figure 5 Percentage decrease in compressive strength at- (a) 7 days, & (b) 28 days

It is evident that the compressive strength of each concrete mixture diminishes with increasing temperature. Across all curing durations, the RB50-F0 mixture consistently exhibits lower compressive strength in comparison to the other mixtures. Specifically, the compressive strength of the RB50-F1 mixture surpasses that of RB50-F0 but remains inferior to that of NA-F0 at both curing durations. This can be attributed to the presence of porous old cement mortar within the recycled brick aggregate (RBA), which contributes to the reduced compressive strength observed in the RB50-F0 and RB50-F1 mixtures. Similar findings were reported by Guo et al. [4]. However, the inclusion of hooked-end steel fibers in the RB50-F1 mixture enhances the bond between mortar and aggregate, a phenomenon consistent with the observations made in the study conducted by Guo et al. [30]. Additionally, the fibers resist the propagation of cracks that may already exist within the RBA or have developed due to thermal stresses. The favorable impact of incorporating hooked-end steel fibers is evident in the compressive strength values of the mixtures with and without fibers. Notably, the RB50-F1 mix exhibits a higher compressive strength than the RB50-F0 mix.

Furthermore, it is important to note that the percentage decrease in compressive strength values is more pronounced at 7 days in comparison to 28 days. Up to 28 days, most of the hydration reactions have reached completion, resulting in a denser internal structure of concrete due to the presence of a greater volume of hydration products. Consequently, the influence of temperature on compressive strength is less pronounced at 28 days when contrasted with the effects observed at 7 days.

Split-tensile strength

The results of the split-tensile strength test are graphically represented in Figure 6, and the variation of split-tensile strength with temperature, as well as the percentage decrease in its value at different temperatures, are depicted in Figures 7 and 8, respectively.

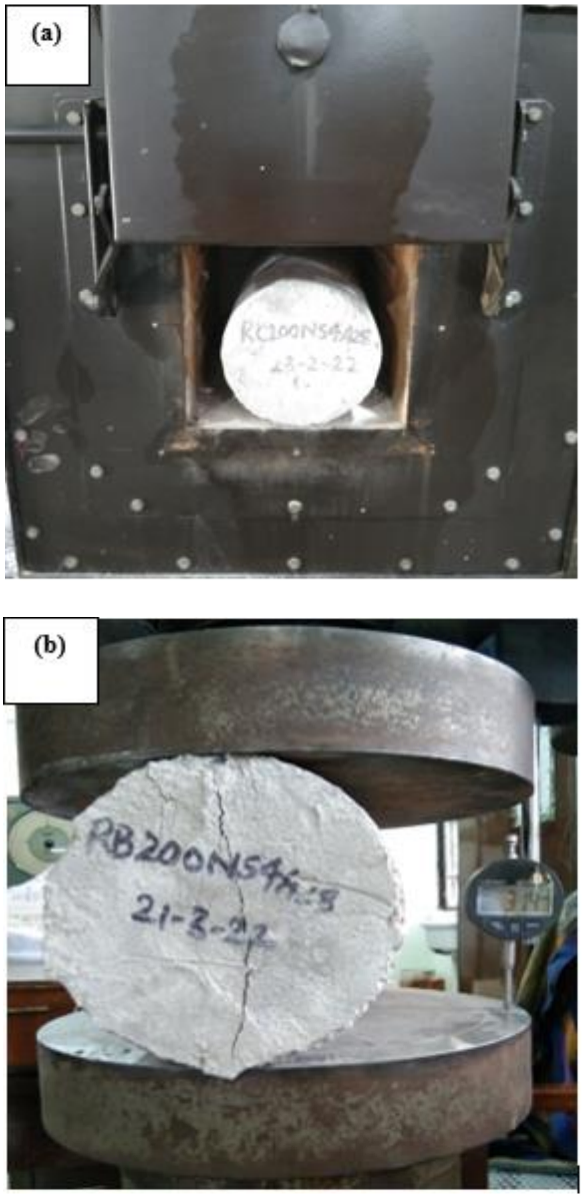
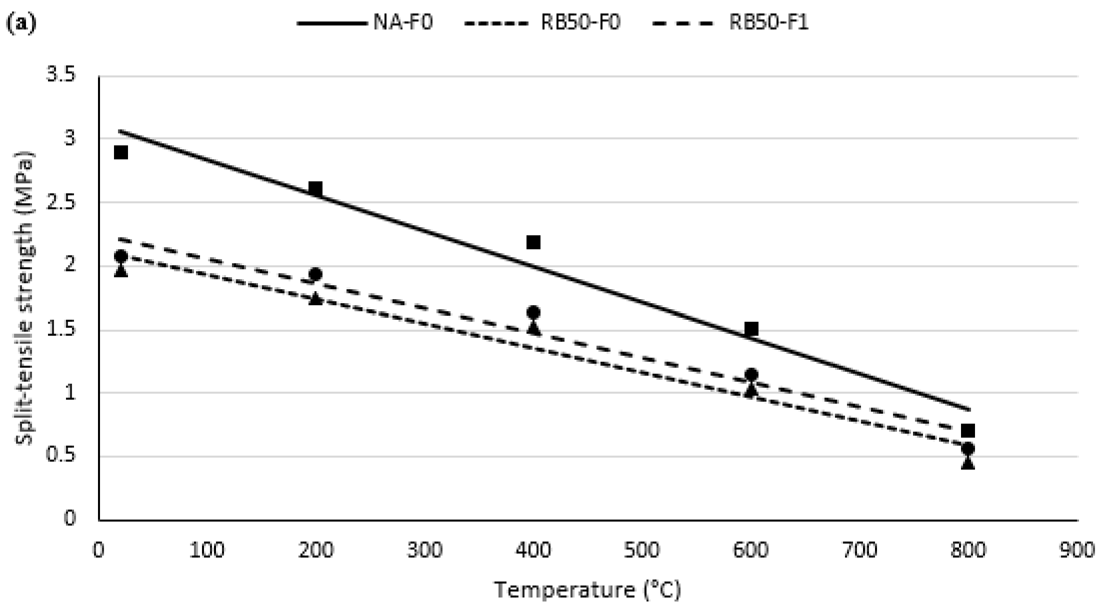


Figure 6 Split-tensile strength test- (a) specimen in furnace, and (b) specimen under test



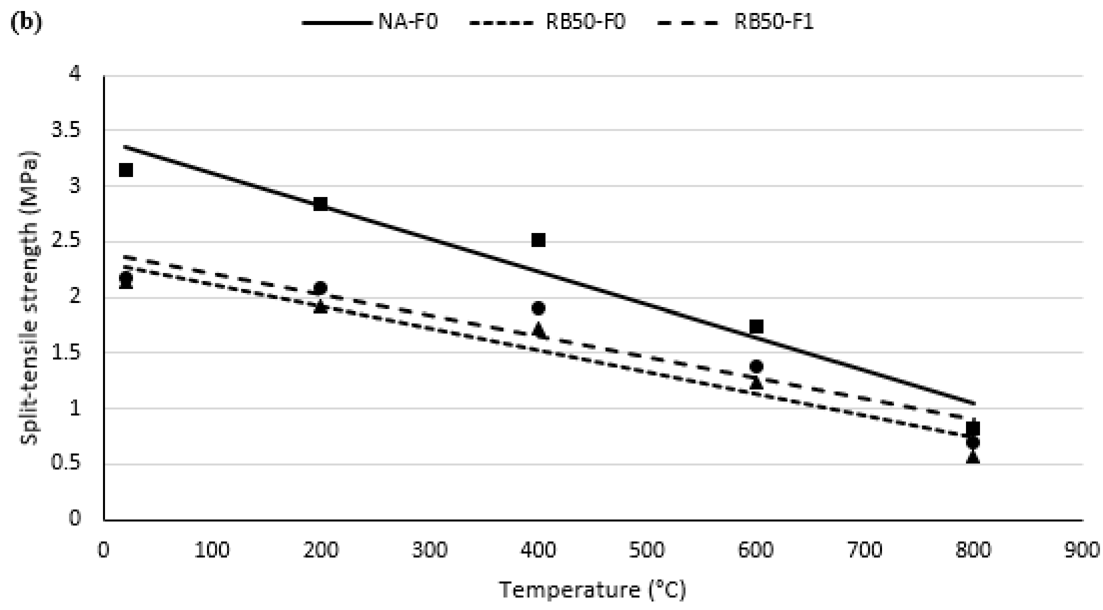
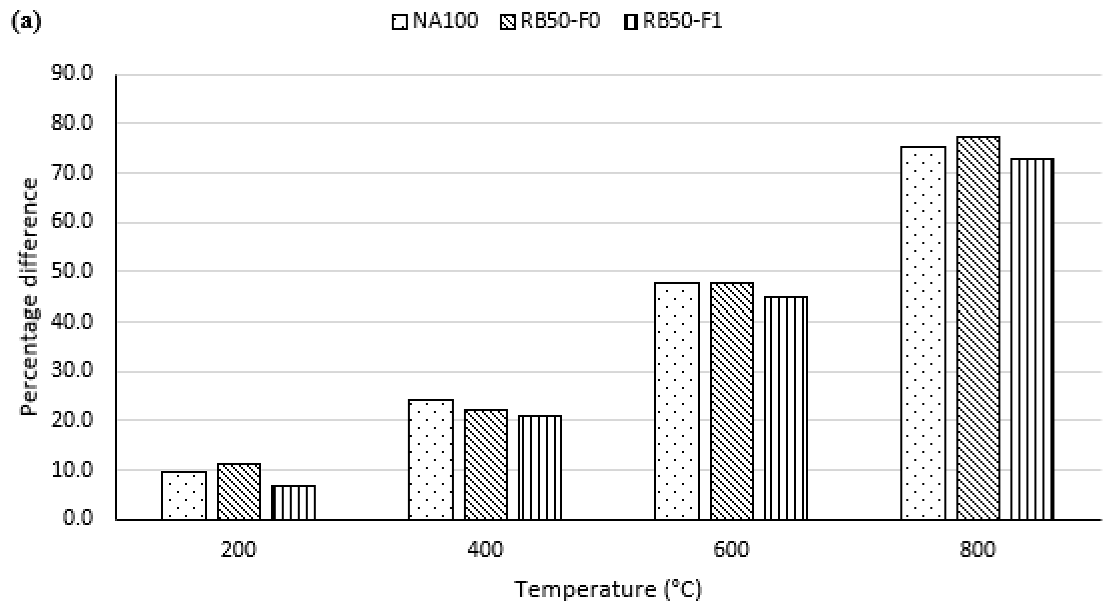


Figure 7 Split-tensile strength test results at- (a) 7 days, & (b) 28 days



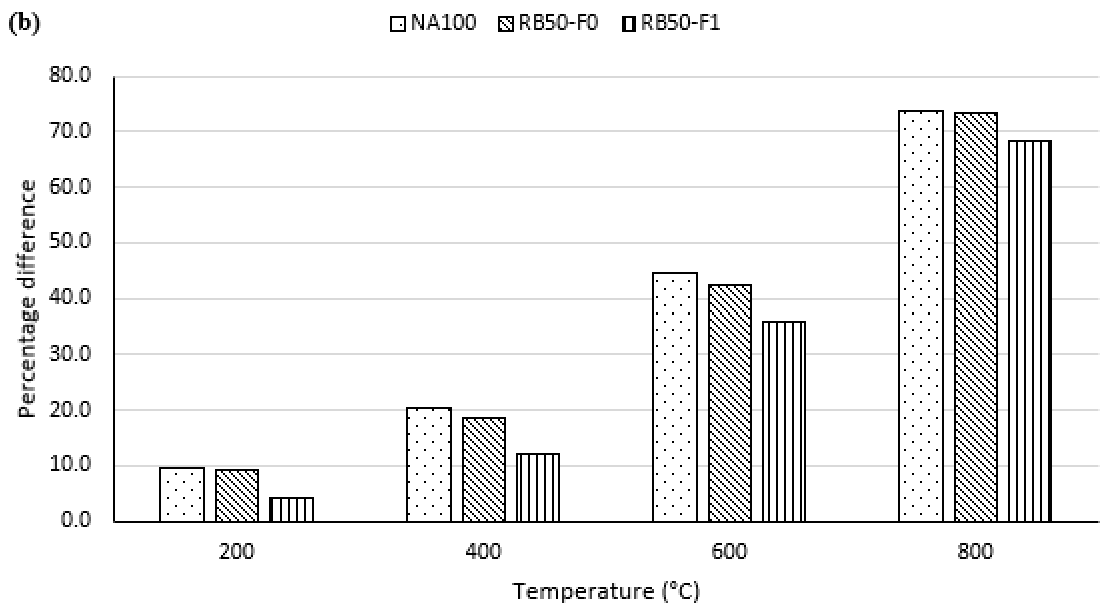


Figure 8 Percentage decrease in split-tensile strength at- (a) 7 days, & (b) 28 days

Analogous to the compressive strength, a similar pattern is observed in the behavior of split-tensile strength with increasing temperature. As the exposure temperature rises, there is a continuous reduction in split-tensile strength.

Remarkably, the split-tensile strength of RB50-F1 significantly surpasses that of RB50-F0, primarily attributable to the crack-bridging effect facilitated by the inclusion of hooked-end steel fibers. This phenomenon aligns with prior research findings [31,32]. The elevation in temperature induces water evaporation, thereby generating new pores in addition to those pre-existing within the concrete structure. Given the sensitivity of split-tensile strength to pore content, a substantial reduction is observed at each exposure temperature [33].

Similar to compressive strength, the decline in split-tensile strength is more pronounced at 7 days in comparison to 28 days, owing to the continued development of hydration products over the 28-day curing period. Furthermore, the decrement in split-tensile strength is more accentuated at higher temperatures. Up to 200 °C, the decrease is relatively modest, primarily attributed to water evaporation being the dominant cause behind the deterioration in the internal structure of concrete. However, around 400 °C, the decomposition of calcium hydroxide (CH) and calcium silicate hydrate (C-S-H) gel commences [34]. The reduction in strength is consequently influenced by both factors, resulting in a more rapid decrease in split-tensile strength values.

VI. CONCLUSIONS

- The introduction of recycled materials and steel fibers exerts a detrimental impact on the workability of concrete. RB50-F0 exhibits a lower slump value than NA100, primarily attributed to the elevated water absorption capacity of recycled brick aggregate (RBA). Remarkably, RB50-F1 records the lowest slump value among all the concrete mixtures, attributable to the enhanced interlocking and cohesion facilitated by the presence of steel fibers.
- Compressive strength experiences a consistent decline in each concrete mixture with increasing temperature. This reduction is attributed to water loss through evaporation and the decomposition of hydration products. The compressive strength of the RB50-F1 mixture falls between that of RB50-F0 and NA100. The inclusion of hooked-end steel fibers in RB50-F1 mitigates crack propagation, contributing to its intermediate strength. Notably, the decline in strength is more pronounced at 7 days in comparison to 28 days, primarily due to the nearing completion of cement hydration reactions over the 28-day curing period.
- The trend in split-tensile strength closely mirrors that of compressive strength across the varying temperature range. Elevated temperatures induce the formation of pores within the concrete matrix, consequently diminishing split-tensile strength. The reduction in strength becomes more rapid at temperatures exceeding 400 °C, driven by the simultaneous decomposition of hydration products and water evaporation.

In summary, the introduction of hooked-end steel fibers into recycled brick aggregate concrete (RBAC) substantially enhances its performance at both ambient and elevated temperatures. However, it is important to acknowledge that the attained strength levels still do not match those of natural aggregate concrete (NAC). Therefore, further modifications are essential to bridge the gap in mechanical properties between RBAC and NAC.

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