Fiber-reinforced concrete in high-temperature environments: In-depth survey on mechanical performance and rheological features

Satendra Singh | Raman Batra | Beemkumar Nagappan | Deeksha Choudhary

Abstract The successful automatic performance of fiber-reinforced concrete (FRC) has led to its widespread application; adding fibers affects its novel properties. It is anticipated that concrete's long-term qualities will be impacted by its workability. A comprehensive assessment of the mechanical performance and rheological properties of FRC is given in this study. It presents more detail on how the FRC behaves in searching temperatures and provides an analysis of several heating as well as cooling methods along with the way they affect test outcomes. The study explores how reinforcing fibers, aggregates and substitute materials affect FRC's fire resistance. In particular, the concept of workability, which is a crucial quality in concrete, is studied and rheological models that make use of several rheometers are developed to clarify the rheological behavior of FRC. Several techniques to improve rheological functionality and performance are revealed in this study. The findings highlight the conflicting characteristics of fibers that can enhance the mechanical aspects of cement while reducing its fresh and rheological qualities. A comparable set of benefits and drawbacks complement FRC's fluidity. The research examines feasible approaches to regulate the rheological characteristics of FRC, thereby simplifying and improving the mechanical performance and workability of FRC.

Keywords: reinforcing fibers, rheological qualities, mechanical properties, workability, aggregate

1. Introduction

The use of concrete in high-temperature settings has received much attention because of the demand for building materials that can endure high temperatures without maintaining their strength. With its increased mechanical performance and distinctive rheological characteristics at high temperatures, fiber-reinforced concrete (FRC) has emerged as a viable solution to this problem (Shi et al. 2023). To highlight the feasibility of using FRC as a building material in such difficult circumstances, a thorough examination of the mechanical characteristics and rheological behavior of the material under high temperatures was performed (Alyousef et al. 2023).

1.1. Mechanical Performance of FRC

The main focus of the study is on fiber-reinforced concrete because of its exceptional mechanical performance under hot conditions. Ordinary concrete cannot be used because of its potential to lose durability and structural integrity when subjected to high temperature. However, FRC has better elastic and bending strength and can withstand damage, including spalling and separation, when reinforced with other kinds of fibers, such as steel, polypropylene and glass (Khalel et al. 2021). The methods by which these reinforcing fibers support the mechanical integrity of concrete in high-temperature environments will be examined in the future, offering insights into the suitability of these materials for use in hazardous environments such as nuclear power plants, fire-resistant buildings and industrial furnaces (Zhao et al. 2023).

1.2. Rheological features of FRC

The rheological behavior of FRC is another important factor in how it performs at high temperatures (Khayat et al. 2019). During building and casting operations, the flow and deformation properties of fiber-reinforced composites (FRCs) are critical when working with complicated or elaborate structures. The major goal of the survey was to better understand how FRC maintains its workability, consistency and capacity to self-compact under extremely hot circumstances. The authors hoped to
Singh et al. (2023) demonstrate the versatility of FRC by examining its rheological characteristics in scenarios where traditional concrete could struggle to maintain its desired shape and form at high temperatures (Baharuddin et al. (2020)).

1.3. Limitations

Although there is great potential for fiber-reinforced concrete in high-temperature settings, it is important to recognize the obstacles and constraints associated with its use in real-world situations. There are a number of limitations to using fiber-reinforced composites (FRCs) in hot environments (Zhang et al. 2020). These include potential decreases in certain mechanical qualities above a particular temperature threshold, as well as cost and fiber distribution concerns. These constraints will be covered in the study, which will offer a thorough summary of the elements that might prevent FRC from being used in high-temperature applications as well as possible directions for further investigation and advancement in the area.

The remainder of this paper is structured as follows: Section 2: Materials; Section 3: Cooling and heating techniques; Section 4: FRC characteristics at extreme temperatures; and Section 5: FRC rheological characteristics and evaluation. Section 6: Conclusion.

2. Materials

The elements in FRC, including aggregates, replacement materials and reinforcing fibers, can have a large impact on materials influenced by the mechanical temperature. The next section discusses various component materials and how high temperatures affect their performance in FRC.

2.1. Fibers

Many types of fibers, including steel, glass, basalt, PVA, PP and natural fibers, can be utilized as reinforcements in fiber-reinforced composites (FRCs). Figure 1 displays a number of the most commonly used reinforcing fibers, and Table 1 summarizes their usual material qualities. Diverse varieties of reinforcing fibers can provide distinct qualities to concrete to serve varying functions in enhancing the efficiency of cement-based substances. According to Ríos et al. (2019), concrete will become more resilient and have a higher tensile strength when high-tensile–strength fibers, such as steel fibers, are added to volcanic materials because of their strained capability and utilization of energy capacity. Steel fibers can be used to increase impact resistance.

![Figure 1: Reinforcing fibers.](source)

[Source](a) https://www.researchgate.net/profile/Festus-Olutoge-2/publication/301508641/figure/fig3/AS:362208614731783@1463368671663/Steel-fiber-sample-315-Chemical-admixture.png)
(b) https://5.imimg.com/data5/MR/UU/MY-13536103/basalt-fiber-250x250.jpg
(c) https://www.yarnsandfibers.com/?s=bangladeshi%20jute%20product,
(d) https://www.fiber2fashion.com/fibers/turkey-nylon-fiber-buyers-p260-c170,
(E) https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSgFFEGlHHC1ctDn3coZMzbRxV8Vb8NhYhFRC5gB46l3hFQIA,
According to Lin (2018), PP fibers can increase the porosity of concrete after heat treatment, increasing its susceptibility to cracking, while carbon fibers can improve the conductivity of electricity, temperature sensitivity and electromagnetic susceptibility of the material (Schneider et al. 2019). The chemical properties of the reinforcement fibers at high temperatures were determined. Poor thermal properties can cause fibers to deteriorate and dissolve at the earliest stages of thermal stress (180–300 °C) (Sassani et al. 2017). The resulting fine contacts from the cement discharge the liquid vapor, and the calcium silicate hydrate, known as C-S-H gel, breaks down. This decreases the interior pressure and improves the temperature resistance of the FRC (Li et al. 2019).

### 2.2. Substitutional substances

In highly effective fiber concrete reinforcement, reaction particles, including fly ash, pulverized powdered blast mill slag and silicic oxide, are utilized in part in lieu of regular Portland cement. (Jalal et al. (2015)) their small particle size results in densely microstructured concrete. Reactive particles have been shown to enhance the mechanical characteristics of aggregates at room temperature. Yu et al. (2018) suggested that by encouraging subsequent dehydration, silica fume can increase the amount of C-SH and increase the density of the microstructure. For both ambient and higher-temperature conditions, according to Mahapatra et al. (2019), the perfect alternate ratio of "GGBFS" for outstanding-performing materials was 40%, while for aggregates enhanced with PP and steel fibers, it was 30%. Furthermore, slag, kaolin, met mica and nanoclay cement were used as substitutes. According to Niaki et al. (2018), reactive powder can help FRC operate better at ambient temperature, but it cannot be as helpful as FRC at higher temperatures. For example, the compression forces of FRCs, including silicon dioxide and metakaolin, at room temperature were shown to be greater than those of FRCs without a substitute component. When the temperature was increased to 800 °C, the opposite effect was observed because the microscopic (Xie et al 2018) structure of FRC with MK and SF was more streamlined, which increased the stress compared to that of water vapor. Furthermore, it was discovered that the fumes of silica had no effect or perhaps a detrimental impact on the remaining durability of pavement at extreme temperatures.

### 2.3. Aggregates

The primary ingredient of the concrete was aggregate. There are two categories of carbonate and siliceous aggregates into which traditional aggregates can be separated. When exposed to high heat waves, they exhibit distinct behaviors (Deshpande et al 2019). The initial peak of silicon dioxide aggregates occurred at approximately 500 °C, while the first peak of carbonate aggregation occurred within 150 to 400 °C. Carbon dioxide gas could be produced by carbonate breakdown as a consequence of the disintegration of aluminum as temperatures increase beyond 600 °C. The mineral bicarbonate particles in cement could absorb ten times as much heat as those in concrete with metallic aggregates, resulting in greater resistance to fire due to the disassociation process. Comparing SFRC with a 16% volume fraction of crumbled rubber to SFRC without crumb rubber, the former has a 25% reduction in the strength of compression at 600 °C and a thirty percent reduction at a general temperature (Yu et al 2016). Glass trash can be added to concrete as an aggregate to increase its combustibility. Glass waste aggregates were shown to have comparable compressive properties at room temperature as well as at elevated temperatures. In the demonstration test, adding 10% waste glass aggregate increased the compressive strength of the aggregate by 100% at 700 °C (Yu et al 2016).

### 3. Techniques of cooling and heating

Heating testing was carried out in a heater to examine the influence of the temperature on the FRC. The analyzed properties of FRC change according to various heating techniques (Yermak et al., 2017). The experts used two burning methods. One was to replicate the actual fire state, which involves increasing the temperature to reach the intended level. A number of

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**Table 1 Characteristics of fiber reinforcement.**

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Jute</th>
<th>Nylon</th>
<th>Carbon</th>
<th>Basalt</th>
<th>PVA</th>
<th>PP</th>
<th>PE</th>
<th>Glass</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (°C)</td>
<td>-</td>
<td>233–254</td>
<td>over 4000</td>
<td>1600–1800</td>
<td>230–250</td>
<td>173</td>
<td>144.6</td>
<td>862</td>
<td>1372</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.4–1.47</td>
<td>2.15</td>
<td>1.9</td>
<td>2.9</td>
<td>1.4</td>
<td>0.11</td>
<td>0.97</td>
<td>2.6–2.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Elongation</td>
<td>1.9</td>
<td>16–31</td>
<td>2.6–3.3</td>
<td>3.17</td>
<td>7–8</td>
<td>~26</td>
<td>~20</td>
<td>1.6–3.6</td>
<td>0.6–37</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>14–27.6</td>
<td>2.6–5.18</td>
<td>160–967</td>
<td>50–91</td>
<td>23–43</td>
<td>3.47</td>
<td>0.15–0.42</td>
<td>74</td>
<td>300</td>
</tr>
</tbody>
</table>
fire curves have been developed to mimic real-world fire situations. As shown in Figure 2, among the most frequently utilized combustible curves are those offered by “ASTM E119 and ISO-834”. The two curves nearly overlap. Experiments such as those described are increasingly being conducted using this technique to evaluate the durability of FRC components from spreading.


**Figure 2** Standardized fire curves for ISO-834 and ASTM E119.

It must be noted that performing durability measurements subsequent to heating is difficult because typical fire shapes can cause substance spreading. The initial heating method, which follows the typical fire curve, increases the temperature more quickly than the subsequent approach. Rapidly rising ambient temperatures have the potential to create significant temperature gradients and degrade building materials, which could result in varying thermal strains depending on the location. FRC spalling can result from an extremely high interior pressure of vapor in addition to an elevated temperature gradient. Zhang et al. (2018) reported a range of heating frequencies between 1 °C/min and 10 °C/min. Once the target temperature was reached, it was maintained for a predetermined period of time with the goal of preserving the same conditions inside the sample that was tested. Varying periods would have an impact on the mechanical qualities that were tested. The experimental test’s estimated remaining cementing qualities would be impacted by the cooling technique. Water has a larger specific heat and heat transmission capacity than air, so specimens cooled in water experience a faster temperature change. Rapid dehydration produces an enormous temperature drop in cement due to its low thermal conductivity gradient, which damages the microstructure and reduces its compressive force (Liu et al. 2018). The majority of documented experimental research to date has concentrated on the physical characteristics of regenerated FRCs (Caetano et al. 2019). In actuality, material testing during heating can provide an accurate description of the behavior of the material under temporary heating circumstances (Ahmad et al 2019). The growing trend in interior tensile stresses caused by aggregate expansion during heating can have a major impact on the material strength. Nevertheless, the approach has been presented in very few studies due to its greater testing facility needs.

4. Characteristics of FRC at extreme temperatures

The primary focus of these studies was supplemented using FRC and “steel fiber (SFRC) and PP fiber (PFRC)”. The experiments conducted on the SFRC, PFRC and concrete reinforced with additional fibers under extreme heat are summarized. Reinforcing fibers, substitute materials, aggregates and testing procedures were among the variables considered in these experiments. Investigations were performed on the microscopic changes in FRC as well as its mass loss, elastic modulus, compressive strength, tensile strength and bursting resilience. The level of heat increased steadily in the majority of the published investigations, while most of the experts’ temperature increases were ≤10 °C/min.

4.1. Compressive strength

Initial studies on the mechanical behavior of FRC at low temperatures have been extensive. General fibers have minimal to no effect. The addition of basalt and aluminum fibers increased the compressed toughness, while the FRC compression performance decreased with the addition of PP fibers. Wu et al. (2020) studied FRCs reinforced with PP and steel fibers at high temperatures.

4.2. Tensile strength

The tensile strength of cement-based substances is correlated with the development and spread of small cracks. (Serrano et al. (2016)) The tensile strength of concrete can increase, and microcracks can be controlled by adding fibers, while
the use of fibers with little tensile strength, including PP fibers, might have a smaller impact on the increase in the tensile strength of building materials. Additionally, the addition of strong fibers, such as metals and fiberglass, could increase the elasticity of materials at low temperatures. The complete length of the fiber can have an effect on the tensile strength of the FRC. Larger fibers possess the potential to improve the bending strength of FRC.

4.3. Elastic modulus

The modulus of flexibility of concrete is determined by considering homogeneous chemicals, the general structure of the component and the properties of the transitional section. The structure of the molecules could be altered, and chemical connections could break at high temperatures, which would result in a considerable decrease in the FRC elasticity modulus. The inclusion of fibers has an impact on the material's coefficient of elasticity for FRC at the surrounding temperature. The residual elastic modulus increases as a result of the better architecture of FRC during the heating procedure (Drzymała et al. 2017).

4.4. Toughness

Toughness is a crucial characteristic that establishes the ability of cementitious materials to absorb energy. The region represented by the stress–strain curve is a common definition of concrete toughness. Because the compressive strength decreases as the temperature increases, the toughness of FRC decreases with temperature (Golewski et al. 2018). The FRC toughness at room temperature is positively impacted by the addition of steel fibers, although the addition of PP fibers has almost no effect. Research has revealed that the FRC at elevated temperatures has a negligible impact on the residual toughness of PP fibers. A higher dosage of steel fibers results in a greater toughness and persistent durability, according to Ahmad et al. (2019). Research has revealed that with a tiny addition, granite fiber can be used as a reinforcement material at ambient humidity and high temperatures to improve toughness, fracturing vitality and scratch resistance.

4.5. Breachability

One of the key elements of FRC was breachability. A great deal of porosity translates into high permeability, which reduces the toughness of the material (Amran et al. 2022). The elevated permeability makes it simple for chloride ions to infiltrate the building material matrix’s core, which decreases the FRC’s stability. Limited permeability can result in FRC bursting under elevated temperature conditions.

4.6. Spalling resistance

The material can undergo FRC spalling if it is subjected to harsh environments, including high concentrations of chlorine ions, fast elevated temperatures, and intense heat and explosion shocks (Choe et al. 2019). At high temperatures, bursting is not necessarily a problem for ordinary concrete (Zhang et al. 2018). Due to its lower permeability, high-strength fiber reinforced concrete (FRC) has a smaller water (Figueiredo et al. 2019) to binder percentage (w/b) than regular strength concrete, making it less able to offer an adequate passage for moisture to leave the material and making splitting more probable (Mahapatra et al. 2017).

5. FRC rheological characteristics and evaluation

5.1. FRC rheology models

Compared to standard functionality tests, which rely on intuition and empirical information, rheology is a more precise and objective science that characterizes a substance according to exogenous shear stresses and its potential for distortion. It is a useful instrument for forecasting stability, pumpability, shootability and constancy for evaluating workability and fluidity (Jiao et al 2017). Therefore, using various rheological models to predict or determine the rheological characteristics of cement has received much interest in the field of concrete manufacturing (Dauksys et al. 2018). Most of these studies have been conducted with highly flexible mortar or building materials, and insufficient research on the stress-related rheology of FRC based on material fracture and plasticity is available, as depicted in Figure 3. Fiber-containing cementitious materials are concentrated. As Figure 3 illustrates, the type of network formed by fibers depends on the way they communicate with particles, additives and cementing. Three flow patterns result from fiber interactions, which include mechanical contacts and hemodynamic impacts (Tseng et al 2019). The amount of hydrodynamic pressure on the outermost layer of particles is determined by the thickness of the phases of the liquid-suspended particles. The particles must avoid one another for flow to occur. Fibers revolve and reorient during flow due to their extended form. Neighboring particles or fibers influence and oppose motion.
5.2. Assessment of rheological properties

5.2.1. Evaluating FRC rheology with straightforward workability test techniques

The properties of FRC are determined by its fluidity, thermoplastic density, loading capability and release capability. One further crucial (Güneyisi et al. 2019) characteristic was separation obstruction, which is important for fiber reinforcement (Ahmad et al. 2018) and self-contracting concrete (FRSCC). Therefore, (Jung-Hoon et al. 2018), it is essential to consider these factors to determine the quality of the aggregates at construction locations. Many academics have conducted tests that are advised by regulations for evaluating the various flow behaviors of concrete. Furthermore, (Teng et al. 2018), during the past few decades, a variety of studies have described the impact of totaling fibers on the workability using conventional, straightforward evaluation techniques (Liu et al. 2019).

5.2.2. Rheometers

Traditional functionality test methods contain artificial error since they rely on length and time estimates provided by a timepiece and a ruler. In addition, assessing cement for functionality is a tedious and time-consuming procedure. Determining the impact of outside factors on the variability of the workability (Soualhi et al 2017) outcomes is challenging. Furthermore, these approaches do not produce concrete rheological curves or the information required to determine the velocity and stress resistance of the concrete. These approaches are empirical, subjective and devoid of a quantitative foundation (Dauksys et al. 2018). In certain cases, stiff FRC cannot be tested using conventional test procedures. Using fundamental rheological characteristics, new FRC parameters must be obtained to minimize human error. To compare numerous kinds of cement and determine how they behave in relation to numerous components, a rheometer is an essential tool that checks the effects of different modifications on the theoretical qualities of bolsters and mortars. As a result, the elastic characteristics of FRCs have been modified and frequently assessed using rheometers. In Table 2, eight viscometers and rheometers that are used for FRC are mentioned in addition to their benefits and drawbacks.

<table>
<thead>
<tr>
<th>Appliances</th>
<th>Benefits and drawbacks</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>BML Viscometer ConTec</td>
<td>It is feasible to utilize cement and mortar compositions that incorporate fine aggregate, as they offer ease of loading and cleaning. The utilization of a substantial sample capacity is necessary, because it was associated with the potential occurrence of flow plugs and wall slide phenomena.</td>
<td></td>
</tr>
</tbody>
</table>
**CAD Rheometer**

It is feasible to utilize pourable liquids, such as concrete paste, due to their ease of loading and cleaning. The rate of shear is nonuniform, which is suitable for straight elastomeric liquids and not for complex liquids.

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**Rheometer BTRHEOM**

The study employed a limited sample size, allowing for potential improvements in temperature manipulation, while mitigating slip and plug flow. Furthermore, the loading and cleaning processes were found to be straightforward. It is an expensive technique that necessitates specialization.

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**Cranfield Ultra-DV III**

In order it is conceivable to utilize pourable liquids such as paste of cement. The shear speed was nonuniform.

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**Heathrow RST-SST**

The device in question possesses compact dimensions, low weight, user-friendly functionality and is suitable to use with mortar. It demonstrates a high level of efficacy in preventing slippage.

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**Rheometer ICAR**

The proposed equipment possesses characteristics of compactness, low weight, user-friendly operation, compatibility with concrete compositions using coarse collective and the ability to avoid slippage. The acquisition of an adequate sample quantity is necessary and the transformation process is challenging due to the significant disparity.

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5. **Final considerations**

An assessment of the rheological properties and mechanical behavior of FRC was performed. The data from the study are used to perform a detailed investigation of the behaviors of FRC at high temperatures. Various methods of heating and cooling have been studied, along with how they affect the test findings, yet the impact of reinforcement fibers, particles and substitute components on the combustibility of FRC has been established. The phrase "workability" cannot be defined effectively yet, before it is one of the most significant qualities of concrete. Based on data from multiple rheometers, rheological frameworks have been developed to explain the rheological behavior of FRC. A number of methods have been discovered to improve rheological performance and functionality. Although fibers can improve the mechanical performance of concrete, they decrease its fresh and rheological properties. In contrast, there are benefits and drawbacks to the flexibility of these materials. Thus, it was crucial for establishing equilibrium among the actions of the newly produced state that can be identified by remarkable functioning as well as equilibrium, with the toughened nation that was distinguished by an enormous framework and extreme durability.

**Ethical Considerations**

Not Applicable.

**Conflict of Interest**

The authors declare no conflict of interest.

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