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Mechanical properties of macro synthetic fiber reinforced concrete at elevated temperatures: A systematic review and meta-analysis

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Abstract

The current infrastructure boom combined with the latest outcomes from 26th UN Climate Change Conference of the Parties (COP 26) seeking a carbon neutral society by 2050 have driven the increasing need for sustainable alternatives to be considered in construction. One such alternative is macro synthetic fibers, which have been gaining acceptance on major infrastructure projects. However, only limited uptake has occurred in permanent structures, due to a lack of knowledge around the behavior of macro synthetic fiber reinforced concrete (MSFRC) when exposed to elevated temperatures. Existing Australian and international design standards do not take into account the loss of strength for MSFRC after exposure to elevated temperatures. Hence, this systematic review sets out to combine all the existing knowledge on the mechanical properties of MSFRC and lay the groundwork for determining acceptable relationships between relative strengths and elevated temperatures. This study proposes relationships between temperature and compressive strength, splitting tensile strength, elastic modulus, flexural strength and residual flexural, and tensile strengths of MSFRC. These are compared to existing relationships determined for plain concrete and steel fiber reinforced concrete to position MSFRC within the context of existing and accepted knowledge.

KEYWORDS

elevated temperature, fire, macro synthetic fibers, residual strengths, systematic review

1 | INTRODUCTION

While fiber reinforced concrete (FRC) has been studied for over 50 years,[1] its introduction into mainstream construction has accelerated over the last 15 years. This adoption has been driven by tangible technical, economic, and sustainability benefits, when compared to conventional reinforced concrete solutions.[2,3] Over half the concrete produced in developed countries is utilized in structural applications,[4] thus research into FRC has increasingly

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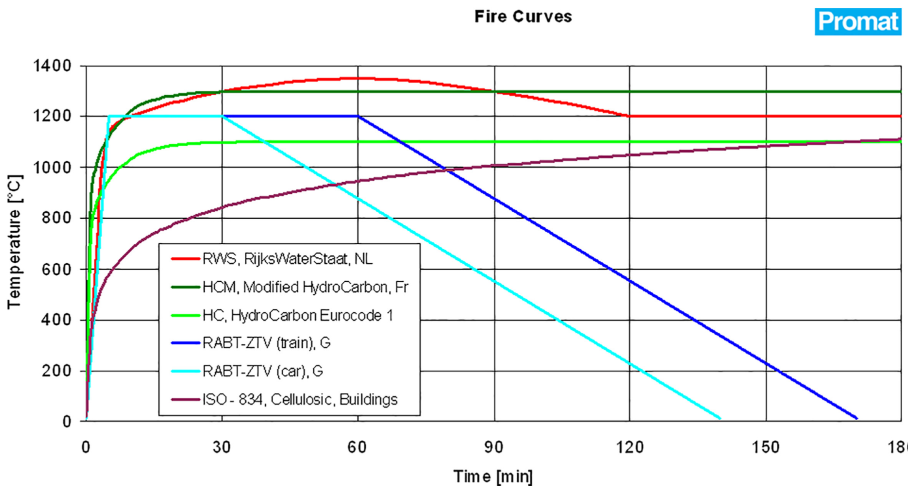

FIGURE 1 Internationally recognized design fire curves[20]

been focused on replacing reinforcement in these applications. Research into these areas has been extensive and has led to the incorporation of structural FRC into several design codes such as the *fib* Model Code 2010, ACI 318, Italian and Australian (AS5100 and AS3600) Codes.[5–9] 9 Most of this research however has focused on structural behaviors in static conditions,[10–12] with a few recent efforts devoted to long-term behavior[13] and durability.[14] The more recent introduction of macro synthetic fibers (MSFs) into FRC has meant that some aspects of their properties are still in the early stages of research, such as the behavior of these fibers at elevated temperatures.

One of the main applications of macro synthetic fiber reinforced concrete (MSFRC) is in the concrete lining of tunnels, hence their behavior when subject to fire is extremely important to understand, as this type of event can have catastrophic consequences if not adequately considered. Notable examples of this were observed in accidents such as the Mont Blanc tunnel fire, where 39 people lost their lives due to collapse of the tunnel lining,[15] or the Channel tunnel fire, where significant portions of the concrete tunnel lining were lost due to spalling.[16] Spalling occurs when concrete is exposed to a rapid heat increase, such as a tunnel fire, where it is believed that the dense concrete matrix does not provide sufficient channels for moisture to escape. As it transitions from liquid to gas, the pressure build-up causes pieces of concrete to explode from the surface allowing the pressure to escape, which is commonly referred to the moisture clog spalling theory.[17] Significant thermal stresses also build up in the exposed faces of the concrete during this heat transfer, which also impacts its spalling behavior.[18] It has been discovered that the inclusion of micro polypropylene (micro-PP) fibers in the concrete matrix reduces the propensity for concrete spalling, as the fibers melt at a relatively low temperature (approximately 160°C) leaving channels through which the expanding water vapor can escape.[19]

MSFs, while made of the same base material as the micro-PP fibers, perform a different function in the concrete matrix, and do not impart the same reduction in the propensity for concrete spalling. MSFs are used to add residual strength to the concrete matrix and often replace conventional steel reinforcement or steel fibers. However, as they melt at the same temperature as the micro-PP fibers (160°C), the study of their behavior at elevated temperatures is crucial to understanding the residual strength that remains after a fire. Also, due to this low melting point, the residual behavior is likely to be very sensitive to the temperature gradient within the concrete section, which in turn is dependent on the fire exposure. Numerous "design fires" have been developed over the years to replicate the time–temperature curve developed depending on the fuel source,[20] as illustrated in Figure 1.

The temperature gradient within the concrete section is heavily dependent on the amount of spalling suffered during the fire event. Very harsh time–temperature curves, such as the RWS (fire curve developed by the Rijkswaterstaat) or modified hydrocarbon, instigate the most significant spalling within concrete elements, due to their rapid temperature increase.

To explore the impact of elevated temperature, such as that caused by a fire, on the behavior of MSFRC, a systematic review of the literature was undertaken. The purpose of this systematic review is to synthesize findings around the residual strength of MSFRC after exposure to elevated temperatures. It will also review the applicability and relevance of the chosen test methods and their application to full-scale tunnel linings.

2 | RESEARCH SIGNIFICANCE

Methods for assessing the behavior of concrete at elevated temperature are included in various national and international standards[8,21] as well as by numerical analysis.[22] The input values required for these methods are well known for plain concrete, as they are also defined in Eurocode 2 (EC2)[21] for various aggregate types. Steel FRC is detailed by Colombo[23] and implemented in national standards such as CNR DT 206[5] and AS3600:2018,[8] while high strength concrete is described by Aslani and Bastami.[24] The increasing requirement for durable, sustainable infrastructure has led to the implementation of MSFRC for various elements. The inputs for the properties of MSFRC at elevated temperatures are yet to be defined, limiting the current applications for its adoption. This study aims to propose mechanical property relationships for MSFRC as a function of temperature for compressive strength, tensile strength, elastic modulus, flexural strength, residual flexural, and residual tensile strengths, for adoption as material input parameters for the behavior of MSFRC structures at elevated temperatures.

3 | MATERIALS AND METHODS

A systematic literature search was undertaken using electronic databases (American Society of Civil Engineers Library, ProQuest, ScienceDirect, Scopus, SpringerLink, Web of Science, and Wiley Online Library) from January 1, 2000 to February 16, 2021. The starting date was chosen as MSFs were only in the early stages of development prior to this and limited research on them was undertaken prior to the year 2000. The search strategy included the use of terms in three broad categories: (i) the combination of concrete type with particular fiber of interest, (ii) the intervention type, and (iii) the property of interest after the intervention. Title and abstract fields were searched using the following terms:

1. "Fiber reinforced concrete" or "polymer fiber" or "plastic fiber" or "macro synthetic fiber" and;
2. "Fire" or "elevated temperature" and;
3. "Residual strength" or "residual behavior" or "residual properties."

The reference lists of included studies were manually searched for additional relevant articles.

3.1 | Inclusion and exclusion criteria

Studies were included if they met all the following criteria:

1. Tested mechanical properties (e.g., residual flexural tensile strength or compressive strength) of FRCs after exposure to elevated temperatures.
2. Included macro synthetic fibers in the study, except where they were only assessed in a hybrid mix with steel fibers.
3. Only used normal or high strength concrete (i.e., <100 MPa).

Studies were excluded if they included any of the following criteria:

1. Included MSFs but did not test mechanical properties after exposure to elevated temperatures.
2. Used high performance or ultra-high performance concretes (i.e., >100 MPa).
3. Were a review paper or in a language other than English.

3.2 | Study selection, data extraction, and analysis

All abstracts from the literature search were uploaded into Covidence systematic review software (www.covidence.org) to facilitate the various steps of the review. After removal of duplicates, two authors (Authors 1 and 2) screened the initial studies based on title and abstract for inclusion in the full-text review (Stage 1). The same two authors then screened the full texts against the inclusion and exclusion criteria to determine the final studies to be included. Where disagreements arose regarding inclusion or exclusion of a study, consensus was agreed by discussion (Stage 2). One author (Author 1) scanned the reference lists of the included studies for additional studies that should be included.

Studies were only included if they investigated a control set of specimens that was tested without exposure to elevated temperatures, enabling comparisons to be made to demonstrate the impact of the intervention (i.e., elevated temperature).

3.3 | Data collection process and data items

Characteristics of studies were extracted by one author (Author 1), while the results of the studies were extracted by two authors (Authors 1 and 2). Studies were grouped according to the mechanical tests performed. For each test type (e.g., compressive strength, residual flexural tensile strength, etc.) the effect of elevated temperature was recorded as the proportion of the mechanical property at the certain temperature level relative to the ambient control. The data were then analyzed to determine whether a statistically significant correlation exists between the various studies, and an equation could be proposed for the reduction of that property of MSFRC based on the temperature of exposure.

3.4 | Quality assessment

Due to the limited number of studies included in this review, along with the varied nature of experiments conducted within them, it was determined that an assessment of the quality of each article could not be adequately conducted for this review.

3.5 | Statistical methodology for outliers and defining the proposed relationship

For each mechanical property, the extracted data set was compiled, and a linear regression analysis was conducted to find an initial relationship. A widely accepted criterion for detecting outliers in linear regression is the maximum studentized residual, according to Paul and Fung.[25] From this initial regression analysis, the absolute value of the studentized residuals were studied and outliers determined through statistical inference. A result, or cluster of results, was deemed to be an outlier if it met the following criteria:

1. The absolute value of the studentized residual was greater than 2, and
2. The studentized residual (or cluster of residuals) was 0.5 greater than the nearest point.

The studentized residuals from the initial relationship for splitting tensile strength are depicted in Figure 2, with the outliers highlighted in red. These outliers were then removed, and another regression analysis conducted.

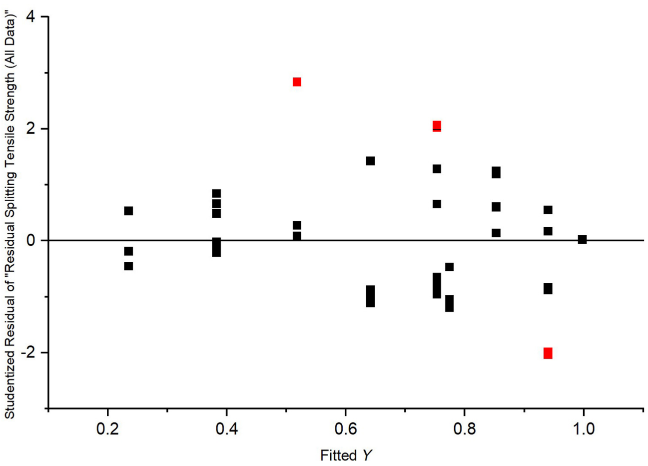

FIGURE 2 Studentized residuals from regression analysis of splitting tensile strength data

From the second regression analysis, the 80% confidence interval was calculated and the lower bound extracted. A line was plotted which best fit these lower bound values but was adjusted so that at ambient temperature (e.g., 23°C) it passed through 1. The equation of this line is then used as the proposed equation to define the mechanical property as a function of temperature so that 90% of results will fall above the proposed relationship.

4 | RESULTS

The combined search retrieved 1338 peer-reviewed articles published in English between January 1, 2000 and February 16, 2021. After removing duplicates, 1271 studies were selected, and the review conducted in two stages. In the first stage, two authors (Authors 1 and 2) screened the studies by title and abstract for relevance against the inclusion and exclusion criteria (i.e., did they study the impact of elevated temperatures on the mechanical properties of MSFRC). From this, 107 articles were subjected to a full text review by the same two authors, which yielded a cohort of 21 studies. The reference lists of these studies were searched by one author (Author 1) for further studies that should be included in the review. This search produced two further studies that met all the criteria and hence were also included. This process delivered a final collection of 23 studies for inclusion in this systematic review and meta-analysis.

Of these studies, 18 reviewed compressive strength, 7 studied indirect tensile strength, 6 analyzed elastic modulus, 4 studied ultrasonic pulse velocity, 7 reviewed residual flexural tensile strength via bending tests, and 2 studied residual tensile strength by means of the double punch (Barcelona) test. Figure 3 depicts an overview of this process, while the characteristics of the included studies are reported in Table 1. Outcomes from each study were extracted as the ratio of the property at the defined elevated temperature for each dose rate of MSF compared to the property of the control specimen at ambient temperature for that dosage. The results are illustrated and described in the following sections.

While some studies adopted unusual constituents or methods in their investigation, such as crumbed rubber aggregates,[26] prepacking of aggregates,[27] lightweight aggregates,[28,29] and styrene butadiene rubber latex,[30] the majority used fairly standard concrete materials. In the assessment of the results, where studies with these unusual constituents contained a control or alternative specimen that adopted MSFRC in typical concrete, then these results were included in the analysis, whereas if the only data available were for the MSFRC with said constituent, then it was included in the analysis but critically assessed as to whether the unusual constituent had an impact on the result.

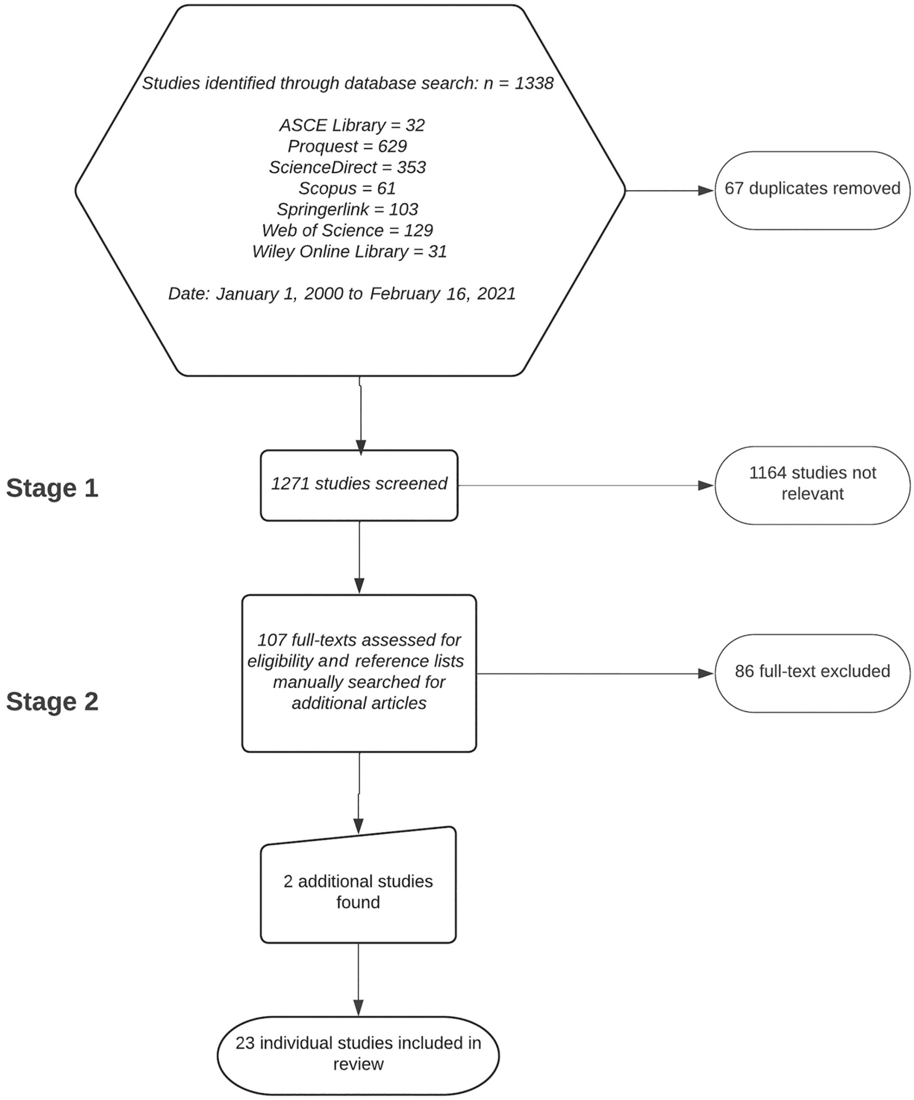

FIGURE 3 Flow chart of the various stages of the systematic review

4.1 | Effect of elevated temperature on compressive strength

Compressive strength is one of the most important mechanical properties of concrete. Hence, understanding any changes that may occur due to exposure to elevated temperatures is of critical importance. Many studies have been conducted to understand this change on plain concrete[31–33] and steel FRC.[34–36] Micro-PP fibers are well known for their ability to reduce concrete spalling and therefore help to maintain concrete's compressive strength.[37–39] However, as can be seen in Table 2, only 18 studies have considered the impact of elevated temperature on the compressive strength of MSFRC.

For measurement of compressive strength, all studies adopted either compressive cubes or cylinders that were cast, or cores extracted from fire exposed specimens. Most specimens were kept in an oven at the target temperature for a prolonged period of time, to homogenize the temperature within the sample, however others, such as Maluk et al.,[15] exposed larger specimens to a time–temperature curve replicating a tunnel fire and then extracted cores afterwards, leading to a temperature gradient within the tested samples. In this case, all studies included the temperature distribution through the section of the large specimen, so the average temperature in the tested sample was estimated from this data. This is valid for all the other mechanical properties discussed in this review.

Figure 4 illustrates the results extracted from each study which have been normalized by representing the relationship between the compressive strength of each parameter at elevated temperature with its compressive strength at ambient temperature.

It can be clearly seen that as the temperature increases, the compressive strength of the concretes decrease, a trend that is common across most of the studies. Overlain on the data is the EC2 relationship for

TABLE 1 An overview of the studies found in the systematic review and included in the meta-analysis

Author (year) and country	Macro synthetic fibers used	Cement replacements	Unusual constituents used	Curing and conditioning of specimens	Fire curve used (or other in °C/min)	Method of heating	Max temperature/s the specimens were exposed to	Mechanical properties were measured after heating	Age mechanical testing undertaken
Abaeian (2018), Iran[42]	Yes	None	-	7 or 28 days—curing not reported	ISO 834	Oven	100, 200, and 300°C	Compressive strength, splitting tensile strength, and flexural strength	7 and 28 days
Alberti (2020), Spain[54]	Yes	Limestone powder @ 21% replacement	-	Not reported	Other: 2.8°C/min	Oven	150, 165, 175, 185, and 200°C	UPV, elastic modulus (by ultrasound), compressive strength, fracture energy, and residual flexural strength	Not provided
Alimrani (2020), Hungary[43]	Yes	-	-	7 days water curing then 28 days in ambient (laboratory) conditions	ISO 834	Oven	150, 300, 500, and 700°C	Compressive strength, flexural strength, shear strength, and stress–strain properties	35 days
Aslani (2019), Australia[26]	Yes	Fly ash @ 30%, slag @ 22%, silica fume @ 8% (cement is the other 40%)	Crumbed rubber aggregates	28 days @ 95% humidity and 20°C	Not reported	Other: not reported	100, 300, and 600°C	Compressive strength, splitting tensile strength, and modulus of elasticity	28 days
Balazs (2012), Hungary[55]	Yes	-	-	7 days water cured then 28 days in ambient (laboratory) conditions	ISO 834	Other: not reported	50, 150, 200, 300, 400, 500, 600, and 800°C	Compressive strength	35 days
Cavdar (2013), Turkey[44]	Yes	-	-	40 days water cured then oven dried @ 100°C for 24 h	Other: 6°C/min	Oven	100, 450, 650 and 850°C	Compressive strength and flexural strength	41 days

(Continues)

TABLE 1 (Continued)

Author (year) and country	Macro synthetic fibers used	Cement replacements	Unusual constituents used	Curing and conditioning of specimens	Fire curve used (or other in °C/min)	Method of heating	Max temperature/s the specimens were exposed to	Mechanical properties were measured after heating	Age mechanical testing undertaken
Choumanidis (2016), Greece[46]	Yes	CEM IV and silica fume	—	26 days water cured @ 20°C	Other: 2°C/min	Furnace	280°C	Compressive strength, residual flexural tensile strength, elastic modulus, energy absorption, and toughness index	28 days
Choumanidis (2017), Greece[45]	Yes	Silica fume and CEM IV	-	Water cured @ 20°C for 28 days then fire tested	Other: 2°C/min	Furnace	280°C	Compression, residual tensile (BCN), toughness (BCN)	29 days
Francioso (2021), USA[56]	Yes	—	—	Moist cured @ 95% RH and 25°C for 27 days, then air cured @ 65% RH and 23°C for 1 days.	Other: 50°C/min up to 200°C	Oven	200°C	Flexural strength, compressive strength, residual flexural strength	28 days
Khalighi (2020), Iran[57]	Yes	Silica fume @ 2%	—	28 days under water, then 47 days at room temperature	Other: heating rate was low (no °C/min provided)	Oven	400, 600 and 800°C	Residual load bearing capacity of RC beams (deflection, flexural stiffness, energy absorption)	76, 83, and 104 days
Maluk (2020), Australia[15]	Yes	Fly ash and silica fume—replacement amounts not reported	-	Kept in molds for 36 hours, placed under water for 7 days, conditioned @ 50% RH and 20°C until testing (284–300 days)	Hydrocarbon	Other: H-TRIS radiant panels	1200°C	Compressive strength, splitting tensile strength	300+ days
Mirza (2021), Australia[40]	Yes	Fly ash @ 30%	-	31 days curing—conditions not provided	Not reported	Oven	200, 400, 600, and 800°C	Flexural and residual flexural strengths	32 days

TABLE 1 (Continued)

Author (year) and country	Macro synthetic fibers used	Cement replacements	Unusual constituents used	Curing and conditioning of specimens	Fire curve used (or other in °C/min)	Method of heating	Max temperature/s the specimens were exposed to	Mechanical properties were measured after heating	Age mechanical testing undertaken
Mohammadhosseini (2020), Malaysia[27]	Yes	Palm oil fuel ash @ 20%	Prepacking of aggregates to make specimens is different to other studies	Water curing/age at fire test not given	Other: 10°C/min	Oven	200, 400, 600, and 800°C	UPV, compressive strength, tensile strength	Age at testing not provided
Rambo (2018), Brazil[41]	Yes	Silica fume @ 5%	—	Cured in a wide electric oven at 40°C during 24 h before demolding. Then maintained in a dry condition for 28 days	Other: 16°C/min	Oven	200, 400, and 600°C	Compressive strength, elastic modulus, residual tensile strength (BCN test)	29 days
Richardson (2017), UK[47]	Yes	Mix design not provided	-	28 days water cured	Other: no set rate—specimens just placed in room @ 60°C	Other: temperature controlled room	60°C	Compressive strength, residual flexural strength, single fiber pull-out resistance	30 days
Serafini (2019), Brazil[48]	Yes	Silica fume @ 5%	—	72 h @ 90% + RH, then 150 days in air	Hydrocarbon	Furnace	1100°C	Compressive strength, residual flexural strength	Minimum 155 days
Sideris (2009), Greece[58]	Yes	Silica fume @ 10% and fly ash @ 13%	-	14 days under water, 14 days under wet burlap then air cured (50–65% RH and 20 ± 2°C) until 120 days from casting	Other: 5°C/min	Oven	100, 300, 500, and 700°C	Compressive strength, UPV and elastic modulus	120 days+
Srikar (2016), India[59]	Yes	Fly ash @ 30%	-	1 day in mold, 27 days water cured	Other: 2°C/min	Oven	150, 200, and 300°C	Compressive strength	28 days

(Continues)

TABLE 1 (Continued)

Author (year) and country	Macro synthetic fibers used	Cement replacements	Unusual constituents used	Curing and conditioning of specimens	Fire curve used (or other in °C/min)	Method of heating	Max temperature/s the specimens were exposed to	Mechanical properties were measured after heating	Age mechanical testing undertaken
Stefan (2020), Czech Republic[28]	Yes	-	Lightweight aggregate (expanded clay) and recycled concrete aggregates	Air cured (25°C and 50% RH) for 56 days	ISO 834	Furnace	1050°C	Compressive strength	58 days
Sukontasukkul (2010), Thailand[49]	Yes	-	-	Water cured for 28 days	Other: ASTM E119-98	Oven	400, 600, and 800°C	Flexural strength and stiffness, toughness index	29 days
Sukontasukkul (2018), Thailand[52]	Yes	-	-	28 days in water then 7 days in air	Other: custom time–temperature curve	Furnace	300, 400, and 410°C (furnace temperature), 225, 275, 300, and 310°C internal temp (10 mm cover)	Residual flexural strength	36 days
Thirumurugan (2015), India[30]	Yes	Fly ash @ 25% and 33%	Styrene butadiene rubber latex	Curing in water (time not reported)	Other: 4°C/min	Oven	200, 400, 600, and 800°C	Compressive strength, elastic modulus	Not provided
Wu (2013), China[29]	Yes	Fly ash @ 30% replacement	Lightweight aggregate	28 days @ 95% RH and 20°C—then tested	Other: 10°C/min	Furnace	200, 400, 450, 500, and 600°C	UPV, compressive strength, flexural strength	28 days

TABLE 2 Studies assessing effect of elevated temperature on compressive strength of MSFRC

Author (year) and country	Macro synthetic fiber dose rate/s (kg/m^3)	Macro synthetic fiber dimensions	Macro synthetic fiber tensile strength	Macro synthetic fiber Young's modulus	Micro synthetic fibers used	Micro synthetic fiber dose rate/s	Micro synthetic fiber dimensions	Hybrid specimens used	Hybrid specimens dose rates and fiber types	Concrete strength grade
Abaeian (2018), Iran[42]	1, 2, and 3	50 mm length and 0.9 mm diameter	700 MPa	3.8 GPa	No	-	-	No	-	65 MPa
Alberti (2020), Spain[54]	0, 3, and 10	60 mm long, 1.13 mm diameter	560 MPa	9 GPa	No	-	-	No	-	50 MPa
Alimrani (2020), Hungary[43]	4	50 mm length and diameter not provided	590 MPa	11 GPa	No	-	-	Yes	2 kg MSF + 40 kg SF	90 MPa
Aslani (2019), Australia[26]	1.56, 2.34, 3.12, and 3.9	65 mm length and 0.85 mm diameter	250 MPa	3 GPa	No	-	-	No	-	30 MPa
Balazs (2012), Hungary[55]	1	40 mm length and 1.1 mm diameter	-	-	Yes	1 kg/m^3	18 mm length and 32 μm diameter	No	-	60 MPa
Cavdar (2013), Turkey[44]	2.73, 5.46, 8.19, and 10.92	10 mm length and 0.75 mm diameter	338 MPa (HPP) and 570-660 MPa (CPP)	1.55 GPa (HPP) and 4.7 GPa (CPP)	No	-	-	No	-	50 MPa (mortar)
Choumanidis (2016), Greece[46]	4.55 and 9.1	52 mm length and 0.46 mm diameter	613 MPa	5.4 GPa	Yes	4.55 and 9.1 kg/m^3	12 mm length and 25 μm diameter	Yes	40 kg steel fiber + 4.55 kg MSF and 4.55 kg MSF + 4.55 kg micro-PP	40 MPa
Choumanidis (2017), Greece[45]	4.55 and 9.1	52 mm length and 0.46 mm diameter	613 MPa	5.4 GPa	Yes	4.55 kg/m^3 and 9.1 kg/m^3	12 mm length and 25 μm diameter	Yes	40 kg steel fiber + 4.55 kg MSF and 4.55 kg MSF + 4.55 kg micro-PP	40 MPa
Francioso (2021), USA[56]	2.6, 5.1, and 7.7	ranges from 2 to 40 mm length and 0.35 mm diameter average	5228 psi = 36 MPa	Not provided	No	-	-	No	-	40 MPa
Maluk (2020), Australia[15]	7	60 mm length and diameter = 0.84 mm	640 MPa	10 GPa	Yes	1 kg/m^3	6 mm length and 32 μm diameter	Yes	7 kg MSF + 1 kg micro-PP	50 MPa

(Continues)

TABLE 2 (Continued)

Author (year) and country	Macro synthetic fiber dose rate/s (kg/m^3)	Macro synthetic fiber dimensions	Macro synthetic fiber tensile strength	Macro synthetic fiber Young's modulus	Micro synthetic fibers used	Micro synthetic fiber dose rate/s	Micro synthetic fiber dimensions	Hybrid specimens used	Hybrid specimens dose rates and fiber types	Concrete strength grade
Mohammad-hosseini (2020), Malaysia[27]	2.2, 4.55, 6.8, and 9.1	30 mm length and 0.45 mm diameter	400 MPa	-	No	-	-	No	-	40 MPa
Rambo (2018), Brazil[41]	8	48 mm length and 0.7 mm diameter	640 MPa	10 GPa	Yes	0.8 kg/m^3	12 mm length and 30 μm diameter	Yes	8 kg/m^3 MSF + 0.8 kg/m^3 micro-PP	50 MPa
Sideris (2009), Greece[58]	5	30 mm length, diameter not provided	-	-	No	-	-	No	-	40 and 80 MPa
Srikar (2016), India[59]	4, 5, and 6	60 mm length and 1.1 mm diameter	618 MPa	10 GPa	No	-	-	No	-	40 MPa
Thirumurugan (2015), India[30]	0.9 and 2.7	48 mm length and 0.6 mm diameter	-	-	No	-	-	No	-	40 MPa
Wu (2013), China[29]	2 and 3	45 mm length, diameter not provided	456 MPa	5.6 GPa	No	-	-	No	-	Not reported

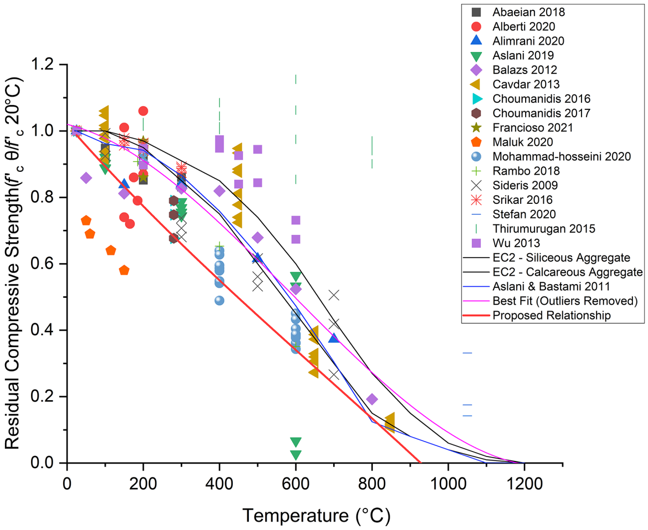

FIGURE 4 Comparison of experimental results for relative compressive strength at elevated temperatures with Eurocode 2 and Aslani and Bastami[24] relationships, as well as the proposed relationship for compressive strength of macro synthetic fiber reinforced concrete as a function of temperature

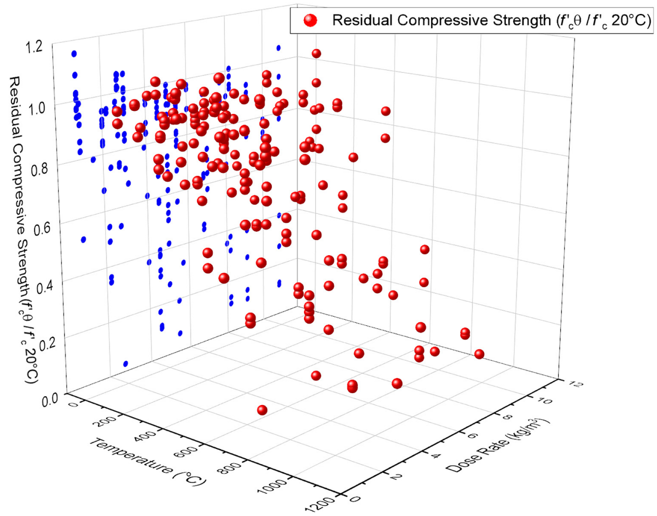

FIGURE 5 Comparison of temperature and dose rate on the relative residual compressive strengths of macro synthetic fiber reinforced concrete

compressive strength versus temperature,[21] which is a good fit for this data. Also included is the relationship for normal strength concrete as proposed by Aslani and Bastami,[24] which is very close to the EC2 curve. Finally, the best fit curve for all data from the included studies (minus outliers, adjusted $R^2 = 0.799$) as well as the proposed relationship representing the lower bound (or 10th percentile), can also be observed in Figure 4. The proposed relationship of compressive strength as a function of temperature is depicted in Equation (1).

$$f'_c\theta = f'_c\left[1.02 - 0.00131\times\theta + 4.14078\times10^{-7}\times\theta^2 - 2.04766\times10^{-10}\times\theta^3\right] \quad (1)$$

when $(0°C \le \theta \le 1200°C)$.

Outlier results were primarily from Thirumurugan,[40] whose study included styrene butadiene rubber latex at 7% by volume in all mixes that included MSFs. These results were all outliers on the high side, where increases in temperature did not seem to impact on the residual compressive strength, maintaining similar strengths at 800°C as they had in ambient conditions. The inclusion of the rubber latex appears to have significantly changed the compressive strength behavior at elevated temperatures. Other results excluded from the fitting for Equation (1) were the lowest result from Aslani, Sun, and Huang,[26] which were not aligned with other results from the same study.

The effect of dose rate on the compressive strength of concrete was also assessed, as it was thought that as the fiber dose rate increased, the compressive strength at elevated temperatures may have been reduced, due to more voids being left behind by melted fibers at the higher temperatures. Figure 5 shows that increasing dose rates had very little impact on the residual compressive strength at higher temperatures, as the relative residual strengths remain quite constant with increasing fiber dose rate for similar temperature levels.

4.2 | Effect of elevated temperature on indirect tensile strength

While concrete is not relied upon for its tensile strength, it remains an important property to understand. As with compressive strength, the same standards and studies provide guidance on the reduction of concrete's tensile strength at elevated temperatures. These defined properties for plain concrete will be compared with the outcomes from the data extracted from the studies in this systematic review.

Seven studies investigated the tensile strength of MSFRC, as shown in Table 3. From these studies all but two adopted the Brazilian splitting test to measure indirect tensile strength, while the other studies used the Barcelona double punch test from which the peak load was taken as the indirect tensile strength. Figure 6 illustrates the different setup of these two test methods.

Maluk et al.[15] studied the splitting tensile strength of cores taken from their fired concrete specimens, however no control specimens were tested so this data could not be used in this analysis as there was no means of normalizing the data to compare with the other studies. Data

TABLE 3 Studies assessing effect of elevated temperature on indirect tensile strength of MSFRC

Author (year) and country	Macro synthetic fiber dose rate/s (kg/m^3)	Macro synthetic fiber dimensions	Macro synthetic fiber tensile strength	Macro synthetic fiber Young's modulus	Micro synthetic fibers used	Micro synthetic fiber dose rate/s	Micro synthetic fiber dimensions	Hybrid specimens used	Hybrid specimens dose rates and fiber types	Concrete strength grade
Abaeian (2018), Iran[42]	1, 2, and 3	50 mm length and 0.9 mm diameter	700 MPa	3.8 GPa	No	-	-	No	-	65 MPa
Aslani (2019), Australia[26]	1.56, 2.34, 3.12, and 3.9	65 mm length and 0.85 mm diameter	250 MPa	3 GPa	No	-	-	No	-	30 MPa
Choumanidis (2017), Greece[45]	4.55 and 9.1	52 mm length and 0.46 mm diameter	613 MPa	5.4 GPa	Yes	4.55 kg/m^3 and 9.1 kg/m^3	12 mm length and 25 μm diameter	Yes	40 kg steel fiber + 4.55 kg MSF and 4.55 kg MSF + 4.55 kg micro-PP	40 MPa
Mohammad-hosseini (2020), Malaysia[27]	2.2, 4.55, 6.8, and 9.1	30 mm length and 0.45 mm diameter	400 MPa	-	No	-	-	No	-	40 MPa
Rambo (2018), Brazil[41]	8	48 mm length and 0.7 mm diameter	640 MPa	10 GPa	Yes	0.8 kg/m^3	12 mm length and 30 μm diameter	Yes	8 kg/m^3 MSF + 0.8 kg/m^3 micro-PP	50 MPa
Sideris (2009), Greece[58]	5	30 mm length, diameter not provided	-	-	No	-	-	No	-	40 and 80 MPa

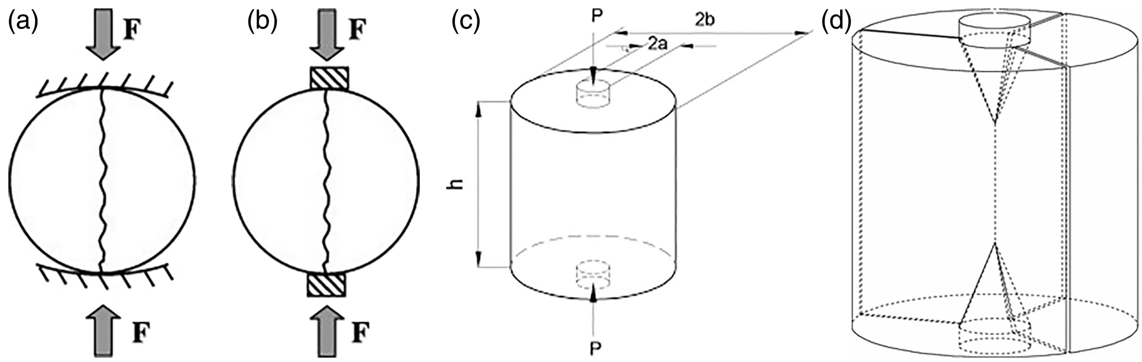

FIGURE 6 (a) Brazilian splitting test—ISMR Brazilian method,[60] (b) Brazilian splitting test—ASTM and AS method,[60] (c) Barcelona test setup,[61] and (d) Barcelona test failure mechanism[61]

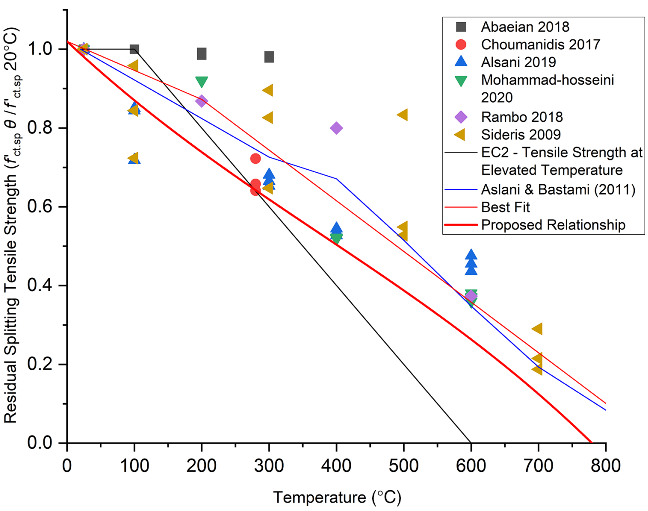

FIGURE 7 Comparison of experimental results for relative tensile strength at elevated temperatures with the Eurocode 2 and Aslani and Bastami[24] relationships, along with the proposed relationship for tensile strength of macro synthetic fiber reinforced concrete as a function of temperature

from the six remaining studies were extracted, normalized, and presented in Figure 7.

As expected, the tensile strength of the MSFRC reduces as the temperature increases, as occurred for compressive strength. A more severe reduction of tensile strength is observed than occurred for the compressive strength relationship, though this is in line with the EC2 equations wherein the tensile strength deteriorates much quicker than the compressive strength at elevated temperatures. The EC2 relationship provides a conservative estimate which, for the most part, encapsulated the lower bound of results, extracted from the systematic review. The best fit curve for the data (once outliers were removed, adj. $R^2 = 0.89$) as well as the proposed relationship are illustrated in Figure 7, while the equation for the proposed relationship for tensile strength as a function of temperature can be seen in Equation (2).

$$f'_{ct}\theta = f'_{ct}\left[1.02 - 0.00171 \times \theta + 1.80468 \times 10^{-6} \times \theta^2 - 1.77752 \times 10^{-9} \times \theta^3\right] \quad (2)$$

when ($0°C \le \theta \le 800°C$).

It is clear from Figure 7 that the best fit is very close to that of Aslami and Bastami.[24] This suggests that the tensile strength results for MSFRC are a close fit to those of plain concrete, hence no significant difference can be observed between the two and the values proposed by either EC2 for plain concrete, the proposed relationship, or a combination of both, can be safely adopted for the design of MSFRC.

4.3 | Effect of elevated temperature on elastic modulus

The change in elastic modulus due to increasing temperature is one that is less frequently covered by international standards, though EC2 provides guidance on the change to strain capacities in compression, hence elastic modulus can be derived from the reduced compressive strength and strain at various temperatures. The details for the six studies that investigated the change in elastic modulus for MSFRC exposed to elevated temperature are displayed in Table 4.

Studying the extracted results, it was observed that there were no outliers but also a very poor fit due to a wide dispersion of the results. While the Thirumurugan[30] results were not classified as outliers during the linear regression for elastic modulus, the fact that they were excluded for compressive strength and their extremely high results for elastic modulus compared to the rest led

TABLE 4 Studies assessing effect of elevated temperature on elastic modulus of MSFRC

Author (year) and country	Macro synthetic fiber dose rate/s (kg/m^3)	Macro synthetic fiber dimensions	Macro synthetic fiber tensile strength	Macro synthetic fiber Young's modulus	Micro synthetic fibers used	Micro synthetic fiber dose rate/s	Micro synthetic fiber dimensions	Hybrid specimens used	Hybrid specimens dose rates and fiber types	Concrete strength grade
Alberti (2020), Spain[54]	0, 3, 10	60 mm long, 1.13 mm diameter	560 MPa	9 GPa	No	-	-	No	-	50 MPa
Aslani (2019), Australia[26]	1.56, 2.34, 3.12, and 3.9	65 mm length and 0.85 mm diameter	250 MPa	3 GPa	No	-	-	No	-	30 MPa
Choumanidis (2016), Greece[46]	4.55 and 9.1	52 mm length and 0.46 mm diameter	613 MPa	5.4 GPa	Yes	4.55 and 9.1 kg/m^3	12 mm length and 25 μm diameter	Yes	40 kg steel fiber + 4.55 kg MSF and 4.55 kg MSF + 4.55 kg micro-PP	40 MPa
Rambo (2018), Brazil[41]	8	48 mm length and 0.7 mm diameter	640 MPa	10 GPa	Yes	0.8 kg/m^3	12 mm length and 30 μm diameter	Yes	8 kg/m^3 MSF + 0.8 kg/m^3 micro-PP	50 MPa
Sideris (2009), Greece[58]	5	30 mm length, diameter not provided	-	-	No	-	-	No	-	40 and 80 MPa
Thirumurugan (2015), India[30]	0.9 and 2.7	48 mm length and 0.6 mm diameter	-	-	No	-	-	No	-	40 MPa

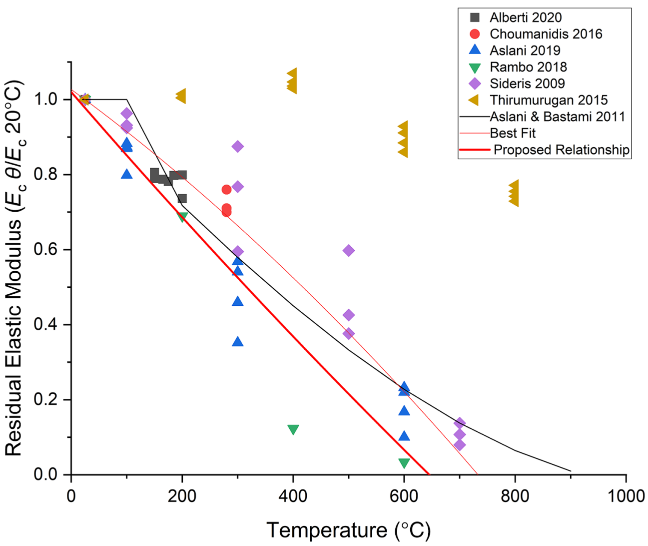

FIGURE 8 Comparison of experimental elastic modulus results at elevated temperatures with the Aslani and Bastami[24] relationship and the proposed relationship for elastic modulus of macro synthetic fiber reinforced concrete as a function of temperature

to their exclusion when determining the proposed relationship. With those results included the $R^2 = 0.417$, whereas when they, as well as one low result from Rambo[41] (which becomes an outlier once the other results are removed), are excluded the adjusted R^2 increases to 0.888. The extracted results from the six studies can be found in Figure 8 which also includes the proposed relationship.

The equation of the proposed relationship for the lower bound of the results for the reduction of elastic modulus of MSFRC at elevated temperatures can be found in Equation (3).

$$E_c\theta = E_c\left[1.02 - 0.00171 \times \theta + 1.97352 \times 10^{-7} \times \theta^2\right] \quad (3)$$

when ($0°C \leq \theta \leq 700°C$).

4.4 | Effect of elevated temperature on flexural strength

The flexural strength, or modulus of rupture (MOR), of concrete, is defined as the stress at which the first crack occurs when tested under a flexural load. For plain concrete, this would also mean failure of the specimen, as once a crack occurs there is nothing holding the crack together and hence brittle failure occurs. When fibers are incorporated into concrete, this flexural crack is held together and the concrete gains some residual flexural strength, which will be discussed in detail in later sections.

The 10 studies that reviewed the impact of elevated temperature on the flexural strength of MSFRC are detailed in Table 5. Some studies purely studied the flexural strength of the MSFRC,[29,42–45] while from others, the flexural strength was measured as part of the test measuring residual flexural tensile strength.[40,46–49] As an example, Serafini et al.[48] utilized EN 14651 beams in their research, where the f_{LOP} data were extracted and utilized for comparison with the other studies' flexural strengths.

Normalized relative residual flexural strengths were extracted from each study and can be observed in Figure 9. It must be noted that two outliers were detected, being the two highest values from the Francioso study.[45] These were removed prior to determining the best fit for flexural strength as a function of temperature, which was a reasonable fit of the data (R^2 adj. $= 0.744$). The proposed relationship, representing the lower bound of flexural strength as a function of temperature is depicted in Equation (4).

$$f'_{ct.f}\theta = f'_{ctf}\left[1.02 - 0.00153 \times \theta + 6.30913 \times 10^{-7} \times \theta^2 - 5.57095 \times 10^{-10} \times \theta^3\right] \quad (4)$$

when ($0°C \leq \theta \leq 800°C$).

4.5 | Effect of elevated temperature on residual flexural/tensile strength

Residual flexural strength is taken to be that strength which can be sustained by FRC after the first cracking (MOR) of the concrete has occurred. It is measured in numerous ways by standards proposed in various countries, however the two most common methods are the EN 14651[50] test method and the ASTM C1609 method.[51] The two test setups can be seen in Figure 10.

These two tests were the only ones adopted by the seven studies in this review that tested the residual flexural strength of MSFRC exposed to elevated temperatures. Details of these studies can be found in Table 6. For comparison, the ASTM C1609[51] results have been converted into EN 14651[50] format, wherein $f_{L/600} = f_{R1}$ and $f_{L/150} = f_{R4}$, acknowledging that these are not exactly the same crack width, but with the published data provides the best means of comparison. It is also for this reason that only the f_{R1} and f_{R4} values will be assessed in this study, with these values illustrated in Figures 11 and 12, respectively.

TABLE 5 Studies assessing effect of elevated temperature on flexural strengths of MSFRC

Author (year) and country	Macro synthetic fiber dose rate/s (kg/m^3)	Macro synthetic fiber dimensions	Macro synthetic fiber tensile strength	Macro synthetic fiber Young's modulus	Micro synthetic fibers used	Micro synthetic fiber dose rate/s	Micro synthetic fiber dimensions	Hybrid specimens used	Hybrid specimens dose rates and fiber types	Concrete strength grade
Abaeian (2018), Iran[42]	1, 2, and 3	50 mm length and 0.9 mm diameter	700 MPa	3.8 GPa	No	-	-	No	-	65 MPa
Alimrani (2020), Hungary[43]	4	50 mm length and diameter not provided	590 MPa	11 GPa	No	-	-	Yes	2 kg MSF + 40 kg SF	90 MPa
Cavdar (2013), Turkey[44]	2.73, 5.46, 8.19, and 10.92	10 mm length and 0.75 mm diameter	338 MPa (HPP) and 570–660 MPa (CPP)	1.55 GPa (HPP) and 4.7 GPa (CPP)	No	-	-	No	-	50 MPa (mortar)
Choumanidis (2016), Greece[46]	4.55 and 9.1	52 mm length and 0.46 mm diameter	613 MPa	5.4 GPa	Yes	4.55 and 9.1 kg/m^3	12 mm length and 25 μm diameter	Yes	40 kg steel fiber + 4.55 kg MSF and 4.55 kg MSF + 4.55 kg micro-PP	40 MPa
Francioso (2021), USA[56]	2.6, 5.1, and 7.7	Ranges from 2 to 40 mm length and 0.35 mm diameter average	5228 psi = 36 MPa	Not provided	No	-	-	No	-	40 MPa
Mirza (2021), Australia[40]	3.77 and 7.46	48 mm length and 0.7 mm diameter	640 MPa	12 GPa	No	-	-	No	-	40 MPa
Richardson (2017), UK[47]	4	40 mm length and 0.95 mm diameter	-	-	No	-	-	No	-	35 MPa
Serafini (2019), Brazil[48]	8	48 mm length and 0.72 mm diameter	640 MPa	10 GPa	Yes	0.8 kg/m^3	12 mm length and 30 μm diameter	Yes	8 kg/m^3 MSF + 0.8 kg/m^3 micro-PP	50 MPa
Sukontasukkul (2010), Thailand[49]	4.6 and 9.2	58 mm length and 0.8 mm diameter	450 MPa	Not provided	No	-	-	No	-	Not tested
Wu (2013), China[29]	2 and 3	45 mm length, diameter not provided	456 MPa	5.6 GPa	No	-	-	No	-	Not reported

It must also be noted that the Mirza et al.[40] study also had specimens with a temperature gradient, however, unlike the other studies where the temperature gradient within the specimen was provided, only the temperature on the specimen's surface was measured. Based on the temperature gradients noted in both Maluk et al.[15] and Sukontasukkul et al.,[52] it was decided to convert the surface temperatures provided in the Mirza et al. studies into an average specimen temperature using Equation (5).

$$\theta_{\text{Ave}} = 0.75 \times \theta_{\text{Surface}}. \tag{5}$$

In terms of the f_{R1} results, it can clearly be seen that there are some outlying data points extracted from the Sukontasukkul et al. study (i.e., the two highest results at 175–200°C). These are strangely high results and are a real anomaly compared to the rest of the dataset. It was proposed by Sukontasukkul et al.[52] that this increase at L/600 at low temperatures was caused by an increased interfacial bond strength being developed due to the slight increase in temperature, however this is not seen in the other studies. Another possible explanation is that the ambient L/600 results were just unusually low and possibly should have been repeated to confirm their suitability or otherwise. Using the statistical method discussed in Section 3.5, the two highest points were identified as outliers. A second assessment, with those removed, highlighted another three results from the same study. While the fit after the third regression was fine (0.564), another look at the studentized residuals highlighted the remaining Sukontasukkul et al.[52] results as outliers, hence it was decided to remove this study altogether from the analysis of the proposed relationship.

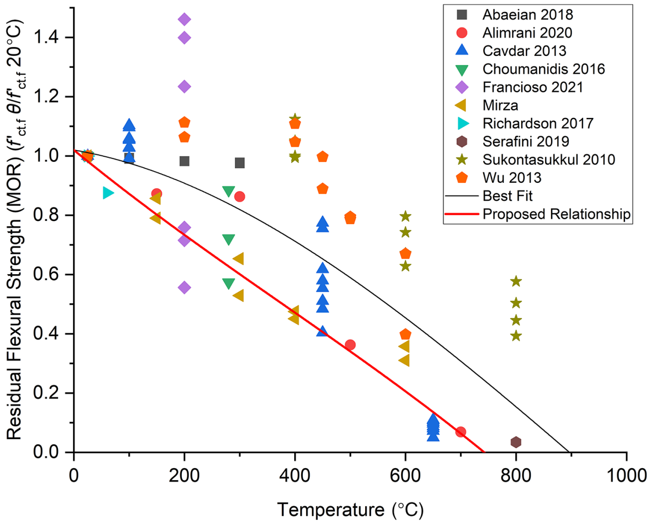

FIGURE 9 Comparison of experimental flexural strength results at elevated temperatures with the proposed relationship for flexural strength of macro synthetic fiber reinforced concrete as a function of temperature

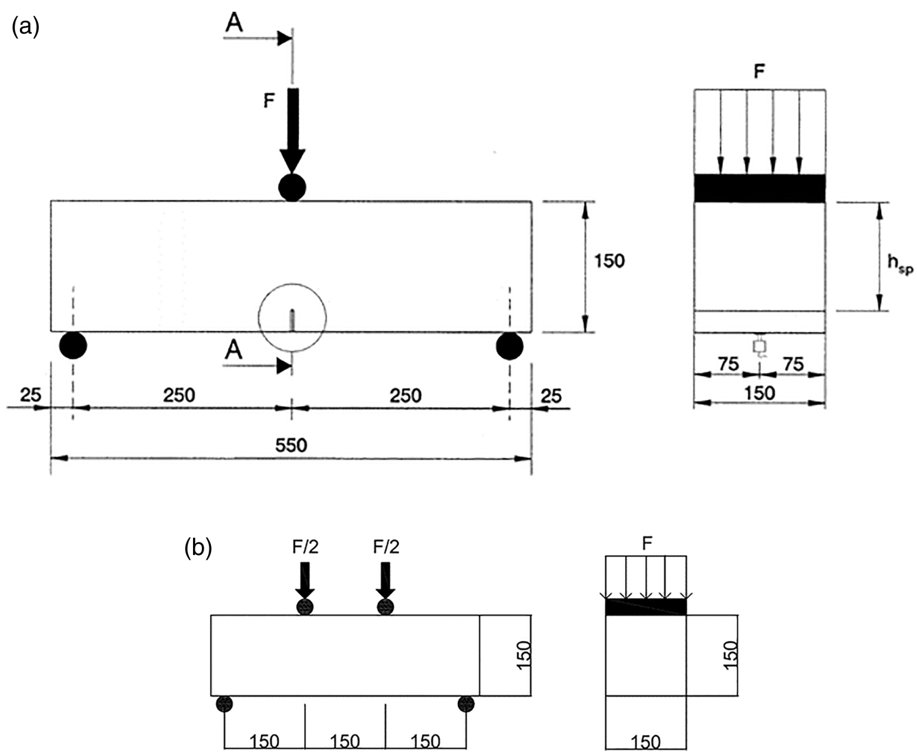

FIGURE 10 Comparison of the (a) EN 14561 notched beam test[59] with the (b) ASTM C1609 un-notched beam test[60]

TABLE 6 Studies assessing effect of elevated temperature on residual flexural tensile strength of MSFRC

Author (year) and country	Macro synthetic fiber dose rate/s (kg/m^3)	Macro synthetic fiber dimensions	Macro synthetic fiber tensile strength	Macro synthetic fiber Young's modulus	Micro synthetic fibers used	Micro synthetic fiber dose rate/s	Micro synthetic fiber dimensions	Hybrid specimens used	Hybrid specimens dose rates and fiber types	Concrete strength grade
Alberti (2020), Spain[54]	0, 3, 10	60 mm long, 1.13 mm diameter	560 MPa	9 GPa	No	-	-	No	-	50 MPa
Choumanidis (2016), Greece[46]	4.55 and 9.1	52 mm length and 0.46 mm diameter	613 MPa	5.4 GPa	Yes	4.55 and 9.1 kg/m^3	12 mm length and 25 μm diameter	Yes	40 kg steel fiber + 4.55 kg MSF and 4.55 kg MSF + 4.55 kg micro-PP	40 MPa
Francioso (2021), USA[56]	2.6, 5.1, and 7.7	Ranges from 2 to 40 mm length and 0.35 mm diameter average	5228 psi = 36 MPa	Not provided	No	-	-	No	-	40 MPa
Mirza (2021), Australia[40]	3.77 and 7.46	48 mm length and 0.7 mm diameter	640 MPa	12 GPa	No	-	-	No	-	40 MPa
Richardson (2017), UK[47]	4	40 mm length and 0.95 mm diameter	-	-	No	-	-	No	-	35 MPa
Serafini (2019), Brazil[48]	8	48 mm length and 0.72 mm diameter	640 MPa	10 GPa	Yes	0.8 kg/m^3	12 mm length and 30 μm diameter	Yes	8 kg/m^3 MSF + 0.8 kg/m^3 micro-PP	50 MPa
Sukontasukkul (2018), Thailand[52]	4.5 and 9.1	58 mm length and 1.1 mm diameter	450 MPa	Not provided	No	-	-	No	-	Not provided

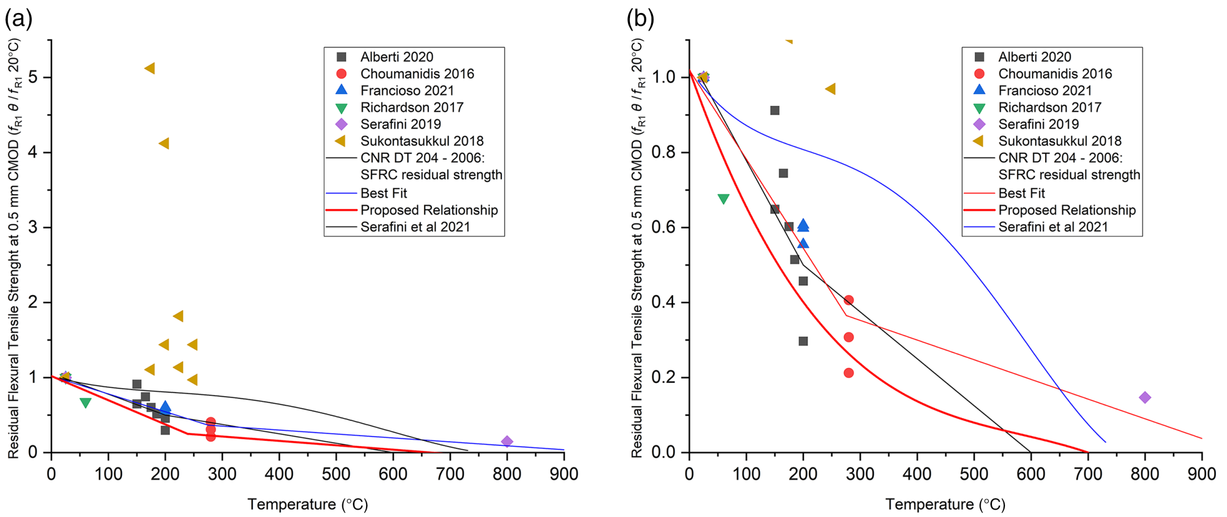

FIGURE 11 Comparison of experimental f_{R1} results at elevated temperatures with the relationship provided by the Italian guideline CNR DT 204 for FRC,[5] the relationship for macro synthetic fiber reinforced concrete proposed by Serafini et al.[61] and the proposed relationship for f_{R1} of MSFRC as a function of temperature (a) all results and (b) only results <1

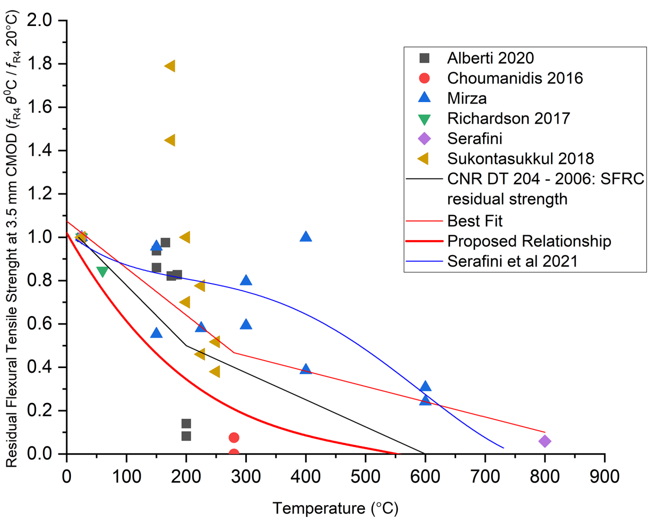

FIGURE 12 Comparison of experimental f_{R4} results at elevated temperatures with the relationship provided by the Italian guideline CNR DT 204 for FRC,[5] the relationship for macro synthetic fiber reinforced concrete (MSFRC) proposed by Serafini et al.[61] and the proposed relationship for f_{R4} of MSFRC as a function of temperature

Figure 11 illustrates the best fit relationship of f_{R1} as a function of temperature (adj. $R^2 = 0.884$), along with the CNR DT 204 published relationship for steel FRC as a function of temperature. Finally, the proposed relationship is also depicted, which provides a lower bound for this critical design value, alongside the relationship proposed by Serafini et al.[53] recently for FRC. The equation for the proposed relationship can be found in Equation (6).

$$f_{R1}\theta = f_{R1}\left[1.02 - 0.00429\times\theta + 6.74121\times10^{-6}\times\theta^2 - 3.85326\times10^{-9}\times\theta^3\right] \quad (6)$$

when ($0°C \le \theta \le 800°C$).

Regarding the f_{R4} results, it was also observed that the results from the Sukontasukkul et al. study for L/150 at 175°C were clear outliers from the dataset according to the studentized residuals from the regression analysis. It is suggested again here that the ambient results for the 0.5% dose rate were far lower than expected and possibly should have been repeated in the study for validation of the low results. However, even with those results removed, the dispersion was quite large, so the studentized residuals were studied again and a further three results were deemed outliers and removed from the determination of the proposed relationship. These were the highest result from Mirza et al.[40] and the lowest results from Alberti et al.[54]

Figure 12 depicts the experimental f_{R4} results extracted from the various studies, compared with a best fit of f_{R4} as a function of temperature (adj. $R^2 = 0.661$), along with the CNR DT 204[5] relationship for SFRC. Also highlighted in Figure 12 are the proposed relationship from this study and that proposed by Serafini et al.[37] for FRC. The proposed relationship encompassing the lower bound of outcomes is illustrated in Equation (7). As with Equation (6), Equation (7) provides a conservative fit for this critical MSFRC design parameter.

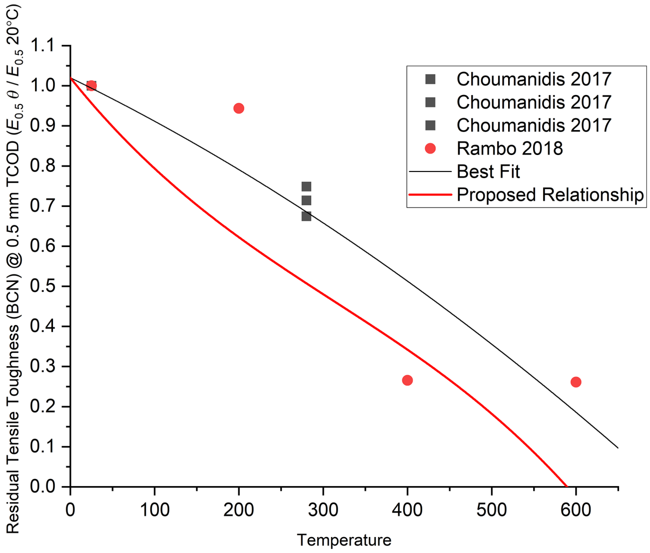

FIGURE 13 Comparison of experimental residual tensile toughness at 0.5 mm total circumferential opening displacement (TCOD) results at elevated temperatures with the proposed relationship for residual toughness at 0.5 mm TCOD of macro synthetic fiber reinforced concrete as a function of temperature

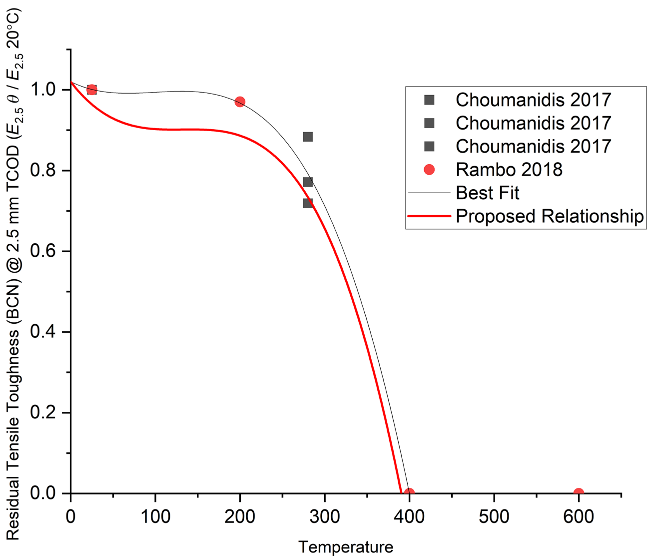

FIGURE 14 Comparison of experimental residual tensile toughness at 2.5 mm total circumferential opening displacement (TCOD) results at elevated temperatures with the proposed relationship for residual toughness at 2.5 mm TCOD of macro synthetic fiber reinforced concrete as a function of temperature

$$f_{R4}\theta = f_{R4}\left[1.02 - 0.00487\times\theta + 8.60126\times10^{-6}\times\theta^2 - 5.66849\times10^{-9}\times\theta^3\right] \quad (7)$$

when $(0^\circ C \le \theta \le 600^\circ C)$.

Finally, two studies utilized the Barcelona double punch test as a means of assessing the residual tensile capacity of MSFRC exposed to elevated temperatures. The test setup was depicted earlier in Figure 6c,d and utilizes punches on the top and bottom of a cylindrical specimen to induce tensile forces in the cylinder and initiate cracks in such a way to force the cylinder to expand circumferentially. As results from one of the studies only considered two strains when recording their results, then only these two values can be shown. Also, while Rambo et al.[41] reported both residual strength and toughness, Choumanidis et al.[45] only reported toughness. Hence, Figures 13 and 14 depict the normalized toughness results extracted from these two studies at 0.5 and 2.5 mm total circumferential opening displacement (TCOD) (Table 7).

It can be seen in Figure 13 that the 600°C result of 0 is the same as the 400°C result meaning that the 600°C result is practically void. Hence, this 600°C result was removed from the regression analysis. Equation (8) depicts the proposed relationship illustrated in Figure 12 (best fit curve – adj. R^2 = 0.86), while Equation (9) shows the relationship proposed in Figure 13 (best fit curve – adj. $R^2 = 0.978$).

$$E_{0.5}\theta = E_{0.5}\left[1.02 - 0.00273\times\theta + 2.08156\times10^{-5}\times\theta^2 - 5.25443\times10^{-8}\times\theta^3\right] \quad (8)$$

when $(0^\circ C \le \theta \le 700^\circ C)$.

$$E_{2.5}\theta = E_{2.5}\left[1.02 - 0.00483\times\theta + 8.27136\times10^{-6}\times\theta^2 - 5.53994\times10^{-9}\times\theta^3\right] \quad (9)$$

when $(0^\circ C \le \theta \le 500^\circ C)$.

5 | DISCUSSION

5.1 | Heating regimes and temperatures

The primary aim of this systematic review was to assess the relative strength of MSFRC at elevated temperature by extracting this data from the included 23 studies. Various heating regimes were employed by each author using different equipment (as seen in Table 1) making the task of combining these results to make an overall assessment challenging. Many authors adopted slow heating rates

TABLE 7 Studies assessing effect of elevated temperature on residual tensile strength (Barcelona test) of MSFRC

Author (year) and country	Macro synthetic fiber dose rate/s (kg/m^3)	Macro synthetic fiber dimensions	Macro synthetic fiber tensile strength	Macro synthetic fiber Young's modulus	Micro synthetic fibers used	Micro synthetic fiber dose rate/s	Micro synthetic fiber dimensions	Hybrid specimens used	Hybrid specimens dose rates and fiber types	Concrete strength grade
Choumanidis (2017), Greece[45]	4.55 and 9.1	52 mm length and 0.46 mm diameter	613 MPa	5.4 GPa	Yes	4.55 and 9.1 kg/m^3	12 mm length and 25 μm diameter	Yes	40 kg steel fiber + 4.55 kg MSF and 4.55 kg MSF + 4.55 kg micro-PP	40 MPa
Rambo (2018), Brazil[41]	8	48 mm length and 0.7 mm diameter	640 MPa	10 GPa	Yes	0.8 kg/m^3	12 mm length and 30 μm diameter	Yes	8 kg/m^3 MSF + 0.8 kg/m^3 micro-PP	50 MPa

using oven equipment to apply heat to all sides of their specimens, aiming to achieve a constant temperature throughout, while others utilized a furnace and only exposed one side of the specimen to the elevated temperatures, leading to significant temperature gradients within the specimens. Even those who utilized the oven system may still have a slight temperature gradient within the specimen as discussed by Rambo et al.[41] who noted that in their specimens that were subjected to 400°C in the oven had only 52% of the cylinder in which the MSFs had melted, meaning that the inner portion of the specimen had remained below 200°C. Some studies left specimens in the oven for prolonged periods at the target temperature which may have led to a uniform temperature in their specimens.

For the purpose of defining a relative strength at each temperature, a uniform heating through the specimen is ideal, however in reality, fire often only impacts a concrete element from one side, such as a tunnel lining, and hence a temperature gradient is a more realistic outcome. The other key point to note here is that where a temperature gradient occurs in the cross section, the thickness of the cross section starts to have a much greater impact on the residual behavior of the element, as thicker cross sections will lose significantly less capacity than thin sections, due to concrete's excellent insulating properties.

5.2 | Compressive and splitting tensile strength

Compressive strength was the mechanical property most commonly examined in the studies considered in this review. While the EC2 values[21] and the Aslani and Bastami[24] relationship were a good fit for the data extracted from this study and matched will with the best fit curve, it is recommended to adopt Equation (1) when assessing the relative compressive strength of MSFRC at elevated temperatures. This provides a conservative estimate for the reduced capacity based on all the studies included in this review. The close fit of the three curves demonstrates that MSFRC can be treated in a similar manner as plain concrete in terms of fire resistance design for compressive strength, with slight modifications as provided in this review.

Splitting tensile strength was another mechanical property prominent in this review. While the test methods for determining the splitting tensile strength may have varied somewhat, the results are comparable as they are all normalized against the behavior at ambient conditions for the chosen mix. A clear trend is evident in the results and the EC2 values provide a conservate estimate for the splitting tensile strength behavior of MSFRC at elevated temperatures, although Equation (2) provides a better fit for the extracted data and is slightly more conservative at lower temperatures, whereas the EC2 values are more conservative at the higher temperatures.

5.3 | Flexural and residual flexural strength

Flexural strength of MSFRC was the second most commonly studied mechanical property in this review. Some studies purely studied the MOR while others investigated a full load deflection curve to determine residual flexural strengths of the FRC. These tests still provide a MOR, or in the case of EN 14651 a strength at the limit of proportionality, which for the purpose of the study was considered equivalent to the MOR when compared in normalized terms. The relative flexural strength at elevated temperatures shows a very similar trend to the relative tensile strength, which could be expected as these properties are related. Hence, even though it is not plotted in Figure 8, the EC2 relationship for tensile strength at elevated temperatures will also provide a conservative estimate for the flexural strength of MSFRC at elevated temperatures, further demonstrating that the addition of MSFs to concrete has little negative impact on the main mechanical properties of plain concrete.

Residual flexural strength, while being one of the most important properties of FRC, was one of the least studied mechanical properties in the literature. While some clear outliers were observed, the general trend was quite similar for both f_{R1} and f_{R4} with the relative strengths trending to 0 between 550 and 700°C. Plotted against the extracted experimental results is the relationship described in the Italian CNR DT 204[5] that was originally proposed by Colombo[23] for SFRC, along with the relationship determined by Serafini et al.[37] for FRC. The best fit curve and the CNR DT 204 relationship are quite similar for both f_{R1} and f_{R4} both in terms of shape and magnitude. The proposed relationship accounts for the lower bound so that 90% of results will fall above it, leading to a slightly more conservative approach in both cases than the CNR DT 204 relationship. The relationship proposed by Serafini et al.[53] based on the work conducted by Serafini et al.[48] that was included in this review is less conservative, providing the least reduction in strength with increasing temperature. This was based on a single experiment and still fits within the envelope of data extracted in this study, further proving the proposed relationships to be a good and conservative approach.

The Barcelona test was also adopted by two authors to assess the residual strength of MSFRC at elevated temperatures. As discussed, both studies included toughness results, so these were used for comparison in this research. These results depict a less severe reduction in residual tensile behavior of MSFRC at lower temperatures than that suggested by the beam tests, while the reduction as the temperatures increase is significantly more pronounced. This could have occurred due to the significantly smaller specimen size leading to a larger percentage of the specimen being impacted by the elevated temperature and hence a more severe degradation of the results as temperatures increase. It could also be due to the difference of measurement used for the comparison, one being residual strength while the other was toughness.

6 | CONCLUSIONS

Starting with 1338 titles and abstracts, this systematic review found 23 papers that studied the impact of elevated temperatures on the mechanical properties of MSFRC. From there, the characteristics of the studies were obtained and summarized in tables, while the mechanical properties of MSFRC subject to elevated temperatures were extracted from each study and normalized against the control specimen for that mix at ambient temperatures. This enabled comparison of the results between studies and relationships to be formed based on the combined datasets. The key findings from this review are:

1. The main mechanical properties of concrete, such as compressive and tensile strength, are unchanged at elevated temperatures with the addition of MSFs. Both properties are well characterized by the EC2 relationships for plain concrete, however a more conservative approach is provided for compressive strength based on the extracted data.
2. The elastic modulus of MSFRC at elevated temperatures was also found to match that of plain concrete and was well characterized by the previously derived relationship for concrete at elevated temperatures proposed by Alsani and Bastami.[24] Again, a more conservative relationship was proposed based on the extracted data.
3. The residual flexural/tensile strengths were also presented as normalized results against the control specimens at ambient conditions. Key parameters such as f_{R4} and $E_{2.5}$ were compared from the respective studies with the outcomes suggesting that these parameters could also be well characterized by existing relationships proposed by the Italian CNR DT 204 for steel FRC at elevated temperatures. Slightly more conservative relationships for f_{R1} and f_{R4} were proposed based on the extracted data to ensure safety when implementing MSFRC in fire critical infrastructure.

Further research is required in this area with a focus on the residual flexural strength of MSFRC at elevated temperatures. It is clear from this study that the temperature gradient within the specimen has a large impact on the final outcome and hence the specimen size will also have a significant role to play. Therefore, experiments considering the effect of specimen size and temperature gradient on the impact of elevated temperature of MSFRC would provide a significant enhancement to data presented in the current study.

NOMENCLATURE

θ	temperature (°C)
E_c	elastic modulus of concrete
$E_c\theta$	elastic modulus of concrete at specified temperature (θ)
$E_{0.5}$	energy absorbed at 0.5 mm TCOD (Barcelona test)
$E_{2.5}$	energy absorbed at 2.5 mm TCOD (Barcelona test)
$E_{2.5}\theta$	energy absorbed at 2.5 mm TCOD (Barcelona test) at specified temperature (θ)
f'_c	compressive strength of concrete (MPa)
$f'_c\theta$	compressive strength of concrete (MPa) at specified temperature (θ)
f'_{ct}	tensile strength of concrete (MPa)
$f'_{ct}\theta$	tensile strength of concrete (MPa) at specified temperature (θ)
f'_{ctf}	flexural strength of concrete (MPa)
$f'_{ct.f}\theta$	flexural strength of concrete (MPa) at specified temperature (θ)
$f_{L/600}$	residual flexural strength of FRC at a displacement equal to the $\frac{span}{600}$ (according to ASTM C1609)
$f_{L/150}$	residual flexural strength of FRC at a displacement equal to the $\frac{span}{150}$ (according to ASTM C1609)
f_{R1}	residual flexural strength of FRC at a crack mouth opening displacement (CMOD) of 0.5 mm
$f_{R1}\theta$	residual flexural strength of FRC at a CMOD of 0.5 mm at specified temperature (θ)
f_{R4}	residual flexural strength of FRC at a CMOD of 3.5 mm
$f_{R4}\theta$	residual flexural strength of FRC at a CMOD of 3.5 mm at specified temperature (θ)
UPV	ultrasonic pulse velocity of hardened concrete specimens
UPV_θ	ultrasonic pulse velocity of hardened concrete specimens at specified temperature (θ)
θ_{Ave}	average temperature within a concrete section after being subject to elevated temperatures
$\theta_{Surface}$	surface temperature of a concrete section while being subject to elevated temperatures

AUTHOR CONTRIBUTIONS

All authors equally contributed to this manuscript. All authors have read and agreed to the published version of the manuscript. **Todd Clarke:** conceptualization, data analysis, formal analysis, investigation, methodology, resources, software, visualization, original draft. **Matt Ghiji:** investigation, methodology, software, review and editing. **Sam Fragomeni**: review and editing. **Maurice Guerrieri:** software, review and editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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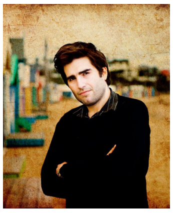

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