Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 31 No. 1s (2024)

Nonlinear Analysis of Steel Fiber Reinforced Recycled Aggregate Concrete under Compression, Tension, and Elevated Temperatures

Dr. Uday Shankar Patil[1], Dr Udaykumar Phatak[2], Prof. Neeraj Arun Gangurde[3], Prof. Ajinkya Suresh Hasabe[4], Dr. Shika Bharadwaj Shrivas[5], Dr. Uday Chandrakant Patkar[6]

[1]Head of Department of Civil Engineering

Bharati Vidyapeeth's College of Engineering, Lavale, Pune, India.

uday.patil@bharatividyapeeth.edu

[2]Associate Professor, Civil, ADCET Ashta.

[3]Assistant Professor Civil, Bharati Vidyapeeth's College of Engineering, Lavale, Pune.

Email ID: neeraj.gangurde@bharatividyapeeth.edu

[4]Assistant Professor Civil, Bharati Vidyapeeth's College of Engineering, Lavale, Pune.

Email ID: ajinkya.hasabe@bharatividyapeeth.edu

[5]Head of Department of Engineering Science

Bharati Vidyapeeth's College of Engineering, Lavale,Pune, India

shikha.shrivas@bharatividyapeeth.edu

[6]Head of Department of Computer Engineering

Bharati Vidyapeeth's College of Engineering, Lavale , Pune, India

uday.patkar@bharatividyapeeth.edu

Article History:

Received: *24-01-2024*

Revised: *29-03-2024*

Accepted: *15-04-2024*

Abstract:

In this study, we report on experiments conducted to determine the compressive behaviour of steel fibre reinforced-recycled coarse aggregate concrete (SFRCAC). Many researchers are interested in exploring the utilize of recycled aggregate in concrete for its potential to reduce environmental impact. By using recycled materials in place of natural ones, Recycled Aggregate Concrete (RAC) represents a novel environmentally friendly construction material. Processing waste concrete with a high proportion of building waste yields recycled aggregates. Natural sand & gravel reserves have been drastically depleted, and natural resources used, as a result of the expansion of the construction sector. Fire damage caused by spalling is a major issue when considering the use of such concrete in construction. SFRAC could help with this. In this research, we provide the outcomes of an investigational study into the compressive properties, particularly the compressive strength, of SFRAC cylinders subjected to extreme temperatures. Compressive mechanical characteristics of concrete were studied as a function of temperature (room temperature, 200 °C, 400 °C, & 600 °C) & steel fibre volume percentage (0%, 0.5%, 1%, 1.5%). Adding steel fibres to RAC that has been heated at high temperatures greatly improves its ductility & cracking behaviour, making it more appropriate for usage in building construction since it lessens the likelihood of spalling

Keywords: Recycled aggregate concrete, SFRCAC, Steel fiber, Elevated temperature, Stress–strain.

1. INTRODUCTION

Its high mechanical strength and improved fracture qualities have drawn researchers and industry worldwide to fiber-reinforced recycled aggregate concrete (FRAC) in practical engineering [1]. When used as recycled aggregate, C&D debris is transformed into a highly sustainable building material known as FRAC. RAC is a type of concrete in which a portion of the traditional natural aggregates (such as gravel and sand) used in conventional concrete is replaced with recycled aggregates derived from various sources. These recycled aggregates can come from crushed concrete waste, demolished structures, construction and demolition debris, and other industrial by-products. Recycled aggregates, steel fibres, & cementitious binders come together to form steel fibre reinforced recycled aggregate concrete (SFR-RAC). Steel fibres improve the concrete's mechanical characteristics and durability, & recycled aggregates lessen the pollution caused by the cement making process.

The effects of elevated temperatures on the compressive properties of SFRAC were the subject of an experimental study reported here. This research contributes to a larger body of work investigating how to mitigate the destructive effects of fire and extreme heat on RAC. The results of this study help increase the usage of RAC in structures, especially building structures, by clarifying the part steel fibres play in the material's performance after being subjected to high temperatures.

Recycled concrete aggregate

The term "recycled concrete aggregate" states to the aggregate material created from crushed building & demolition waste, most of which consists of concrete but also containing sand, gravel, slag, & crushed stones. To be labelled as RCA, the original material must have been concrete [2].

Producers can make concrete aggregate of a desired size and quality by crushing and compressing existing waste concrete & mixing it with aggregate. It also includes reusing items that would have otherwise been dumped in landfills. RCA begins with the collection of concrete from sources such old roadways, bridges, and buildings that have been torn down. The concrete is next refined by removing any foreign components, such wood or metal fragments that could compromise the final product's durability. Recycled concrete aggregate is just one type of aggregate that may be made from waste materials. RCA, while not the best choice for the first layer of a construction on dry or hard ground, is ideal for use in compaction. In comparison to natural stone or traditional concrete, RCA is generally considered to be more cost-effective. This is because it is not a mineral and can be manufactured with little effort. Tax credits and other incentives for businesses that use renewable resources can boost their overall savings.

Strength & Durability of Recycled Aggregate

Recycled aggregate has a penetrability (the ability to absorb water) of 7.5, well over the 3.7 minimum mandated by the WSDOT's construction division. Gravel's inherent absorption rate, along with the paste's, accounts for the increased rate. The strength, compression-resistance, & modulus elasticity of the cured cast are all characterized by the specific gravity of the recycled aggregate, which varies across the aggregate. However, the mix's durability can be negatively impacted by as much as a tenfold by employing recycled aggregate with a percentage of more than 65 percent. A maximum of 35% should be used when mixing with concrete. While recycled aggregate is certainly robust, it is not as sturdy as natural coarse aggregate, as has been demonstrated in a number of trials. However, the mixture can be strengthened by adding elements like fly ash [3].

Designing SF-RAC in artificial intelligence and machine learning

Designing steel fiber reinforced recycled aggregate concrete (SF-RAC) for different loading conditions (compression, tension, and elevated temperature) using artificial intelligence (AI) and machine learning (ML) involves tailoring the mix design and material properties to optimize mechanical performance under specific circumstances. Here's a more focused approach for each loading condition:

1. **Compression Performance:**
   - **Data Collection:** Gather a dataset containing information about SF-RAC mixtures, including steel fiber type, content, recycled aggregate properties, curing conditions, and compressive strength.
   - **Feature Selection:** Identify relevant features such as steel fiber volume, recycled aggregate replacement ratio, curing duration, and mix proportions.
   - **Model Selection:** Use regression algorithms to predict compressive strength based on the input features.
   - **Training and Validation:** Train the model using a subset of the dataset and validate its accuracy on unseen data.
   - **Optimization:** Utilize AI-driven optimization techniques to find the optimal combination of features that maximize compressive strength.
2. **Tension Performance:**
   - **Data Collection:** Gather data related to SF-RAC mixtures and tensile strength measurements. Consider additional data for factors like crack propagation and post-cracking behavior.
   - **Feature Selection:** Choose features such as fiber type, fiber volume, aggregate properties, and curing conditions, along with potential features related to tensile behavior.
   - **Model Selection:** Develop ML models that predict tensile behavior, including crack initiation and propagation, based on input features.
   - **Training and Validation:** Train the model using available data and validate its performance using separate datasets or cross-validation techniques.
   - **Optimization:** Optimize fiber content, aggregate replacement ratio, and other parameters to enhance tensile performance.
3. **Elevated Temperature Performance:**
   - **Data Collection:** Collect data on SF-RAC behavior under elevated temperature conditions, including mechanical properties degradation, spalling behavior, and residual strength.
   - **Feature Selection:** Identify features relevant to temperature effects, such as fiber type, volume, aggregate properties, and temperature exposure.
   - **Model Development:** Build models that predict changes in mechanical properties under elevated temperatures using AI and ML techniques.

Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 31 No. 1s (2024)

- **Training and Validation:** Train the models using data from various temperature exposure scenarios and validate their predictions against experimental results.
- **Optimization:** Incorporate optimization strategies to enhance the SF-RAC mix design for improved performance at elevated temperatures.

4. **Integrated Approach:** Consider an integrated approach that combines the results from the individual loading condition models. For instance, an optimization algorithm can optimize the SF-RAC mixture to simultaneously meet compressive strength requirements under compression, tensile strength requirements under tension, and maintain sufficient residual strength at elevated temperatures.
5. **Deployment and User Interface:** Develop a user-friendly interface or software tool that allows engineers to input loading conditions, performance criteria, and constraints. The tool can then provide optimized SF-RAC mix designs that cater to specific mechanical performance requirements.
6. **Continual Learning and Updates:** As more data becomes available through testing and research, continue to refine and update the AI models to improve their accuracy and applicability.

2. Experimentation

In this investigation, a total of 5 sets of specimens were constructed & evaluated; each set included 12 typical cylinders measuring 150 mm in diameter & 300 mm in height. The next sections detail the composition of the mixture, the method used to prepare the specimens, & loading system that was used.

2.1. Constituent materials

- The supplier's data sheet indicates that the ordinary Portland cement used in the mix has a strength of 42.5 MPa.
- Medium-coarse river sand from natural sources, with a quality modulus of 2.52 & moisture content of 0.8% (by weight) & obvious density of 2580 kg/m3.
- Maximum particle size of 30 millimetres for the limestone used in the NCA.
- The 4-30 mm size range of RCA aggregate is the result of crushing old concrete. According to Xiao [4], the optimum ratio is 3 parts by weight of fine recycled coarse aggregate (FRCA, with diameters between 4 mm & 8.5 mm) to 2 parts by weight of coarse RCA (CRCA, with sizes between 10 & 30 mm).
- Rectangular cross-sectional corrugated steel fibres fabricated from standard steel with a melting point of around 1500 C & density of 7.85 g/cm3. The tensile strength of the fibres was 600 MPa, and their length was 32 mm.
- The solid content of this naphthalene-based admixture is 30%, & water-reducing rate is 20%.

Natural coarse aggregates (NCA) tested at 0.76 percent water absorption, while RCA tested at 3.08 percent. Figure 1 depicts the concrete aggregates & steel fibres.

(a) NCA

(b) FRCA

(c) CRCA

(d) Steel Fibers

Fig. 1. Coarse aggregates & steel fibers

2.2. Mix proportioning

Five different concrete mixes were created to examine the effect of steel fibre content on the axial compressive behaviour of RAC when subjected to increased temperatures (25 °C, 200 °C, 400 °C, & 600 °C). The first batch used natural coarse aggregate, while the next 4 batches substituted RCA for natural coarse aggregates volume for volume. A free water-to-cement ratio of 0.46 was maintained across all five concrete mixtures. The high water absorption capacity of RCA necessitated the addition of an extra 3.08% water by weight of RCA to each of the four RAC mixes. Steel fibres made up 0.5%, 1%, & 1.5% of the volume of three of the RAC blends, respectively. Table 1 summarises the mix specifications, differentiating between the NC (natural aggregate) & RAC concretes. If steel fibres are included, the mix will be labelled as SFRACx, where "x" is the percentage by volume of steel fibres added, for example, SFRAC5 would indicate that 5% of the SFRAC is composed of steel fibres.

Table 1 Proportions mix (kg/m3) & cube compressive strength (28 days and 1 year).

Mix	W/C	W	PC	Sand	NCA	RCA		AW	SF	WRA	28 day cube strength (mpa)	1 yrs cube strength (mpa)
						FRCA	CRCA					
NC	0.46	203.28	440	670	1092					6.6	64.9	66.3
RAC	0.46	203.28	440	670		585	390	30		6.6	57.9	72.6
SFRAC5	0.46	203.28	440	670		585	390	30	39	6.6	55.3	64.3
SFRAC10	0.46	203.28	440	670		585	390	30	78	6.6	51.9	63.8
SFRAC15	0.46	203.28	440	670		585	390	30	117	6.6	52.3	68.3

2.3. Specimen preparation

We used a concrete mixer to combine the ingredients. Plastic moulds were used to cast 12 cylindrical samples of each mix, each measuring 150 mm in diameter & 300 mm in height. Casting each batch of concrete cylinders from the same mould ensured consistency. The concrete was made by adding coarse aggregates, sand, cement, and steel fibres to a mixer, as described in [5]. They were blended for three minutes in a mixer after the addition of water and super-plasticizer. The concrete was mixed for an additional 2 minutes, during which time the steel fibres were uniformly distributed throughout the mix [6]. The concrete's workability was evaluated using the GB/ T 50080-2002 [7] concrete slump test. Cast concrete samples were stored in plastic bags at room temperature for 24 hours before demolding. The samples were cured in water for 28 days after being taken out of the moulds, and then they were kept in the Materials Lab at Guangdong University of Technology at a constant temperature of about 25 °C.

2.4. Test method

2.4.1. Heating scheme

Following this heating strategy, specimens were heating in an electric furnace:

- Heating rate: Poon et al. [8] recommend a steady pace of 2.5 0C/min until the desired temperature is reached. This heated rate is far lower than the typical ISO 834 curve [9], but if just the centre of the columns (i.e., inside the spirals or hoop ties) is of importance, this difference is negligible. It is beyond the scope of this research to discuss how the concrete cover may react to a fast spreading fire. The cover concrete would act as a thermal barrier, reducing the heating rates & peak temperatures within the core concrete. It should also be noted that the heating of concrete within a real structure during a real fire is not necessarily reflective of the typical fire [10].
- Soaking period: Poon et al. [8], Peng et al. [11], & Cavdar [12] all found that 1 hour was the optimal time. A recent study [10] disproved the hypothesis that heating specimens of a similar size to those in this study for just one hour would be adequate to achieve a temperature uniformity throughout. Larger specimens are more likely to have a prolonged period of non-uniform temperature dispersion. Since the behaviour of concrete from various portions of the specimen will vary depending on the temperature antiquity, the residual attributes of a concrete will vary. Therefore, it may be necessary to use specimens of the same size & apply the same heating and cooling conditions in order to obtain similar test findings.
- Cooling rate (cooling curve): After 1 hour of immersion, the furnace was turned off & left closed so that the specimens may cool to room temperature without further exposure to heat, as described in [13]. Eight readings (one every half hour for four hours) of the furnace temperature were taken during the cooling phase (Fig. 2).
- Spalling prevention measures: Preventing spalling caused by excessive moisture emission during heating has previously been studied by heating specimens in the boiler at 105 °C or 120 °C for 24 h or 48 h (Rahim [14]). In this investigation, while one set of samples was being heated, another set was placed outside the boiler for pre-heating, a process that typically took between 6 and 9 hours. Explosive spalling was averted during heating thanks to this treatment and the selected slower rate of heating (2.5 0C/min).

Twelve cylindrical specimens were prepared from each mixture; three were examined directly after curing for around three months, and the remaining nine were divided into three group s& heated to 200 °C, 400 °C, & 600 °C in the electrical furnace, as described above. Fig. 2 displays the time-temperature curves of the heating procedure. All samples underwent pre- and post-heat treatment weighing. All samples were examined for color & crack changes on the surface after being subjected to high temperatures.

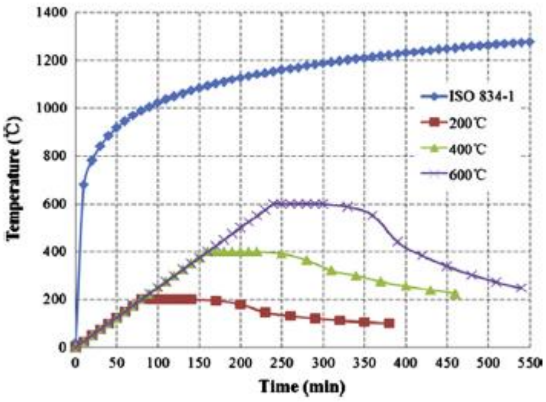
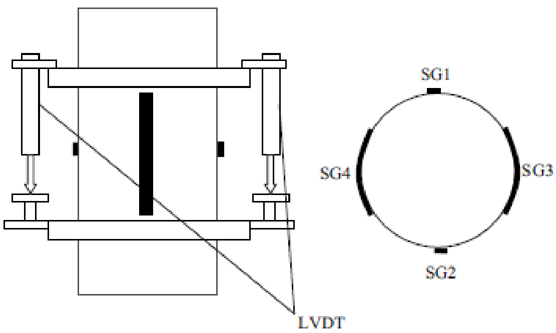


Fig. 2. Furnace temperature–time curve

2.4.2. Compression test

Each cylinder specimen had an even layer of gypsum The plaster used to cover its top and lower surfaces has a compressive strength of 800 MPa, making it very sturdy. According to ASTM C39/C39M [14] (Fig. 3(a)), compression tests were performed on all specimens using a 4000 kN MATEST compression machine at a constant displacement rate of 0.18 mm/min. Two strain gauges spaced 100 mm apart at mid-height were used to measure axial strains in each specimen, while two strain gauges spaced 80 mm apart at mid-height were used to portion hoop strains. Furthermore, two linear variable displacement transducers (LVDT) measuring a height of 120 mm were set 1800 apart to detect axial strains [15] (Fig. 3(b)).

(a) Testing setup



(b) Positions of Strain Gauges & LVDTs

Fig. 3. LVDT and strain gauge placement & testing

3. RELATED WORK

Tan Wang et al. (2023) [16] Uniaxial compressive testing was used to investigate the stress-strain behaviour of SFR-RAC after a fire. Tests are conducted with varying cement-to-water ratios, RCA additions, steel-fibre contents, & heating temperatures. The failure mechanism, strength, elastic modulus, peak strain, and strain-stress response of the samples are analysed. The results show that regardless of the temperature exposure, the compressive strength and elastic modulus decreased with increasing ratios of water to cement and/or RCA replacement ratio. At temperatures of 200, 400, 600, and 800 °C, the residual strength recovered to around 83%, 85%, 56%, and 23% of its original ambient compressive strength. Steel fiber's influence on the material's mechanical properties after heating increases. Results from compression tests were used to develop a simpler explicit formula that predicted the SFR-RAC's compressive strength, peak strain, elastic modulus, and uniaxial compressive stress-strain constitutive model.

Zhenzhen Liu et al. (2023) [17] For broad use of RAs, a novel steel-fiber-reinforced SSRCFST is suggested. The purpose of this research is to investigate what happens to moderately skinny SSRCFST columns when they're subjected to axial compression. The impacts of changing the ratio of steel tube diameter to wall thickness, the concrete strength grade, the rate of RA quality replacement, & percent of steel fibre in the concrete were all tested using a total of 27 specimens. The failure modes, load-deflection relationships, strain responses, ultimate bearing capacities, & deformation capacities of the specimens were investigated through a series of experiments. According to the results of the experiments, increasing the slenderness ratio caused the failure mode to switch from strength failure to buckling failure. While self-stress does increase the SSRCFST columns' ultimate bearing capacity, it also makes the second-order impact more pronounced, leading to a more rapid decline in the columns' strength. Modifications to the concrete constitutive rule and the incorporation of temperature-load applications led to the proposal of a revised finite element model of skinny SSRCFST columns. According to the numerical findings, self-stress has a role in the confinement effect during the first stage of elasticity. The compressive properties of thin SSRCFST columns are also accurately captured in a new prediction model that is proposed.

Qiuhong Zhao et al. (2022) [18] To encourage the use of SF-GRAC in structural engineering, the mechanical properties were studied experimentally. Several SF-GRAC specimens with varying amounts of steel fibres & recycled aggregates were constructed and subjected to compression, splitting tensile, & four-point flexural tests. The microstructure of the ITZ between the geopolymeric matrix & recycled aggregates or steel fibres was studied using a scanning electron microscope (SEM). In this study, we found that replacing Portland cement (OPC) with a geopolymer based on ground granulated blast furnace slag and fly ash significantly boosted the compressive, tensile, and flexural strengths of RCA while simultaneously decreasing its ductility and toughness. Adding steel fibres to SF-GRAC at a rate of up to 1.5% clearly enhanced its compressive, tensile, & flexural behaviour, making it superior to OPC concrete prepared with natural aggregates in terms of suitability for structural applications. The compressive & flexural toughness indices of SF-GRAC with 100% recycled aggregate and 1.5% steel fibres were over 160% & 170% higher than those of OPC concrete with natural aggregates, while the tensile strength improved by 38% & flexural strength by 41%.

Liang Li et al. (2022) [19] During the service life, explosion or impact loads, as well as fire, can all wreak havoc on a building's framework and its constituent parts. High strain rate loads and increased temperatures are sometimes the result of consecutive application to building structures and members. Steel fibre reinforced concrete beams (SFRCB) were tested using a battery of drop-weight impact experiments at high temperatures to learn more about their dynamic responses to blast or impact loads following exposure to fire. The specimens were heated in an electric furnace according to the heat time antiquity stated by the ISO834 normal temperature intensifying curve, and then subjected to drop weight effect loads as soon as they achieved the expected temperature. The dynamic performance of the specimen beams was found to be enhanced after steel fibre was added. When compared to a beam without steel fibre, the peak mid-span displacement at 600 °C is reduced by 8.9% and 19.6% when the steel fibre volume concentration is 1% and 2%, respectively. The specimen beam reinforced with 2% steel fibre has a peak impact force 8.5% higher than the specimen beam without steel fibre when subjected to 400 degrees Celsius. With a volume content of 1% steel fibre, the peak impact force of the specimen beam is 17.5% higher than that of the specimen beam without steel fibre at 600 °C, and with a volume content of 2% steel fibre, the peak impact force is 10.3% higher. Beams used as specimens may have their dynamic performance diminished by the increased temperature. To foretell the dynamic behaviours of the SFRCB after the fire, a finite element pretending model was constructed in LS-DYNA. In order to characterise the mechanical behaviours of SFRCB, the continuous surface cap (CSCM) constitutive model was used. Numerical simulations of the dynamic impact response of specimen beams at increased temperatures were compared with the equivalent experimental findings. The numerical results show a high degree of consistency with the experimental findings. Impact-induced damage to the specimen beams is more severe at elevated temperatures, as evidenced by experimental & numerical data, with more cracks and a bigger mid-span displacement. Both professionals & academics in the field of protective building design will benefit directly from this study.

Xiao-jun Ke et al. (2022) [20] To accomplish both of these goals, architects have developed a novel composite part called the SRRAC short beam. Six SRRAC short beams had their shear performance examined. The study included the shear span-to-depth ratio (0.76, 1.14, & 1.52), section steel types (I14 and I16), & RCA replacement ratio (0%, 50%, & 100%). Using ABAQUS, it was determined that the internal stress flow produced a force transmission channel during the SRRAC shearing process, which linked the loading end to the support. Shear bearing capacity of the short beams increased by 32.5 percent and 78.1 percent, respectively, when the span-to-depth ratio was reduced from 1.52 to 1.14 & 0.76. The short beams' shear performance was unaffected by the RCA replacement ratio. The secant stiffness & shear bearing capacity of the specimens were significantly improved by increasing the section steel composition. Finally, a formula for SRRAC's shear bearing capacity was proposed using modified compression field theory (MCFT). The proposed model demonstrated good applicability compared to the generally used prediction models, study provides a theoretical foundation for future engineering applications.

Xie Jian-he et al. (2015) [21] The use of recycled concrete & crumb rubber as aggregates to create green concrete is an exciting development in the quest for more environmentally friendly building materials. This research looks on the compressive & flexural behaviours of SFRAC, a novel concrete material made from recycled rubber tyres and steel fibres. An experimental investigation was done to examine the influence of the rubber content on the compressive & flexural behaviours of RSRAC in an effort to promote the use of this novel green building material. All together, we tested 18 × 150 mm cubes, 18 × 150 mm cylinders, & 18 × 150 mm 550 mm prisms with axial compressive stress and three-point bending. In the study, we replaced a portion of the sand with crumb rubber at volume fractions of 0%, 4%, 8%, 12%, and 16%. Steel fibre was added at a rate of 1% by volume, and RCA was substituted for natural coarse aggregate (NCA) at a volume of 100%. Compressive & flexural strength, failure mode, modulus of elasticity, and toughness of RSRAC were examined as a function of rubber content. As shown by the findings, RSRAC with the optimum rubber content outperforms regular NCA concrete in compressive strength. RSRAC can be used in place of traditional rubber concrete in the flexural members of concrete buildings, and it does so in a more sustainable manner.

4. OBJECTIVES

1. To determine the effect of high temperature on the mechanical properties of recycled-fiber concrete
2. To examine the effects of high temperatures on the compressive characteristics of SFRAC cylinders

5. RESEARCH METHODS

The methodology of a certain discipline is examined methodically and conceptually within the discipline of methodology. Conventions and assumptions in a given academic topic are the subject of this theoretical inquiry. Research refers to the process of investigating & learning about something new. In other terms, research is the practise of conducting in-depth, methodical studies.

This research paper collects current and pertinent literature on how high temperature affects fiber-reinforced recycled concrete mechanical performance from credible sources. Combinations of "RCA" & "mechanical properties at elevated temperatures," "steel fibre reinforced concrete" and "mechanical properties at elevated temperatures," "fibre reinforced concrete" and "mechanical properties at elevated temperatures," and "basalt fibre reinforced concrete" & "mechanical properties at elevated temperatures" were used in the keyword search. Keywords were used to sift through the existing literature & compile a comprehensive review. After gathering the relevant literature, the keywords were used to search the paper's main title and abstract for matches to the topic of interest.

6. RESULTS & DISCUSSION

Based on the outcomes of the compression tests, this section examines how the presence of steel fibres & high temperatures affect the material's compressive behaviour in terms of, among other things, failure mode, residual strength, Young's modulus (stiffness). We also talked about the outcomes of the mass loss test & visual inspection.

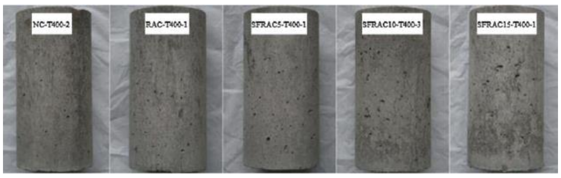
Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 31 No. 1s (2024)

6.1. Testing concrete samples visually

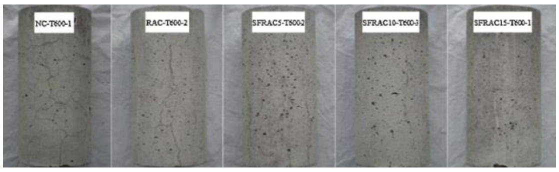
6.1.1. Color variations

Fig. 4 depicts the changes in coloration that occur in concrete at elevated temperatures. Normal room temperature concrete is a pale grey, but at 200 degrees Celsius, 400 degrees Celsius, and 600 degrees Celsius, the surface colour changes to yellow, grey brown, & grey white, respectively. It has been proven that the discoloration of concrete samples is linked to the chemical and physical changes the material undergoes when heated to high levels. [22-23].

(a) 200 degree Celsius-heated concrete cylinders



(b) 400 degree Celsius-heated concrete cylinders



(c) 600 degree Celsius-heated concrete cylinders

Fig. 4. Elevated temperature Celsius-heated concrete cylinders

6.1.2. Spalling

However, not all concrete specimens showed signs of explosive spalling when heated to high temperatures, even though this occurs frequently in concrete, especially high strength concrete [24]. The current study may have avoided spalling because of the slower heating rate (2.5 °C/min). In preliminary testing for this investigation, it was found that both NC and RAC spalled explosively when heated at a rate of 7 °C/min or higher. Explosive spalling failure is uncommon in RAC, which may be due to the steel fibre reinforcement & thermal expansion compatibility between the RCA & nearby cement paste. [8].

6.1.3. Cracking behavior

After being subjected to evaluated temperatures, cracking in RAC can be traced back to the initiation and development of stresses within & between the concrete constituents (cement paste & aggregate) initiating by water vapour pressure, thermal stresses by temperature variation amongs different parts of the concrete, & their interaction [25]. In this investigation, no visible cracks appeared in concrete samples heated to 200 degrees Celsius, whereas a few fine fissures appeared in those heated to 400 and 600 degrees Celsius. Cracks of increasing width and depth were noticed on the surfaces of the concrete specimens without steel fibre as the exposure temperature was raised, and this was the case whether or not RCA were utilised. Table 2 displays the results of crack width measurements taken with an accuracy of 0.01 mm. It is important to note that crack width measurements were taken in a number of different spots on all three specimens made from the same concrete. The widest cracks that were measured are the same as those in Table 2.

Table 2 Maximal crack widths (in millimetres) in concrete cylinders after heating them to 400 & 600 degrees Celsius.

Mix	**Temperature Exposure**							
	400℃				600℃			
	1	2	3	Mean	1	2	3	Mean
NC	0.20	0.20	0.28	0.23	0.54	0.72	0.78	0.68
RAC	0.24	0.28	0.16	0.23	0.66	0.72	0.78	0.72
SFRAC5	0.08	0.14	0.14	0.12	0.44	0.36	0.34	0.38
SFRAC10	0.10	0.08	0.1	0.09	0.36	0.26	0.32	0.31
SFRAC15	0.06	0.10	0.06	0.07	0.12	0.18	0.16	0.15

High-temperature exposure had a similar effect on both NC & RAC, as measured by the crack width, showing identical cracking behaviour. Maximum crack width as a function of steel fibre content is shown in Fig. 7. For each location in Fig. 7, the maximum crack width is an average of the values found in three different cylinders. The rest of the study test findings are presented in the same fashion, unless otherwise specified.

Error bars representing the double-sided standard deviation interludes for the mean values of the greatest crack width are also showed in Fig. 5. As indicated by Fig. 5, the so-called bridging effect of the steel fibres in RAC significantly inhibits the development of cracks caused by high temperature exposure, as found in ordinary concrete [24]. For the target exposure temperatures of 400 °C & 600 °C, the average maximum fracture width for the RAC specimens (RAC, SFRAC5, SFRAC10, & SFRAC15) fell from 0.23 mm to 0.07 mm & from 0.72 mm to 0.15 mm, correspondingly (see also Table 2).

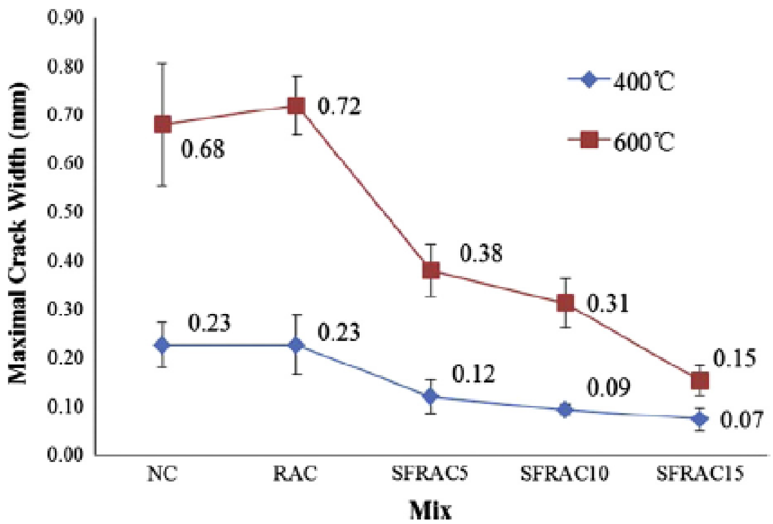
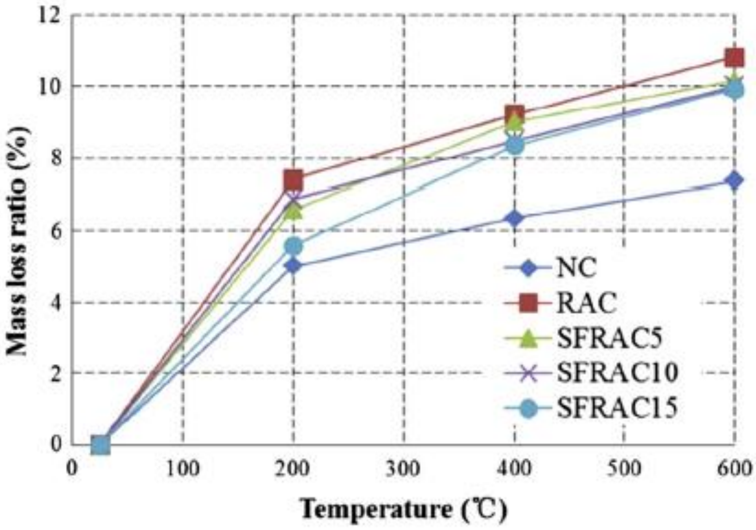


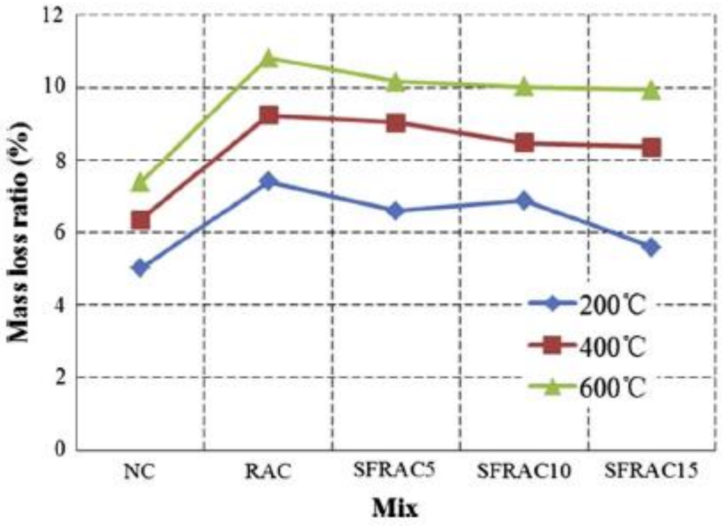
Fig. 5. Concrete specimens' maximum crack width

6.2. Mass loss

In Fig. 6, we see the amount of mass lost as a percentage of the starting quantity of mass due to exposure to high temperatures for a number of concrete mixtures. Figure 6(a) shows that the mass loss for each concrete mixture increased with increasing temperature. Specimens of RAC (specimens RAC + SFRACx in Fig. 6) lose on average of 6.62, 8.77, & 10.23 percent of their mass when heated to 200, 400, & 600 degrees Celsius, accordingly. The greatest amount of mass is lost between 20 & 200 degrees Celsius above ambient temperature. After that point, the loss grew nearly linearly along with the temperature at which it was exposed. This is because the principal cause of mass loss of concrete specimens during heating is water evaporation, which occurs between 25 °C & 200 °C. Evaporation can cause a significant amount of the water that makes up capillary water & physically absorbed water (gel water) in cement paste to be forced out of concrete when the temperature outside is above 200 °Cor. [27]. Water (crystal water) is also present in concrete in the form of calcium silicate hydrate (C-S-H) & calcium hydroxide ($Ca(OH)_2$) [28]. Until the chemical disintegration of $Ca(OH)_2$ or C-S-H at higher temperatures (400-600 °C for $Ca(OH)_2$ and 600-800 °C for C-S-H, respectively), the water contained in cement hydrate compounds remains trapped in the cement paste and is therefore sometimes referred to as "non-evaporable water" [27]. Because RCA concrete absorbs more water, its mass loss ratio is larger than that of regular concrete (Table 1). This is because RCA concrete has a higher percentage of evaporable water than standard concrete. Above 200 °C, most mass loss is due to the evaporation of gel water (between 200 and 400 °C) and crystal water (between 400 and 600 °C) linked with the breakdown of $Ca(OH)_2$ [26]. As can be shown in Fig. 6(b), adding steel fibre to RAC had almost no effect on mass loss for specimens heated beyond 200 °C. This is due to the fact that steel fibres put a cap on fracture growth, which can prevent moisture from escaping during high temperatures. However, since moisture evaporation does not depend on the creation of large fissures, this may have little or no effect.



(a) Influence of temperature exposure on mass loss



(b) Impact of steel fibre on mass loss

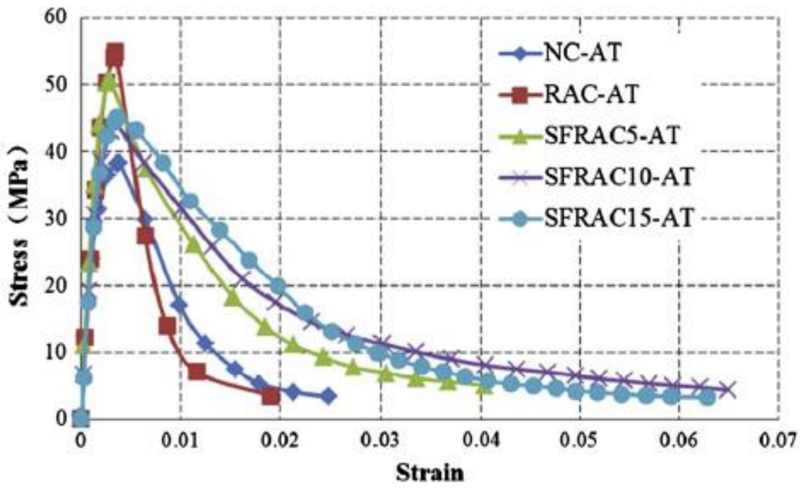
Fig. 6. Ratio of mass reduction caused by heat exposure.

6.3. The failure mode of compression

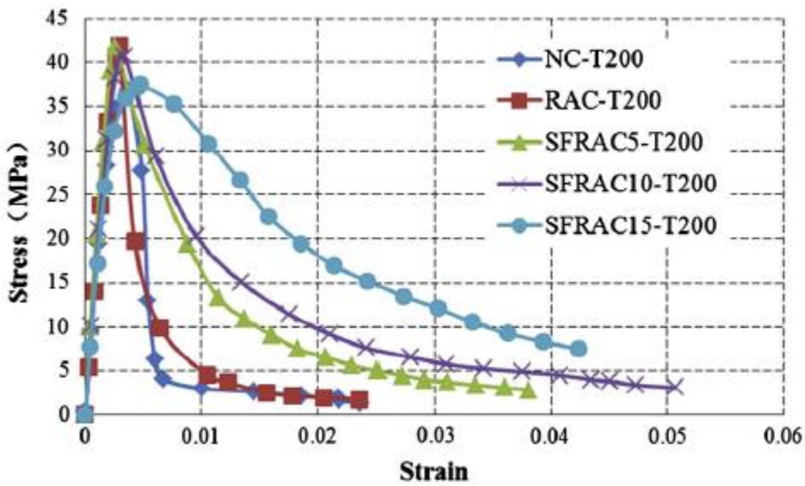
After the cylinders were heated to extreme temperatures, compression tests were performed. Different concrete mixes' failure modes, each one chosen at random from a set of three. Failure process & modes were identical for steel-fiber-free concrete (NC & RAC) when subjected to the same heat treatment. Sounds of cracking & appearance of vertical fissures in the concrete indicated that the specimen's stress level was approaching its peak. After the maximum stress, the cracks rapidly spread across the entire specimen. Because of how rapidly the failure occurred, the stress level dropped off precipitously. The testing machine was only turned off when the stress on the untreated cylinders had been lowered to practically zero, at which point they were all in danger of being crushed. This was done on purpose so that images of the complete cylinders could be taken before they crumbled after being in the testing equipment for so long. For concrete with steel fibres, the tests on unheated cylinders showed that major cracks appeared primarily in the vertical direction when the load was reduced to about 20% of the peak load, while for concrete without steel fibres, the cylinder was completely crushed and/or concrete debris was sheared off.

6.4. Stress–strain curves

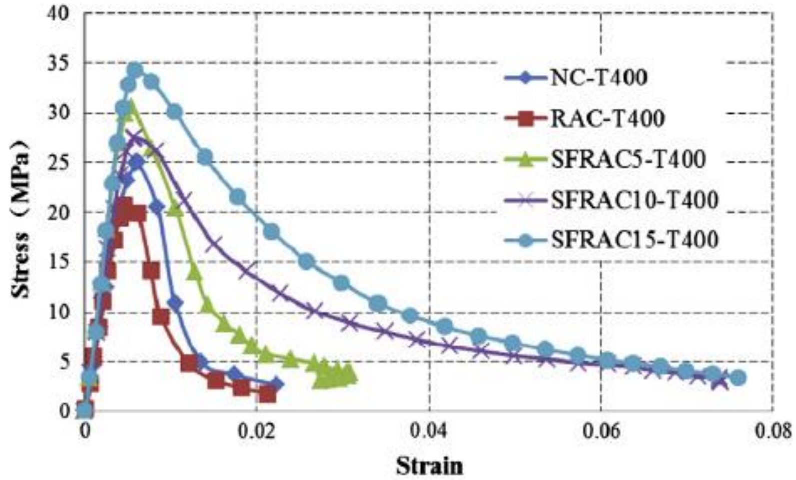
The whole stress-strain curve was obtained for all specimens by compressing cylinders at a displacement rate of 0.18 mm/min. All of the data is plotted in Fig. 7. In each trial, three cylinders were used. Three identical specimens were tested, however due to the great degree of similarity between the stress-strain curves, only one curve is shown in Fig. 7 for each concrete mixture. The key parameters of the stress-strain curves (including strength, elastic modulus, & compressive toughness) were calculated by averaging the results from three identical specimens. It should be noted that two longitudinal 100 mm strain gauges were positioned 1800 apart for each control specimen in order to estimate the axial strains at the mid-height region. These gauges typically failed in the later phases of loading due to concrete cracking, but their early-stage readings were used to fine-tune the setup to reduce loading aberrations. In order to evaluate axial strains, we positioned two linear variable displacement transducers (LVDTs) 1800 apart and 120 mm apart at the mid-height region of all specimens, as recommended by Jiang [15]. End effects [6] cause the average axial strain recorded by the two LVDTs to be smaller than the strain obtained by shortening the cylinders to their full height, as shown in Figure 7. In Fig. 7, we can observe that the descending branch is flatter for a concrete mix that includes steel fibres. This is due to the fact that the addition of steel fibres drastically modifies the stress-strain curve. The initial slope of the exposure temperature & compressive strength, with the latter declining at a much faster pace than the former (details will be discussed in subsequent presentations). Therefore, prolonged exposure to high temperatures boosts peak stress strain. The strain at maximum tension is, on average, around 4.8 times higher in concretes heated to 600 °C than in concretes at room temperature. Table 3 shows that the strain at the peak stress is slightly higher in concrete mixes containing more steel fibres when exposed to higher temperatures (400 & 600 degrees Celsius, respectively).



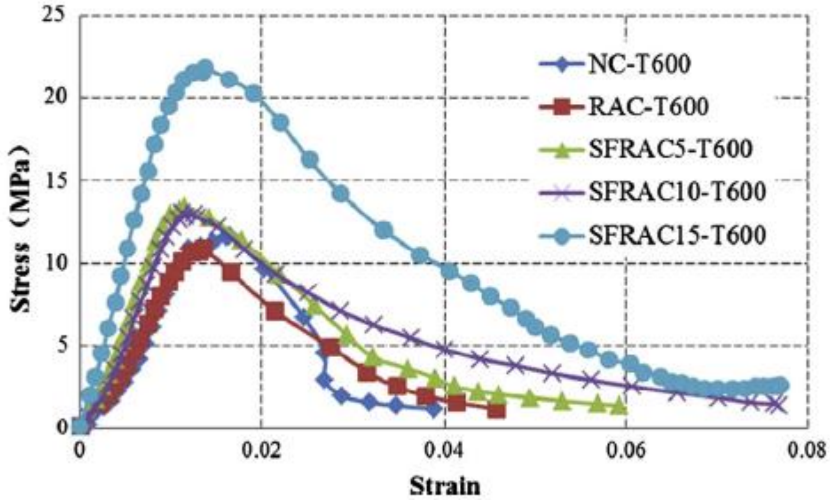
(a) Curve of axial stress vs strain for cold concrete cylinders



(b) Curve of axial stress and strain for concrete heated to 200 degrees Celsius



(c) Concrete axial stress-strain curve after 400 °C exposure.



(d) Concrete axial stress-strain curve after 600 °C exposure

Fig. 7. Concrete axial stress–strain curve after high temperature.

6.5. Compressive strength

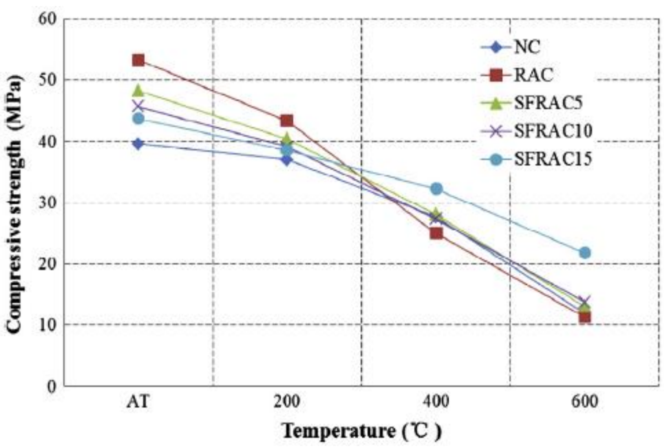
Table 4 shows the difference in residual compressive strength between cylinders made of cold and hot concrete. In Fig. 8, we see the effects of temperature on the residual compressive strength, both in absolute terms (a) and in comparison to the strength of the corresponding unheated concrete mix (c). Compressive strength of unheated concrete specimens improved by 34.62% when NCA was totally replaced by RCA, as seen in Table 4 and Figure 8. This was presumably due to water absorbed by RCA.

The compressive strength of RAC reduces by 9.33%, 14.3%, and 18.0% when 1%, 1.5%, & 2.5% of steel fibres in volume are introduced, respectively, compared to the residual strength of RAC without steel fibres, as in standard concrete [27]. The uneven distribution of steel fibres in RAC could be to blame for this concentrated stress. The type of steel fibre used may also affect the aforementioned strength decrease [27].

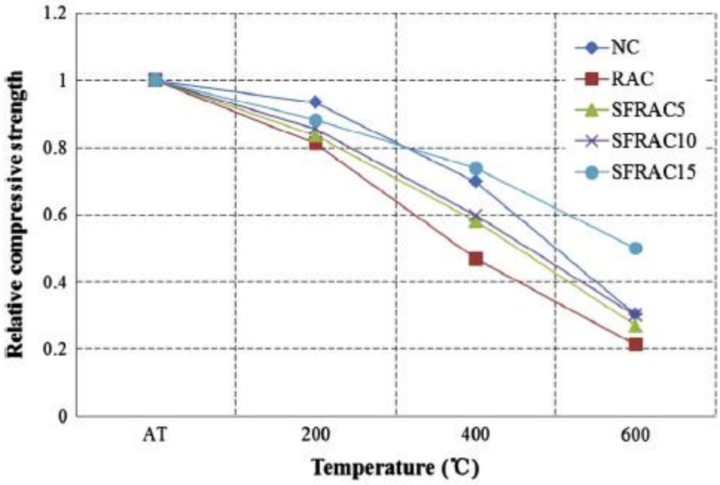
Specimens of RAC (including RAC & SFRACx) were found to have a residual strength of 84.6% after being heated to 200 °C, 59.0% after being heated to 400 °C, and 31.4% after being heated to 600 °C, on average. As can be observed in Fig. 8(a) and (b), the pace at which concrete loses strength is reduced when steel fibre is added. More so between 400 and 600 degrees Celsius. Therefore, after being heated to 400 °C/600 °C, the RAC that was reinforced with steel fibre preserved a higher level of strength than the RAC that was not (see Table 4). However, it should be noted that the addition of steel fibres also considerably diminishes the compressive stress for the concrete specimens heated to 200 °C as for the unheated concrete specimens; this proposes that an appropriate amount of steel fibre content can be used to achieve a balanced compressive strength for both unheated and heated specimens. Furthermore, concrete mixes lose compressive strength more quickly when the desired temperature is above 400 °C (for example, between 400 & 600 °C). Ca(OH)2 (calcium hydroxide) commonly decomposes at temperatures between 400 & 600 °C, which may explain the phenomenon [22]. The compressive strength of RAC mix decreased more rapidly than that of NC after being heated at high temperatures, especially between 200 & 400 degrees Celsius. This might be because of the porous microstructure of RCA. Adding steel fibres to RAC mitigates the material's rapid strength degeneration (Fig. 8). For instance, RAC reinforced with 1.5% steel fibres (i.e. SFRAC15) had a residual strength 1.92 times higher than RAC without steel fibre after being treated to 600 °C, demonstrating that steel fibres are useful in minimising the adverse effect of high temperature on RAC's residual strength. Research into the strength degradation process of SFRAC should explore the microstructure of concrete, as in [22], because the microstructure of RAC and its performance after exposure to high temperature differ from those of normal concrete.

Table 4 Cylinder concrete compression and Young's modulus.

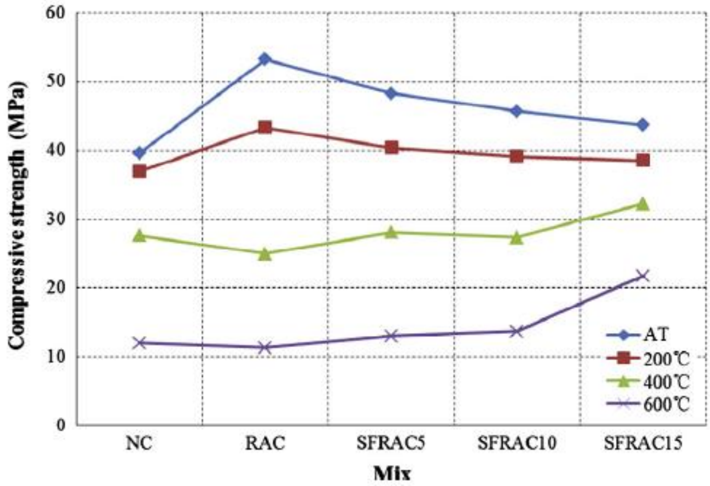
Mix		**Slump (mm)**	**Compressive strength (MPa)**			**Young's modulus (GPa)**			
		AT	**200 °C**	**400 °C**	**600 °C**	**AT**	**200 °C**	**400 °C**	**600 °C**
NC	198	39.57	36.99	27.66	11.98	23.80	17.65	5.90	0.57
RAC	187	53.27	43.34	25.00	11.33	27.23	19.07	5.37	0.74
SFRAC5	154	48.30	40.41	28.08	13.05	26.80	19.43	5.49	0.93
SFRAC10	151	45.67	39.12	27.33	13.73	24.13	16.86	5.00	0.84
SFRAC15	110	43.69	38.56	32.27	21.81	20.89	16.46	6.21	2.06



(a) Impacts the Compressive strength & exposure temperature



(b) Impacts the Relative compressive strength & exposure temperature



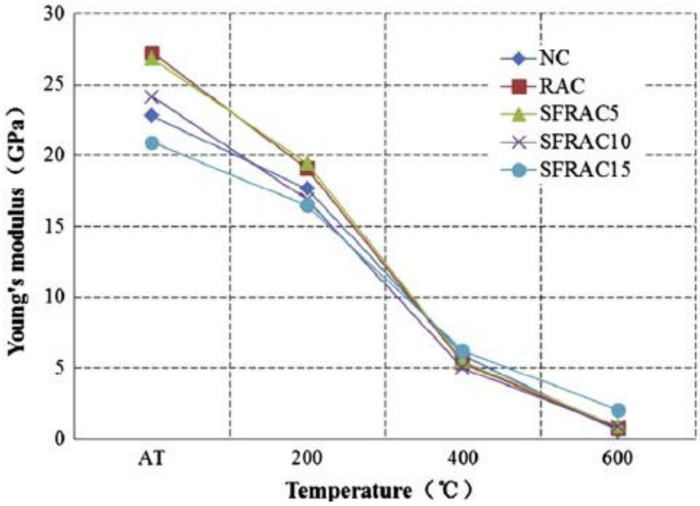
(c) Impacts of Compressive strength & steel fibre content

Fig. 8. Temperature's impact on concrete's compressive strength AT (ambient temperature around 25 °C).

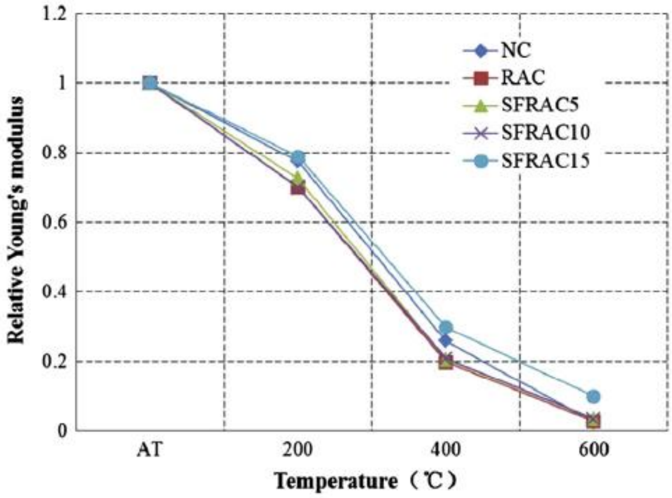
6.6. Young's modulus

Following the method outlined by Poon et al. [6], the Young's modulus of the concrete samples was determined by obtaining the secant modulus of the stress-strain curve at a stress level equal to one-third the peak stress. Tab. 4 displays the outcomes. Young's modulus varies with temperature and steel fibre as shown in Fig. 9. The modulus is presented in Fig. 9(b) as a percentage of the Young's modulus of warmed concrete (the reference value). When comparing the data in Figures 8(b) and 9(b), it is clear that Young's modulus degrades at a significantly faster rate than compressive strength. After being heated to 200 degrees Celsius, the Young's modulus of RAC sample dropped to 72.5 percent of that of unheated concretes, on average. Similar to high strength concrete, significant loss of elastic modulus occurs between 200 and 600 degrees Celsius [31]. It dropped to 22.3% after being heated to 400 °C & 4.61% after being heated to 600 °C. High temperatures have significantly destroyed the microstructure of the concrete cylinders, as seen by the quick fall in Young's modulus. Increasing the steel fibre content of RAC has a negative effect on the elastic modulus at room temperature & after exposure to 200 °C, but a positive effect on the elastic modulus at 400 °C and

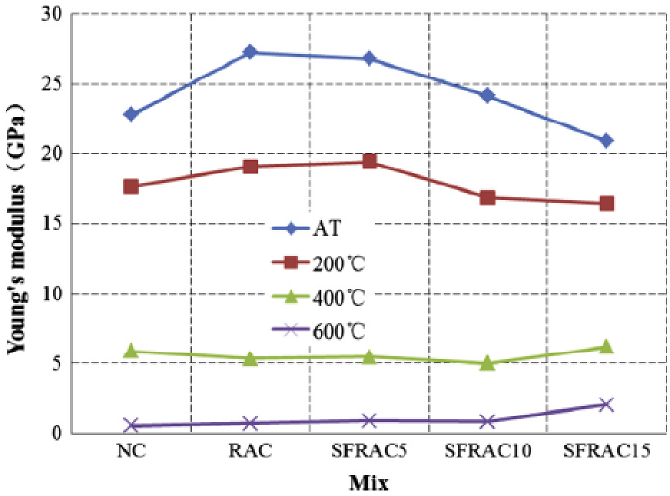
600 °C (see Fig. 9(c)); however, at a steel fibre content of 1.5%, the positive effect on elastic modulus becomes noticeable.



(a) Impacts of Young's modulus due to temperature



(b) Temperature's influence on the Young's modulus



(c) Steel fibre composition affects Young's modulus

Fig. 9. Concrete's Young's modulus & temperature

7. CONCLUSION

In this paper, the impact of temperature on the compressive behaviour of SFR-RAC was experimentally investigated. The effect of steel fibres on compressive behaviour in terms of strength, elastic modulus, has received special study. Similar to what happens with ordinary concrete (NC), heating a RAC sample to 200 °C, 400 °C, & 600 °C caused a change in the surface colour. The concrete cylinders had surface cracks after being heated to 400 and 600 degrees Celsius, which can be seen by the naked eye. The fracture width was significantly reduced when the steel fibre content was increased, proving the efficiency of steel fibres in retarding the spread of cracks. Explosive spalling may not have occurred for any of the specimens because of the low heating rate (2.5 °C/min) & pre-heating technique used in this study. On average, the RAC mixtures kept 85% of their unheated compressive strength after being heated to 200 °C, 59% after being heated to 400 °C, and 31% after being heated to 600 °C.

REFERENCES

[1]. Sagoe-Crentsil KK, Brown T, Taylor AH. Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cem Concr Res 2001;31(5):707–12.

[2]. Patil Uday Shankar, et al. (2021). To study strength of the demolished concrete aggregate under compression by performing compressive strength test. Design Engineering ISSN: 0011-9342 | Issue: 6, pages 7970-7982

[3]. Patil Uday Shankar, Dr. Ramana Reddy Y., Dr. Indrajeet Yadav. (2021). A Review Study on the Aggregate Properties of Demolished Concrete. Journal of Advances and Scholarly Researches in Allied Education Vol. 18, Issue No. 4, ISSN 2230-7540

[4]. Xiao JZ. Recycled Concrete. Beijing: China Architecture & Building Press; 2008 [in Chinese].

[5]. CECS 13:89. The testing methods of steel fiber reinforced concrete. China Association for Engineering Construction Standardization; 1991 [in Chinese].

[6]. GB/T 50080. Standard for test method of performance on ordinary fresh concrete. People’s Republic of China Building Material Industry Standards; 2002 [in Chinese].

[7]. Gao DY, Zhao J, Zhu HT. Design and application of steel fiber reinforced concrete. Beijing: China Architecture & Building Press; 2002 [in Chinese

[8]. Poon CS, Shui ZH, Lam L. Compressive behavior of fiber reinforced highperformance concrete subjected to elevated temperatures. Cem Concr Res 2004;34(12):2215–22.

[9]. ISO. Fire-resistance tests – elements of building construction – Part 1: General requirements, ISO 834-1:1999. Geneva, Switzerland: International Organization for Standardization; 1999

[10]. Bisby LA, Chen JF, Li SQ, Stratford TJ, Cueva N, Crossling K. Strengthening firedamaged concrete by confinement with fibre-reinforced polymer wraps. Eng Struct 2011;33:3381–91.

[11]. Peng GF, Yang WW, Zhao J, et al. Explosive spalling and residual mechanical properties of fiber-toughened high-performance concrete subjected to high temperatures. Cem Concr Res 2006;36(4):723–7.

[12]. Cavdar A. A study on the effects of high temperature on mechanical properties of fiber reinforced cementitious composites. Compos B Eng 2012;43(5):2452–63.

[13]. Rahim A, Sharma UK, Murugesan K, et al. Multi-response optimization of postfire residual compressive strength of high performance concrete. Constr Build Mater 2013;38:265–73.

[14]. ASTM C39. Standard test method for compressive strength of cylindricalconcrete specimens; 2009

[15]. Jiang T. FRP-confined RC columns: analysis, behavior and design. Ph.D. dissertation, The Hong Kong Polytechnic University; 2008.

[16]. Wang, T., Yu, M., Shan, W., Xu, L., Cheng, S., & Li, L. Y. (2023). Post-fire compressive stress–strain behaviour of steel fibre reinforced recycled aggregate concrete. *Composite Structures*, *309*, 116735.

[17]. Liu, Z., Zong, S., Wu, H., & Lu, Y. (2023, October). Axial compression behavior of steel tube filled with steel-fiber-reinforced self-stressing recycled aggregate concrete with moderate slenderness. In *Structures* (Vol. 56, p. 104958). Elsevier.

[18]. Zhao, Q., Wang, Y., Xie, M., & Huang, B. (2022). Experimental study on mechanical behavior of steel fiber reinforced geopolymeric recycled aggregate concrete. *Construction and Building Materials*, *356*, 129267.

[19]. Li, L., Wang, H., Wu, J., Du, X., Zhang, X., & Yao, Y. (2022). Experimental and numerical investigation on impact dynamic performance of steel fiber reinforced concrete beams at elevated temperatures. *Journal of Building Engineering*, *47*, 103841.

[20]. Ke, X. J., Tang, Z. K., & Yang, C. H. (2022, November). Shear bearing capacity of steel-reinforced recycled aggregate concrete short beams based on modified compression field theory. In *Structures* (Vol. 45, pp. 645-658). Elsevier.

[21]. Xie, J. H., Guo, Y. C., Liu, L. S., & Xie, Z. H. (2015). Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber. *Construction and Building materials*, *79*, 263-272.

[22]. Zheng WZ, Li HY, Wang Y. Compressive behaviour of hybrid fiber-reinforced reactive powder concrete after high temperature. Mater Des 2012;41: 403–9.

[23]. Lau A, Anson M. Effect of high temperatures on high performance steel fibre reinforced concrete. Cem Concr Res 2006;36(9):1698–707..

[24]. Tai YS, Pan HH, Kung YN. Mechanical properties of steel fiber reinforced reactive powder concrete following exposure to high temperature reaching 800 _C. Nucl Eng Des 2011;241(7):2416–24.

[25]. Ozawa M, Uchida S, Kamada T, et al. Study of mechanisms of explosive spalling in high-strength concrete at high temperatures using acoustic emission. Constr Build Mater 2012;37:621–8.

[26]. Kodur VKR, Sultan MA. Effect of temperature on thermal properties of highstrength concrete. J Mater Civ Eng 2003;15(2):101–7.

[27]. Zhang BS. Effects of moisture evaporation (weight loss) on fracture properties of high performance concrete subjected to high temperatures. Fire Saf J 2011;46(8):543–9.

[28]. Savva A, Manita P, Sideris KK. Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates. Cement Concr Compos 2005;27(2):239–48.

[29]. Gao DY, Lou ZH, Wang ZQ. Experimental study on the compressive strength of steel fiber recycled concrete. J Zhengzhou Univ (Eng Sci) 2007;28(2):5–10 [in Chinese].

[30]. Cree D, Green M, Noumowe A. Residual strength of concrete containing recycled materials after exposure to fire: a review. Constr Build Mater 2013;45:208–23

[31]. Wu B, Su X, Li H, et al. (2002) Effect of high temperature on residual mechanical properties of confined and unconfined high-strength concrete. ACI Mater J;99(4):399–407.