FLEXURAL BEHAVIOUR OF STEEL FIBRE REINFORCED CONCRETE AT ELEVATED TEMPERATURES USING ABAQUS

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Steel Fibre Reinforced Concrete (SFRC) has been very widely used in the structures such as thermal power plants due to its bonding effect, ductility, durability and stability of the structures at high temperatures. The concrete structure when exposed to high temperatures, shows the numerous chemical changes in the concrete which leads to deterioration of the structure. The flexural behaviour of the concrete prism with steel fibre volume fraction of 1.35% and without steel fibre, at room temperature (28ºC) and when exposed to elevated temperatures of 150ºC, 350ºC, 550ºC and 750ºC for the time period of 1 hour were observed. The Finite Element Analysis was done for the prism, to find the deflection on the plain concrete and steel fibre reinforced concrete when subjected to the same temperatures as mentioned above. The main objective of this study was to decrease the structural element failure when exposed to elevated temperature, which in turn increases the evacuation period of the occupants during fire accidents.

Keywords: *SFRC, High temperature, Flexural strength, FEA, Deflection, ABAQUS*

1. Introduction

Concrete buildings have been broadly used for structural stability and the strength of the structure. Concrete has better compression resistance than tension resistance [1]. Concrete structures when exposed to fire, the temperature in the concrete can reach 1000ºC, which may, in turn, lead to a lot of chemical and physical changes, finally leading to the failure of the structure [2]. Sukontasukkul et al [3]conducted an experiment on the beam specimens, stated in his study that steel fibre concrete subjected to an elevated temperature of 400ºC, 600ºC and 800ºC showed high flexural toughness. Post-peak toughness and strength increased at the temperature of 400ºC and started decreasing beyond that temperature. Spalling is one of the leading factors that lead to the deterioration of the structure. Spalling is mainly caused due to the thermal incompatibility, gradient and different thermal coefficient of the fine aggregate, coarse aggregate, cement [4-7] in the pressure of pores in concrete. In the case of calcareous aggregates, calcination of $Caco_3$ takes place at 600ºC - 900ºC, which in turn leads to the pore pressure [8].

Steel fibre reinforced concrete is very widely used in the structure, in order to increase the structural performance. The incorporation of the steel fibres in the concrete improves the absorption of energy, ductility, performance, resistance to corrosion and thus delays the development of cracks [9]. Steel fibre concrete is capable of surviving extreme conditions such as fire, because of its bond strength between the matrix and steel fibres. Physiochemical bond and mechanical bond are the two types of bonds which help to maintain the bond strength [10]. Randomly oriented and uniformly distributed short fibres are necessary to produce homogeneous tensile properties of concrete [11].

The melting point of steel fibre is noted to be high compared to other materials, which adds as a beneficial feature for adding steel fibres in concrete when subjected to high temperature. Steel fibre incorporation of 1% in the concrete does not create any harmful effect in concrete when subjected to the temperature of 1200ºC. The addition of steel fibres in concrete leads to an increase in mechanical strength of concrete compared to the strength of normal concrete [12 - 16]. Steel fibre reinforced concretecompressive strength increases with steel fibrecontent increase. At 200ºC and 400 ºC, the compressive strength of 1% steel fibre volume fraction in concrete showed an increase in strength compared to reference concrete. When the steel fibre content is 2% and 3%, the compressive strength showed goodstrength increase at 200ºC and 300ºC, beyond 400ºC, there was a gradual decrease in strength [17 - 19]. Higher steel fibre volume fraction beyond a certainlimit does not enhance the compressive strength at high temperature, thus leading to the deterioration of the structure [20]. The residual strength of steel fibre concrete at 400ºC, 600ºC and 800ºC was found to be 90%, 60% and 38% respectively [21]. Compressive strength reduction for steel fibre concrete was found to be 78 to 96% for the temperature at 900 - 1200ºC [22].

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When micro steel fibres of volume fraction 1%, 2% and 3% were added, the flexural strength was observed to between 6.59 MPa to 9.97 MPa. When compared to the reference specimen, the percentage increase in flexural strength was observed to be 32%, 47.8%, 58.27%. The maximum increase in flexural strength was observed at 3% steel fibre content [9]. After exposure to 200ºC, the increase in flexural strength was observed to be 11.20% and 17.95% for 2% and 3% steel fibre content respectively [23].

This paper mainly presents the experimental study on flexural performance of plain concrete and steel fibre reinforced concrete (SFRC) prism of dimension 100mmx100mmx500mm, when subjected to room temperature and various elevated temperatures of 150ºC, 350 ºC, 550 ºC and 750ºC. The main objective is to do structural model and analyse the concrete prism using ABAQUS and to compare with the experimental results. The most widely used application of steel fibre reinforced concrete are industrial floors, explosion resistant structures, refractory concrete, pavements of highway and airport, hydraulic structures, etc. The practical application of this study is to reduce the rapid failure of structure when exposed to fire accidents and to increase the evacuating period for the people who are inside the building. As per IS 3809 (1979) [24], the rise in furnace elevated temperature was observed to be 718ºC at 15 minutes of the time period. Thus, in this study, the structural element behaviour was observed at various elevated temperatures of 150ºC, 350 ºC, 550 ºC and 750ºC.

2. Experimental study

2.1. Materials

Ordinary Portland Cement (OPC) of grade 53, fine aggregate, coarse aggregate and super plasticizer was used in this study. Mix design for M-30 concrete grade was designed according to the Indian Standard code IS 10262:2009 [25]. Hooked-end steel fibres (aspect ratio 60) were used.

2.2. Mix proportions

The mix proportions consist of fine aggregate 938 kg/m^3, cement 320 kg/m^3 and coarse aggregate 1146kg/m^3. The materials have been laid in the order of coarse aggregate, fine aggregate, cement. The materials are initially dry mixed inorderto make the uniform distribution of materials. Further, addition of water and super plasticizer is done and the mixture is mixed further. Wet mixing is done until the concrete mix becomes workable. Hooked-end steel fibres of 1.35% were added. Hooked end steel fibre used in this study was shown in Fig 1. The mechanical properties of steel fibres used are mentioned in Table 1.

Fig. 1- Hooked-end steel fibres

2.3. Casting, curing and heating process

The casting is done on the cast iron moulds, which is wiped and cleaned to remove the dust particles. The moulds should be checked for proper condition, ensuring that there is no gap left, which may lead to the leakage of concrete, resulting in irregular shape of specimen. Before filling the moulds with concrete, the moulds are applied with oil on all sides. The moulds are then placed on the uniform surface. The uniformly mixed concrete is then filled in the moulds. The mixtures without steel fibre content and 1.35% steel fibre content were cast into the steel moulds (100 x 100 x 500mm). The concrete which is excess on the top of the mould is removed and levelled. Each mix consists of ten specimens which are shown in Fig 2(a) and Fig 3 (a). The specimens after failure are shown in Fig 2 (b) and Fig 3(b). The cast specimens were placed in the mould for the period of 24 hours at ambient temperature. After 24 hours, the cast specimens were de-moulded and were placed for 28 days period of water curing. Curing has a vital role in attaining concrete strength and durability. The concrete specimens are placed inside the water curing tank, immediately after demoulding. The specimens should be completely immersed inside the water. The curing should be maintained until the date of testing.After 28 days, the specimens were removed from curing tank and dried. The two specimens for each temperature were subjected to

Table 1

Mechanical properties of steel fibres

Type of fibre	Diameter (mm)	Length (mm)	Aspect ratio (l/d)	Density (kg/m^3)	Elastic modulus (GPa)	Tensile strength (MPa)
Hooked-end	0.5	30	60	7900	200	1195

Fig. 2(a) - Cast normal beams

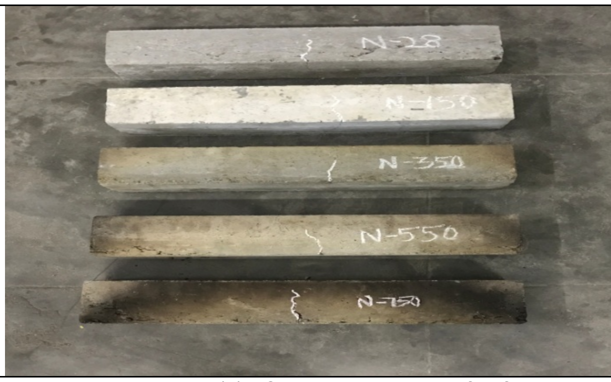

Fig. 2(b) - Cast normal beams after failure

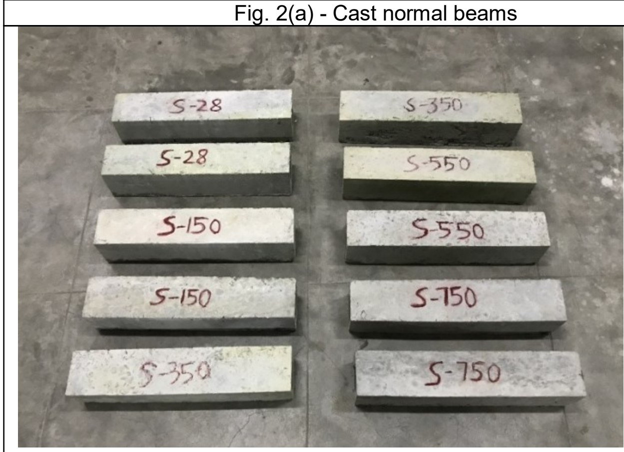

Fig. 3(a) - Cast beams with 1.35% steel fibre content

Fig. 3(b) - Cast beams with 1.35% steel fibre content after failure

the temperature of 150ºC, 350ºC, 550ºC and 750ºC. The specimens were placed in a furnace and subjected to the temperature for one hour. Fig 4 shows the furnace setup. Later, the specimens were cooled inside the furnace and tested for flexural strength after 24 hours.

Fig. 4 - Furnace set-up

3. Results and discussions

The results obtained from the experimental study are tabulated in Table 2.

Table 2

Experimental results

S. No	Steel fibre content (%)	Time (hr)	Temperature (ºC)	Deflection (mm)	% difference in deflection	Flexural strength (MPa)	% difference in flexural strength
1	0	1	28	0.31	-	4.96	-
			150	0.28	-	4.72	-
			350	0.21	-	3.04	-
			550	0.19	-	1.92	-
			750	0.16	-	0.96	-
2	1.35	1	28	0.44	29.54	7.28	31.86
			150	0.40	30.00	6.56	28.04
			350	0.38	44.73	5.68	46.47
			550	0.20	5.00	3.36	42.85
			750	0.18	11.11	1.84	47.82

3.1. Flexural strength

After the 28 days curing period and specimen subjected to various elevated temperatures of 28 ºC, 150 ºC, 350 ºC, 550 ºC and 750ºC, flexural strength was carried out on the prism specimens according to IS 516-1959 (Reaffirmed 2004) [26]. The flexural strength results exposed to various temperatures were illustrated in Fig 5.

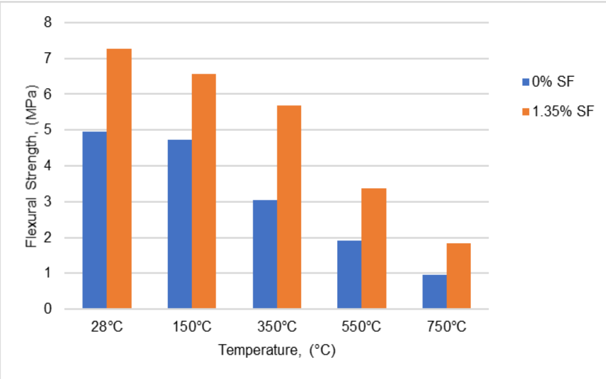

Fig. 5 - Flexural strength test at various elevated temperatures

It is observed from the Fig 5 that the concrete prism with 1.35% steel fibre content shows the good flexural strength results compared to the concrete prism without steel fibre content. The flexural strength reduction can also be due to the formation ofmicro cracks on concrete. Due to themicro cracks, the bond among the aggregate and cement paste is weakened [27, 28]. The concrete when exposed to elevated temperature also leads to the dehydration of concrete, which in turn causes the reduction in flexural strength of concrete [29].The undesirable C-S-H configuration leads to poor micro-structure. Further, the cracks on the concrete prisms increases after exposure to elevated temperature and long-narrow C-S-H crystals are developed. In turn, this occupies less space in the concrete matrix subjected to elevated temperature after a decrease in microstructure density [30]. Therefore, this affects the flexural strength of concrete prism.

Fig 5 shows that 1.35% of steel fibre content in concrete prism showed good flexural strength at all elevated temperatures compared to reference prism. The flexural strength increase of 1.35% steel fibre content was found to be 31.86% at 28 ºC when compared to reference concrete prism. At 150ºC, 350 ºC, 550 ºC and 750ºC,the flexural strength increase of 1.35% steel fibre content was found to be 28.04%, 46.47%, 42.85% and 47.82% respectively when compared to reference concrete prism.

3.2. Load to deflection at various temperatures

The load to deflection curve was considered as the most important method for determining the performance of the fibre, rather than the parameters such as flexural and compressive strength [3]. There was initially fall in load after the initial crack, but due to the bridging effect of the hooked end steel fibre, the load increased. This increase in load showed the exact behaviour of the steel fibres. As the steel fibre volume fraction increased, flexural strength increased. In this experiment, the steel fibre volume fraction of 1.35%, flexural strength at room temperature, was found to increase by 31.86% than the normal concrete. In many studies, irrespective of the fibre variety, the first peak is found to be lower than the second peak, which shows that thefibre load carrying capacity is more compared to the normal concrete [3].

The type of fibre and content also has a great influence on the load carrying capacity. At 750ºC, the maximum load drop of around 80.64% has been observed when compared withreference prism. Whereas, for the steel fibre volume fraction of 1.35%, the load drop was observed to be 74.72%. This clearly shows that the increase in the hooked end steel fibre content improves the load carrying capacity and decreases percentage drop.

4. Finite element analysis

The finite element modelling techniques are mainly adopted to improve the efficiency of the finite element results. The finite element analysis efficiency is calculated by the effort to accuracy ratio. The factors which have to be considered for the good finite element model are as follows: the method of analysis, purpose of the analysis, element type used, boundary conditions and loading conditions. Meshing is one of the important factors which have to be considered to reduce the DOFs. Controlling the mesh density in the finite element analysis is often done using mesh seeds. After the geometry creation, the mesh seeds are created before meshing. If the displacements are continuous along all the edges of the elements, then the mesh is said to be compatible [31].

4.1. Methodology

In view of the time consumption concept and to avoid the material wastage, the numerical analysis was conducted. The modelling and analysis were done in ABAQUS, the finite element software, to predict the performance of steel fibre concrete prisms when subjected to various elevated temperature. The prism modelling was done similar to the test circumstances. Initially, the control concrete prism specimens were modelled and analysed, which was compared with the experimental results. Then, the steel fibre concrete prisms wereanalysed and compared with the experimental results.

4.2. Material properties details

The element property used for normal concrete was 8- noded hexahedral with reduced integration (C3D8R). For the concrete subjected to the temperature, the element types used was coupled displacement-temperature 8 node solid element with full integration (C3D8T). Meshing was done, in order to subdivide the entire model into the smaller domain, which is called elements, which in turn solves a set of equations. Meshing is mainly done to obtain accuracy in the output results. The material properties for the modelling are given as input values [32]. The boundary conditions were given as simply supported. The main prediction made in the analysis was the deflection of normal and steel fibre concrete prisms when subjected to load and various temperatures.

Fig 6-10 shows the deflection output of the normal concrete when subjected to various elevated temperatures. Fig 11-15 shows the deflection of steel fibre concrete at various elevated temperatures.

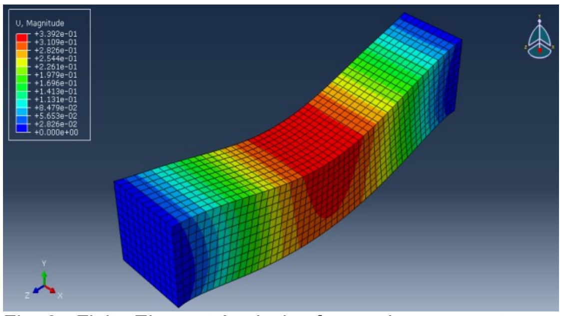
Fig. 6 - Finite Element Analysis of normal concrete at room temperature

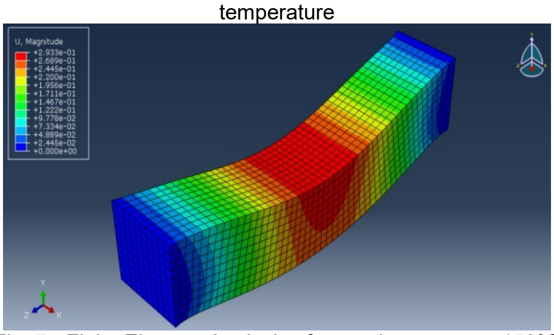
Fig. 7 - Finite Element Analysis of normal concrete at 150°C temperature

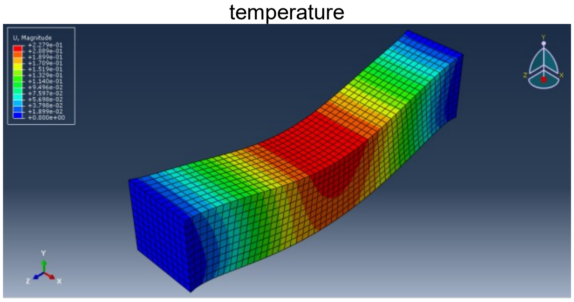
Fig. 8 - Finite Element Analysis of normal concrete at 350°C temperature

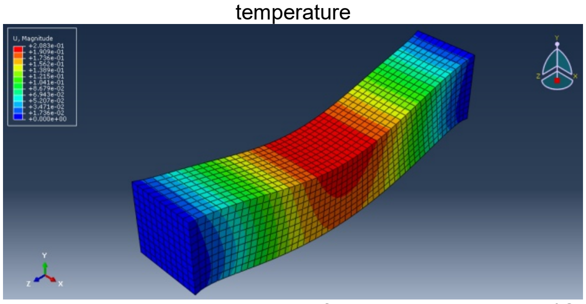
Fig. 9 - Finite Element Analysis of normal concrete at 550°C temperature

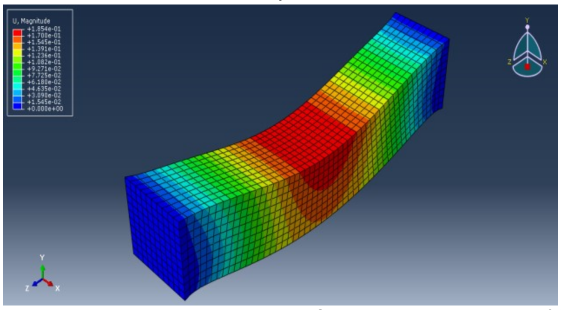
Fig. 10 - Finite Element Analysis of normal concrete at 750°C temperature

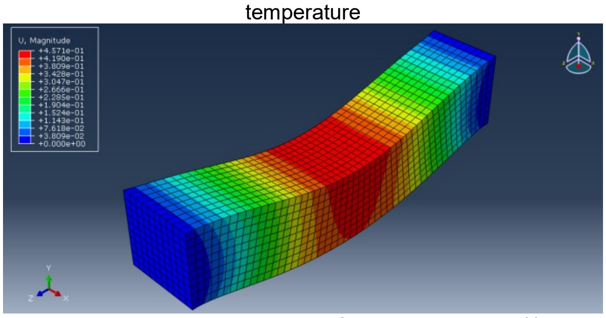
Fig. 11 - Finite Element Analysis of concrete with 1.35% steel fibres at Room temperature.

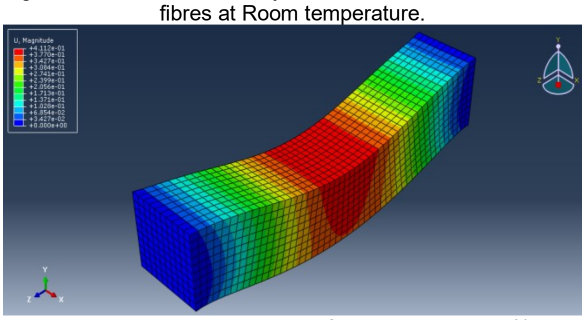
Fig. 12 - Finite Element Analysis of concrete with 1.35% steel fibres at 150°C temperature

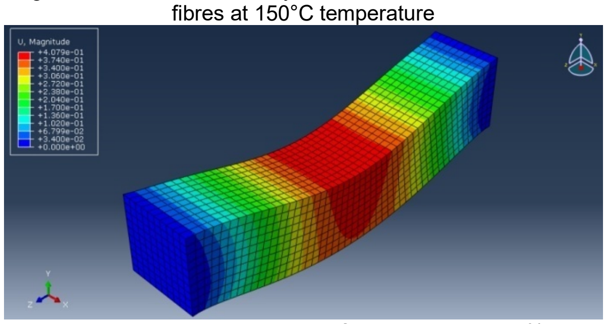
Fig. 13 - Finite Element Analysis of concrete with 1.35% steel fibres at 350°C temperature

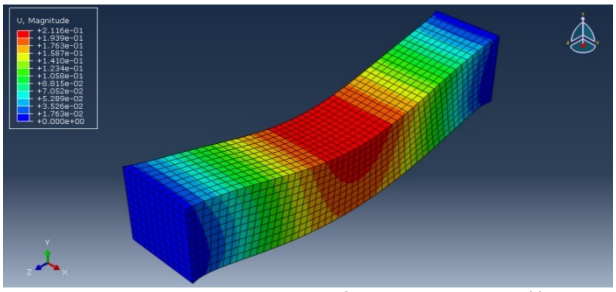

Fig. 14 - Finite Element Analysis of concrete with 1.35% steel fibres at 550°C temperature.

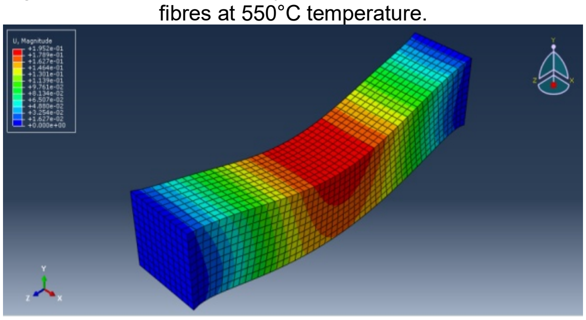

Fig. 15 - Finite Element Analysis of concrete with 1.35% steel fibres at 750°C temperature.

The percentage error between the experimental and the analytical prediction was tabulated in Table 3.The numerically predicted deflection values were almost closer to the experimental deflection value and did not show the larger difference. The maximum percentage error between the experimental and analytical prediction was less than 15%.

5. Conclusions

In this study, the experiment was conducted on the concrete prisms with 1.35% steel fibre volume fractions and without steel fibre content,atroom temperature and various elevated temperatures of 150ºC, 350ºC, 550ºC and 750ºC. The finite element modelling was done using ABAQUS software for the concrete prism model with steel fibres and without steel fibres when subjected to different temperatures.

1) In this experimental study, it is found that the flexural strength increases as the steel fibre content increases. The flexural strength increasepercentages for 1.35% steel fibre content compared to reference concrete specimens was found to be 31.86%, 28.04%, 46.47%, 42.85% and 47.82% when subjected to the temperature of 28ºC, 150ºC, 350ºC, 550ºC and 750ºC respectively.

2) The deflection percentage difference for 1.35% steel fibre content when compared to reference specimen was observed to be 29.54%, 30.00%, 44.73%, 5.00% and 11.11% when subjected to the temperature of 28ºC, 150ºC, 350ºC, 550ºC and 750ºC respectively.

3) In the finite element modelling using ABAQUS, the percentage error was noted to be within 2% and 11.11%.

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Table 3

Comparison of experimental and analytical results

S. No	Steel fibre content (%)	Time (hr)	Temperature (ºC)	Experimental deflection (mm)	Predicted deflection (mm)	Percentage error (%)
1	0	1	28	0.31	0.33	6.06
			150	0.28	0.29	3.44
			350	0.21	0.22	4.54
			550	0.19	0.20	5.00
			750	0.16	0.18	11.11
2	1.35	1	28	0.44	0.45	2.22
			150	0.40	0.41	2.43
			350	0.38	0.40	5.00
			550	0.20	0.21	4.76
			750	0.18	0.19	5.26

REFERENCES

[1] Sumathi Arunachalam, Vuppalapatti Manish Kumar Reddy, Sarvana Raja Mohan Kaliaperumal, Strength evaluation of hybrid fiber reinforced concrete, Romanian Journal of Materials, 2017, **47**(4), 500–504.
[2] J. Kim, G. P. Lee, D. Y. Moon, Evaluation of mechanical properties of steel-fibre-reinforced concrete exposed to high temperatures by double-punch test, Construction and Building Materials, 2015, **79**, 182.
[3] P. Sukontasukkul, W. Pomchiengpin, S. Songpiriyakij, Post-crack (or post-peak) flexural response and toughness of fiber reinforced concrete after exposure to high temperature, Constructionand Building Materials, 2010, **24**(10), 1967.
[4] F. Aslani, B. Samali, Constitutive relationships for self-compacting concrete at elevated temperatures, Materials and Structures, 2015, **48**, 337.
[5] D. Foti, Prestressed slab beams subjected to high temperatures, Composites Part B Engineeri ng, 2014, **58**, 242.
[6] C.G Bailey, E. Ellobody, Whole-building behaviour of bonded post-tensioned concrete floor plates exposed to fire, Engineering Structures, 2009, **31**(8), 1800.
[7] F. Aslani, Prestressed concrete thermal behaviour, Magazine of Concrete Research, 2013, **65**(3), 158.
[8] A.E. Ahmed, A.H. Al-Shaikh, T.I. Arafat, Residual compressive and bond strengths of limestone aggregate concrete subjected to elevated temperatures, Magazine of Concrete Research, 1992, **44**(159), 117.

[9] A. Sumathi, K. Gowdham, K. Saravana Raja Mohan, Strength and durability studies on alccofine concrete with micro steel fibres, Romanian Journal of Materials, 2018, **48**(1), 58-63.
[10] S. Abdallah, M. Fan, K. A. Cashell, Bond-slipbehaviour of steel fibres in concrete after exposure to elevated temperatures, Construction and Building Materials, 2017, **140**, 542.
[11] T. Shanmuga Priya, S. Thirumalini, Evaluation of strength and Durabilty of natural fibre reinforced high strength concrete with M-sand, Romanian Journal of Materials, 2018, **48**(4), 483-490.
[12] A. Lau, M. Anson, Effect of high temperatures on high performance steel fibre reinforced concrete. Cement and Concrete Research, 2006, **36**, 1698.
[13] G.M.Chen, Y.H. He, H. Yang, J.F. Chen, Y.C. Guo, Compressive behavior of steel fiber reinforced recycled aggregate concrete after exposure to elevated temperatures, Construction and Building Materials, 2014, **71**, 1.
[14] D. Choumanidis, E. Badogiannis, P. Nomikos, & A. Sofianos, The effect of different fibres on the flexural behaviour of concrete exposed to normal and elevated temperatures, Construction and Building Materials, 2016, **129**, 266.
[15] Ruben Serrano, Alfonso Cobo, María Isabel Prieto, María de las Nieves Gonzalez, Analysis of fire resistance of concrete with polypropylene or steel fibers, Construction and Building Materials, 2016, **122**, 302.
[16] Xiangjun Dong, Yining Ding, Tianfeng Wang, Spalling and mechanical properties of fiber reinforced high-performance concrete subjected to fire, Journal of Wuhan University of Technology-Mater. Sci. Ed, 2008, 743.
[17] Yuh-Shiou Tai, Huang-Hsing Pan, Ying-Nien Kung, Mechanical properties of steel fiber reinforced reactive powder concrete following exposure to high temperature reaching 800ºC, Nuclear Engineering and Design, 2011, **241**, 2416.
[18] Wenzhong Zheng, Haiyan Li, Ying Wang, Compressive stress–strain relationship of steel fiber-reinforced reactive powder concrete after exposure to elevated temperatures, Construction and Building Materials, 2012, **35**, 931.
[19] Faiz Uddin Ahmed Shaikh, Anwar Hosan, Mechanical properties of steel fibre reinforced geopolymer concretes at elevated temperatures, Construction and Building Materials, 2016, **114**, 15–28.
[20] Wenzhong Zheng, BaifuLuo, Ying Wang, Stress–strain relationship of steel-fibre reinforced reactive powder concrete at elevated temperatures, Materials and Structures, 2015, **48**, 2299.
[21] B. Chen, J. Liu. Residual strength of hybrid fibre reinforced high strength concrete after exposure to high temperatures, Cement and Concrete Research, 2004, **34**, 1065.
[22] O. Dugenci, T. Haktanir, F. Altun, Experimental research for the effect of high temperature on the mechanical properties of steel fibre reinforced concrete, Construction and Building Materials, 2015, **75**, 82–88.
[23] H. Li, Q.I. Qiao, B. Zhang, Flexuralproperties of reactive powder concrete after high temperature, 2018, **48** (4), 491–498.
[24] IS 3809: 1979. Fire resistance test of structures (FirstRevision). Bureau of Indian Standards, New Delhi.
[25] IS 10262: 2009. Concrete MixProportioning- Guidelines. Bureau of Indian Standards, New Delhi.
[26] IS 516: 1959 (Reaffirmed 2004). Methods of tests for strength of concrete.Bureau of Indian Standards, New Delhi.
[27] X. Chan, L.W. Sun, Compressive strength and pore structure of high performance concrete after exposure to high temperature up to 800 ºC, Cement and Concrete Research, 2000, **30**, 247.
[28] L. Alarcon-Ruiz, G. Platret, E. Massieu, A. Ehrlacher, The use of thermal analysis in assessing the effect of temperature on a cement paste, Cement and Concrete Research, 2005, **35**,609.
[29] T.C. Ling, C.S. Poon, S. Kou, Influence of recycled glass content and curing conditions on the properties of self-compacting concrete after exposure to elevated temperatures, Cement and Concrete Research, 2012, **34**, 265.
[30] K. Sakr, E.E. Hakim, Effect of high temperature or fire on heavy weight concrete properties, Cement and Concrete Research, 2005, **35**, 590.
[31] G.R. Liu, S.S. Quek, The finite element method – A practical course, An imprint of Elsevier Science, 2003, 246.
[32] D.J. Naus, A compilation of elevated temperature concrete material property data and information for use in assessments of nuclear power plant reinforced concrete structures, United States Nuclear Regulatory commission, 2010, 183.

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