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Effect of Elevated Temperature on Engineered Cementitious Composites using Natural River Sand

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ABSTRACT

Engineered cementitious composites (ECC) is a recent construction material with better properties than conventional concrete. Currently, post-earthquake, fire in a building is one of the most serious disasters. The amount and size of sand used in ECC are important parameters for the performance under thermal conditions. Micro silica sand is utilized in the majority of ECC experiments related to thermal response. The study aim is to explore the impact of river sand (RS) on the ECC performance exposed to elevate temperatures up to 800^{0}C, through a series of experimental tests on compressive strength, mass losses, ultrasonic pulse velocity (UPV) and microstructure. For this purpose, mixes were prepared with the incorporation of RS with varying particle sizes (2.36mm, 1.18mm, 0.60mm) instead of micro silica sand. There's no spalling in ECC containing RS of varying particle sizes. The compressive strength, mass loss and UPV all reduced with increasing temperature, according to the findings. However, RS-ECC performs better with 0.60mm than 1.18mm and 2.36mm RS.

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1. INTRODUCTION

ECC is also known as Strain Hardening Cementitious Composites (SHCC) due to its high ductility in tension [1]. Micro silica sand is used in the majority of PVA-ECC and is of 200 microns size [2]. It is expensive and difficult to obtain, using local river sand of normal size would allow ECC to be used in more practical engineering applications while saving both material cost and manufacturing cost [3, 4]. In terms of environment, it is advantageous to use waste materials like waste polymers and recycled aggregate [5].

In recent years, numerous researchers have conducted studies on the performance of ECC under high temperature. The components used (fly ash, PVA fiber and aggregate) have an effect on how well ECC performs after a fire. Additionally, variations in fly ash amount, fiber percentage, and fiber type, ECC's performance at high temperatures may vary. According to Lachemi and Li [6], the use of PVA fiber improves eliminates explosive spalling. Also, the fire resistance of ECC is improved with the addition of fly ash. The authors also noted that when the temperature approached 400^{0}C, the majority of the fibers melted [7]. Liu et al. [8] investigated residual properties and spalling resistance of ECC using class C fly ash rather than class F fly ash with PVA and steel fibers. Pourfalah [9] found that utilizing steel fibers increased the integrity of ECC exposed to high temperatures. According to Liu and Tan [10] adding two types of fibers (PVA and steel) is also helpful at preventing explosive spalling of ECC at high temperatures. The improvement is also observed in concrete as well like self-compacting concrete containing steel and hybrid fibers has higher mechanical properties and spalling resistance with temperature increase [11]. Wang et al. [12] briefly highlighted improved residual compressive strength under high temperatures with basalt and PVA fibers. Concrete with polypropylene fiber has a higher relative compressive strength than concrete without fibers [13]. Existing research also investigated the effect of the curing period, duration of temperature exposure and specimen type of ECC. Compared to air cooled, water quenched specimens developed better mechanical properties [14]. ECC has a high spalling

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resistance even after six hours of exposure to 600^0C [15]. The residual characteristics of ECC are not influenced by the size of the specimen [16].

The earlier research on the impact of high temperatures on ECC using micro-sized sand has yielded important insights (110-300 microns). However, characterization of the mechanical behaviour of fiber reinforced cementitious composites under high temperature is developed, in that quartz sand is used instead of micro silica sand [17]. Another study performed on high strength ECC under impact of elevated temperatures, RS of 2 mm particle size is used [18]. One more study conduced on effect of elevated temperatures on nano-silica-modified self-consolidating ECC, as a fine aggregate RS of an average size of 450 microns is used [19], but the effect of various particle sizes at high temperatures has not been well understood. Based on the aggregate type and particle size, as well as the curing procedure, the size and connectivity of pores in a gel network may change [20]. Several studies have already pointed out the relation between the aggregate type and particle size [21]. Changes in aggregate also contribute to the overall loss of structural safety. The strength reduction depends on the specimen's moisture content, cement paste and aggregate [22]. Therefore, it is crucial to consider the impact of local RS particle size under fire. However, research on the RS-ECC with different particle sizes of RS under high temperatures is not conducted so far.

The objective of the current study is to assess the performance of RS-ECC under high-temperature for that, experimental research is done to determine how the ECC performs both before and after temperature exposure. In particular, UPV, mass loss and compressive strength are assessed. A Scanning Electron Microscope (SEM) is also used to analyze the microstructure of the composite.

2. EXPERIMENTAL PROGRAM

Figure 1 describes the flow chart of the current study and characterization methodology. For compressive strength test, 70.7 mm x 70.7 mm x 70.7 mm size cube, a 500 mm x 100 mm x 100 mm prism for flexural test are used. The flowability test is conducted to investigate the fresh characteristics of ECC.

2. 1. Materials and Specimen Preparation ECC mixes are produced from Ordinary Portland Cement (OPC) 43 grade, Class F FA and RS confirms to zone II is used. Table 1 displays the chemical composition of binder materials and RS. In this study, Polyvinyl Alcohol (PVA) fibers with a diameter40 microns, length 12 mm and volume fraction of 1%, were utilized. Also, PVA fibers have elastic modulus (40.0 GPa), elongation (6%).

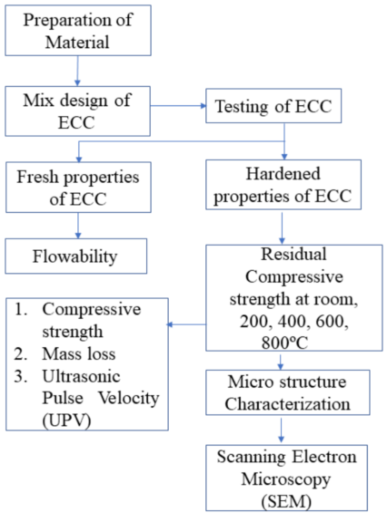

Figure 1. Flow chart of current study

To achieve the appropriate flow of mixes, a superplasticizer (Polycarboxylic type) is added.

2. 2. Specimen Preparation In the ECC mix design, the mix proportion of a standard ECC mixture M45 (Table 2) is adopted acorrding to literature [23]. In all the mixes, the particle sizes of RS were varied (2.36mm, 1.18mm and 0.60mm). The volume percentage of fibers is used only 1% for all mixes, higher content may leads to fiber clumping due to the larger aggregate size used in the current study. water content and superplasticizer is adjusted according to local ingredient condition and to achieve good fiber dispersion. A standard ECC mixing process is used in the production of ECC mixes [24]. The specimens were demoulded after 48 hours and cured in water before being tested.

2. 3. Elevated Temperature Exposure The RS-ECC specimens are heated in a muffle furnace once water curing is completed. The exposure temperatures are 200^0C, 400^0C, 600^0C and 800^0C [6] and the time of exposure is determined according to ISO 834 guidelines

TABLE 1. Chemical composition of binder materials and RS from Energy-Dispersive X-ray Spectroscopy (EDS)

Chemical Composition (wt%)	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	K_2O	Na_2O
Cement	68.62	4.71	15.11	1.32	3.84	2.55	0.83
Fly ash	1.36	25.23	62.84	0.61	4.68	2.43	0.13
River sand	2.21	11.47	67.65	0.31	7.10	9.68	-

TABLE 2. Mix proportion

Mix	Mix proportion (% by weight of cement)					Volume ratio (%)
	Cement	Fly ash	Water	River sand	Superplasticizer	PVA
M0ECC [23]	1	1.2	0.66	0.8	0.013	2
M1	1	1.2	0.64	0.8	0.015	1
M2	1	1.2	0.64	0.8	0.015	1
M3	1	1.2	0.64	0.8	0.015	1

[25]. M0ECC (reference mix) and in the Mix the M letter indicates particles size T letter indicates the exposure temperature. For example, M1, M2 and M3 are Mix with 2.36mm, 1.18mm and 0.60mm passing RS and T0, T1, T2, T3 and T4 represent 28^{0}C, 200^{0}C, 400^{0}C, 600^{0}C and 800^{0}C respectively.

3. RESULTS AND DISCUSSION

3. 1. Flowability The spreading flow of RS-ECC reduced when the gradation varied from 2.36mm to 0.60mm in flowability tests for the three-particle size distribution of RS. Table 3 summarized the percentage drop in flowability concerning M1. Due to the increased specific surface area of finer RS, the flowability of RS-ECC decreases when the particle size of RS is lowered (M3). It's worth mentioning that the superplasticizer dosage is kept constant to assess the influence of RS on flowability. The spread flow achieved by M1, M2 and M3 is similar to that described by Huang et al. [26]. The flowability of ECC normal [27] is lower than the RS-ECC in current study the difference may be due change in aggregate size and fiber content.

3. 2. Compressive Strength Figure 2 depicts the change in strength as a function of RS particle size. The strength of M3 is greater than that of M1 and M2. The enhancement of compressive strength is improved by finer RS particles. The possibility for fiber agglomeration reduces as the aggregate particle size decreases. Given that 0.60mm, RS particles are significantly smaller than 2.36mm and 1.18mm RS particles, 0.60mm presented a lower probability of fiber agglomeration, which results in a weak area within the composite. Furthermore, because of its small particle size, 0.60mm may act as a filler material, thus enhancing particle packing and the matrix's microstructure. As a result, improvements in the strength of RS-ECC at all ages may be possible [28]. After 90 days the strength of M3 is 63.898 MPa. ECC employing micro silica sand achieved a similar result, according to Liu et al. [29] and Sherir et al. [30]. The strength of RS-ECC is higher than ECC normal [31], the reason may be due to change in fiber content and aggregate size.

TABLE 3. Flowability of RS-ECC

Mix	Flowability (mm)	Percentage variation concerning M1 (%)
ECC normal [27]	180	-
M1	210	0
M2	195	7.142
M3	185	11.90

3. 3. Ultrasonic Pulse Velocity For all, the quality grading of all RS-ECC mixes meets IS 13311: 1992 criteria. Table 4 shows that the UPV of M3 is slightly higher as compared to M1 and M2. The RS-ECC increases from a particle size of 2.36mm to 0.60mm as the particle size of the sand gradation gets finer. M3 increased UPV may be related to its better compactness.

3. 4. Experimental Results After Temperature Exposure

3. 4. 1. Mass Loss and Appearance Figures 3 and 4 show the mass loss of the RS-ECC specimens, it is

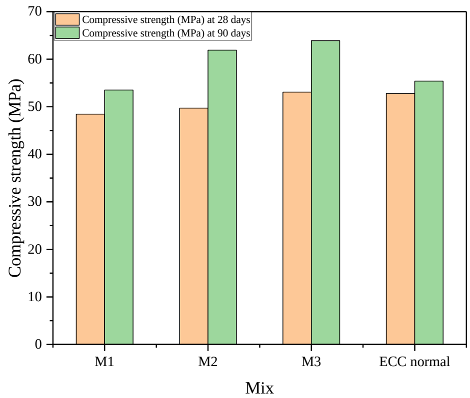

Figure 2. RS-ECC Compressive strength and ECC normal at room temperature

TABLE 4. UPV and the percentage variation of RS-ECC at room temperature

Mix	UPV (m/s) in days		Percentage (%) variation concerning M1 in days	
	28	90	28	90
M1	3854	3862	0	0
M2	3867	3883	0.337	0.543
M3	3911	3918	1.478	1.450

noticed that when the temperature rises, the weight of all RS-ECC specimens decreased. Dehydration happened as the temperature increases, and moisture escapes from the matrix. As a result, the specimen undergoes internal damage and weight loss. Up to 800^{0}C, considerable weight loss occurred is seen for all the mixes. Due to the denser formation in the cementitious system, which leads to decreases hydrates decomposition rate, mass loss is lower than higher particle sizes at all exposure temperatures for 28 and 90 days [18]. Due to reduced water in the microstructure of RS-ECC, mass loss is somewhat lower at 90 days than 28 days [32].

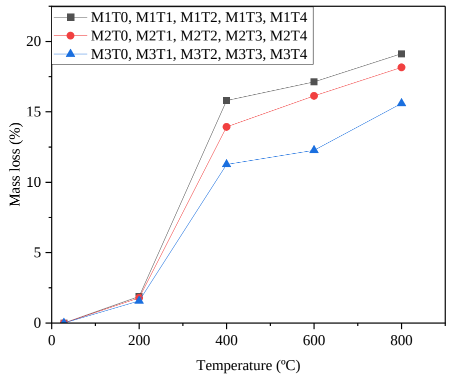

Figure 3. Mass loss of RS-ECC of 28 days after temperature exposure

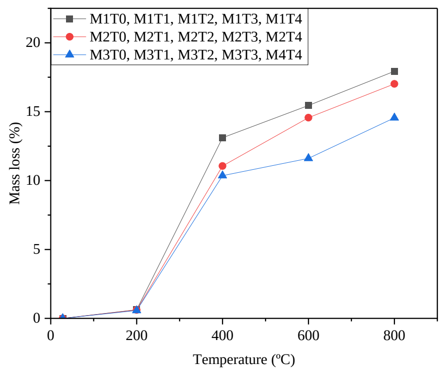

Figure 4. Mass loss of RS-ECC at 90 days after temperature exposure

(a) (b)

Figure 5. The appearance of RS-ECC after temperature exposure: **A** 28 days; **B** 90 days

3. 4. 2. Compressive Strength at Various Temperatures Figures 6 and 7 demonstrate the variations of normalized residual compressive strength (N_{CS}) of RS-ECC at 28 and 90 days. N_{CS} is expressed by $C_{S,\ T}$ / $C_{S,}$ where $C_{S,\ T}$ is the residual strength of the specimens after exposure to different temperatures, and C_S is the compressive strength at 28^{0}C. The strength of RS-ECC increased (7% and 4%) at 200^{0}C and 400^{0}C after 28 days. In other study the phenomenon is obtained [33]. It is due to accelerated pozzolanic reaction, but for 90 days it shows 6.8% and 10% reduction in strength. When the specimens were exposed to 600^{0}C the RS-ECC mix retained 76% and 63% of Compressive strength, while the residual strengths are 43% and 36% at 800^{0}C at 28 and 90 days. The decrease in strength is due to melting of fibers, partial dehydration of C-S-H occurs between 200^{0}C to 400^{0}C. The dehydration of hydration products, enhanced micro-cracking and coarsening of the pore structure are the major causes of the rapid decrease in N_{CS} between 400^{0}C and 600^{0}C [32]. The bonding between the aggregates and the hydration products is deteriorated significantly [34]. The major reason for the loss in compressive strength after exposure to 600^{0}C is both the

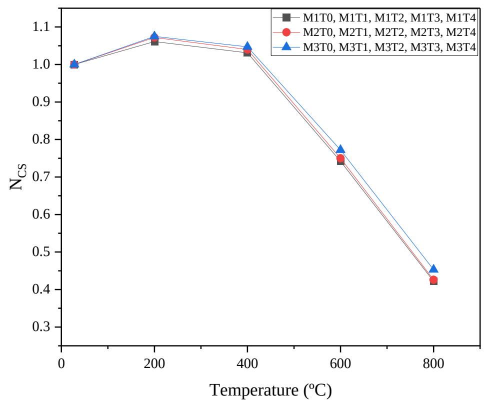

Figure 6. Normalized residual compressive strength at 28 days

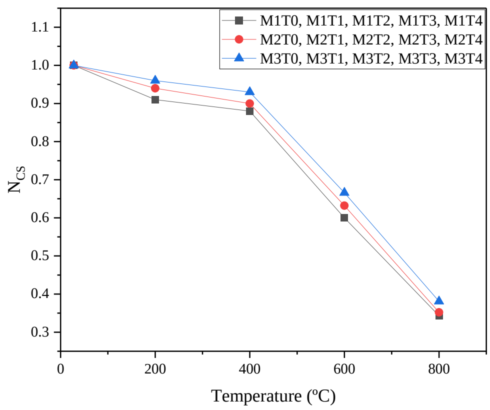

Figure 7. Normalized residual compressive strength at 90 days

physical transformation of the matrix and the chemical transformation of the hydration products [14]. Another cause might be that, due to the higher particle sizes, thermal incompatibility is expected more severe in the mix with 2.36mm and 1.18mm RS, resulting in more micro-cracks and a lower strength after exposure [35]. At varied temperature exposure for 28 and 90 days, the lower particle size of RS has greater normalized strength than the higher particle size of RS.

Figure 8 compares the normalized compressive strength of standard M45 ECC collected from literature [6, 16, 36]. The difference in strength is due to the fiber content up to 400^{0}C, after 400^{0}C the difference in strength is comparable with the reference literature with micro silica sand.

3. 4. 3. Stress-strain Curves The ultimate stress decreased as the temperature increases, especially when the temperature is above 400^{0}C (Figure 9). As expected, the post-peak stress drops rapidly as the exposure temperature rises, as predicted, resulting in a smaller post-peak area under the curve. When the exposure temperature reaches 800^{0}C, this behaviour becomes clearer. RS-ECC specimens failed immediately after reaching their maximum stress. This means that when the exposed temperature rises, the ductile characteristic of RS-ECC tends to become brittle nature.

3. 5. Ultrasonic Pulse Velocity at Various Temperatures Figures 10 and 11, show the normalized residual Ultrasonic Pulse Velocity (Nuv) of RS-ECC after being exposed to various temperatures. The value of Nuv is expressed by $U_{V,T} / U_V$, where $U_{V,T}$ is the residual Ultrasonic Pulse Velocity of the specimens after exposure, and U_V is the Ultrasonic Pulse Velocity at room temperature. The N_{UV} decreased from 200^{0}C to 800^{0}C for all mixes, indicating that more defects and pores are formed by the decomposition of hydrates and melting of PVA fibers [17]; but, lower loss in UPV is observed for smaller particle size.

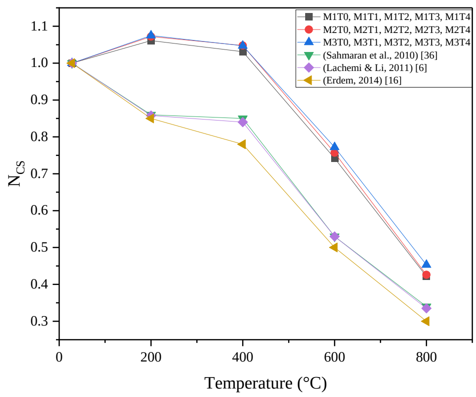

Figure 8. Comparison of Normalized compressive strength from different literature

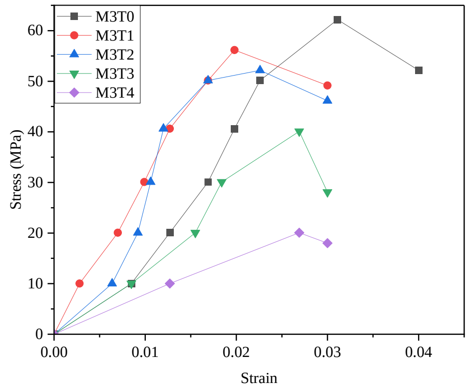

Figure 9. Stress-strain curves of RS-ECC at 90 days

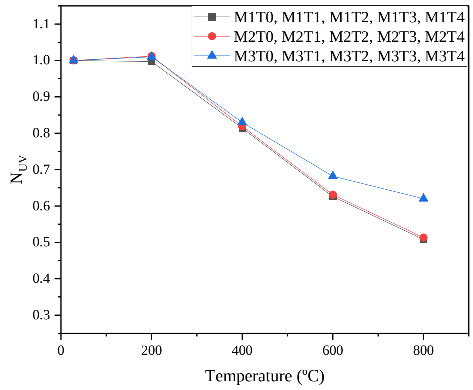

Figure 10. Normalized residual Ultrasonic Pulse Velocity at 28 days

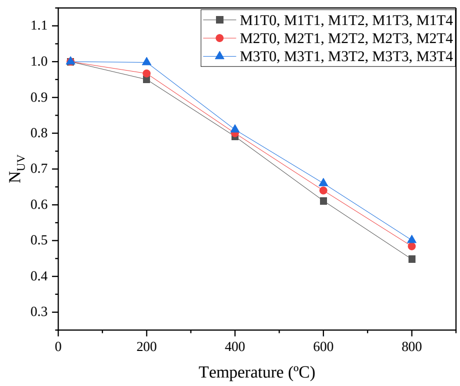

Figure 11. Normalized residual Ultrasonic Pulse Velocity at 90 days

3. 6. Microstructure of Composite Under SEM, Figure 12 shows the microstructure of post-exposure samples. It is evident that, as a result, the shrink PVA fibers separated from the matrix after exposure to 200^{0}C, showing the burning behaviour of PVA fibers, weakening the interfacial transition zone, which might be the cause of performance loss at the macroscale. Fibers are no longer visible as the heating temperature increases to 400^{0}C; Instead, needle-like channels developed in the

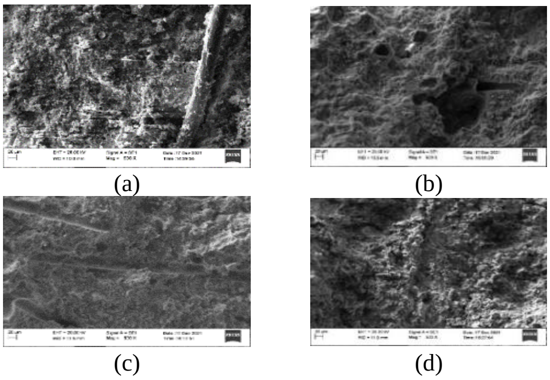

Figure 12. Transformation of PVA fibers in RS-ECC after exposure to various temperatures: **A** 200^0C; **B** 400^0C; **C** 600^0C; **D** 800^0C

PVA fiber sites. These channels offered additional pathways for water evaporation and energy dissipation, which contributed to the avoidance of spalling, longitudinal empty channels may function as an initial flaw in RS-ECC, facilitating the development of microcracks [18].

In Figure 13, it is observed that due to thermo-physicochemical reactions beyond 600^0C, irregular bush-like structures are visible. Interestingly, the channels eventually fill with newly produced compounds, potentially affecting the Pore coarsening effect of cementitious composites at high temperatures. The connections and frictional forces are considerably decreased, resulting in severe damage to the strength of RS-ECC [18]. The FA had completely melted when the temperature reached 800^0C. In the microstructure, more micro-pores from the inner FA are exposed, and dehydrated C-S-H gels, which are completely covered in melted FA, are not visible. The microstructure is seriously deteriorated as a result of the melting of the FA and decomposition of the C-S-H gels, resulting in strength and UPV reduction, increased mass-loss rates of RS-ECC [17, 33].

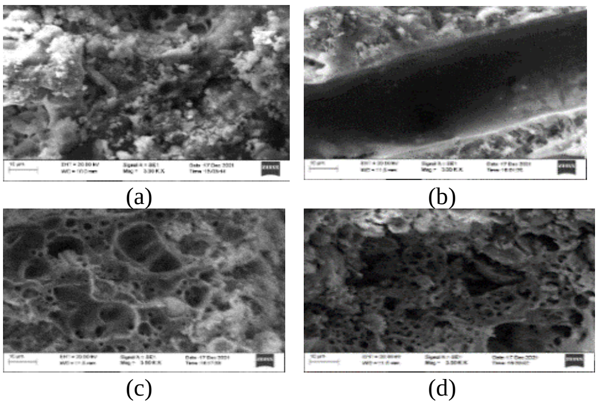

Figure 13. Microstructure of RS-ECC at various temperature exposures: **A** 200^0C; **B** 400^0C; **C** 600^0C; **D** 800^0C

4. CONCLUSIONS

The effects of varying particle sizes of river sand on the flow behavior of RS-ECC in a fresh state, as well as mechanical performance at room and elevated temperatures, are investigated. The conclusions are drawn based on study:

1. The flowability of RS-ECC is reduced for smaller particle size as compared with larger particle sizes at a constant rate of superplasticizer.
2. The compressive strength of RS-ECC mixes increased with both curing ages. But the strength is observed in with smaller particle size as compared with larger particle sizes at room temperature. With tan increase in temperature, the strength is reduced for all particle sizes, but strength loss is lower for smaller particle sizes. No spalling is observed in all RS-ECC mixes.
3. The UPV at room temperature showed slight increase for the mix with smaller particle size in comparison with larger particle sizes. Whereas at higher temperatures for smaller particle size lower loss in UPV is observed.
4. The colour of RS-ECC changed from darker at 200^0C to yellowish grey at 800^0C, the appearance of specimens is comparable at both 28 and 90 days.
5. At different exposure temperatures, the mass-loss increased for all RS-ECC mixes. Among all the lower mass loss is observed in the mix with smaller particle size.

5. CONTRIBUTIONS

In summary, the RS-ECC developed in this study, In the area of concrete structural engineering, certain reliable and useful experimental data is also useful to researchers and structural engineers. This would provide some theoretical background for repairing concrete structures at high temperatures. The research results are also favorable to researchers and practical engineers in the subject of ECC fire proofing.

6. LIMITATIONS

The study is considered to evaluate the residual strength under compression with lower PVA fiber content.

The study results are suited for air cooled contained instead of water quenching after temperature exposure.

7. FUTURE WORK RECOMMENDATIONS

The following issues should be investigated on how elevated temperatures affect RS-ECC:

The influence of increased fiber content on RS-ECC with different particle sizes on mechanical characteristics both before and after exposure.
The impact of high-temperature on properties of hybrid fibers on RS-ECC with different particle sizes.

8. ACKNOWLEDGEMENTS

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Persian Abstract

کامپوزیت های سیمانی مهندسی شده (ECC) یک مصالح ساختمانی مناسب با خواص بهتر نسبت به بتن معمولی است. در حال حاضر، پس از زلزله، آتش سوزی در یک ساختمان یکی از جدی ترین بلایا است. مقدار و اندازه ماسه مورد استفاده در ECC پارامترهای مهمی برای عملکرد در شرایط حرارتی هستند. ماسه میکرو سیلیس در اکثر آزمایشات ECC مربوط به پاسخ حرارتی استفاده می شود. هدف این مطالعه، بررسی تأثیر شن و ماسه رودخانه (RS) بر عملکرد ECC در معرض افزایش دما تا ۸۰۰۰ درجه سانتیگراد، از طریق یک سری آزمایش‌های تجربی بر روی مقاومت فشاری، تلفات جرم، سرعت پالس اولتراسونیک (UPV) و ریزساختار است. برای این منظور، مخلوط هایی با ترکیب RS با اندازه ذرات مختلف (۲.۳۶ میلی متر، ۱.۱۸ میلی متر، ۰.۶۰ میلی متر) به جای ماسه میکرو سیلیس تهیه گردید. در ECC حاوی RS با اندازه‌های مختلف ذرات، پوسته پوسته شدن وجود ندارد. بر اساس یافته‌ها، مقاومت فشاری، کاهش جرم و UPV همگی با افزایش دما کاهش می‌یابند. با این حال، RS-ECC با ۰.۶۰ میلی متر بهتر از ۱.۱۸ میلی متر و ۲.۳۶ میلی متر RS عمل می کند.