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Rebar properties in sand-substitute mortars after exposure to high temperatures

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Research Paper

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Rebar properties in sand-substitute mortars after exposure to high temperatures

This study investigates the effects of fire, cooling methods, and cover thickness, on the behaviour (strength and ductility) of 12-mm diameter rebars embedded in mortars with river sand (RS) substitutes such as granite powder and manufactured sand, with 30 and 50 mm cover thickness. Beyond 500 °C, thermal stress induced random spalling of mortar cover, and tension test results showed strength decrement and ductility increment of rebars for air cooling, while the vice versa was observed for water quenching.

Key words:
rebar properties, fire, sand substitutes, cover thickness, air cooling, water quenching

Prethodno priopćenje

Jeyaprabha Balasubramanian, Elangovan Gopal, Dhivya Kamaraj, Sathish Kumar Ponnaiah, Prakash Periakaruppan

Svojstva armature ugrađene u mortove sa zamjenom pijeska nakon izlaganja visokim temperaturama

U ovom se radu istražuje utjecaj zagrijavanja, metoda hlađenja i debljine zaštitnog sloja na ponašanje (čvrstoću i duktilnost) rebraste armature promjera 12 mm ugrađene u mort u kojem je riječni pijesak zamijenjen granitnim prahom i proizvedenim pijeskom, pri čemu debljina zaštitnog sloja iznosi 30 i 50 mm. Na temperaturama iznad 500 °C, toplinsko naprezanje uzrokovalo je nasumično ljuskanje zaštitnog sloja, a vlačna ispitivanja upozorila su na smanjenje čvrstoće i povećanje duktilnosti armature pri hlađenju na zraku, dok je suprotna pojava uočena pri gašenju vodom.

Ključne riječi:
svojstva armature, požar, materijali za zamjenu pijeska, debljina zaštitnog sloja, hlađenje na zraku, gašenje vodom

Vorherige Mitteilung

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Bewehrungseigenschaften in Sandersatzmörteln nach Einwirkung hoher Temperaturen

In dieser Arbeit wird der Einfluss der Erwärmung, die Methode der Kühlung und die Dicke der Schutzschicht auf das Verhalten (Festigkeit und Dehnbarkeit/Duktilität) der Rippenbewehrung mit dem Durchmesser von 12 mm geforscht, welche in den Mörtel eingebaut wurde, in welchem der Flusssand mit dem Granitpulver und dem hergestellten Sand ersetzt wurde, wobei die Dicke der Schutzschicht 30 und 50 mm beträgt. Auf den Temperaturen über 500 °C hat die Wärmespannung das teilweise Abschälen der Schutzschicht verursacht, und die Prüfungen der Zugspannung haben auf die Minderung der Festigkeit und die Erhöhung der Dehnbarkeit der Bewehrung bei der Kühlung an der Luft aufmerksam gemacht, während bei der Löschung mit dem Wasser eine Gegenerscheinung bemerkt wurde.

Schlüsselwörter:
Eigenschaften der Bewehrung, Brand, Materialien für den Sandersatz, Dicke der Schutzschicht, Kühlung an der Luft, Löschung mit Wasser

1. Introduction

River sand (RS) is an important constituent of plain cement concrete, reinforced cement concrete, prestressed concrete, mortar and concrete blocks. The natural formation of RS takes several millions of years. The need for RS is enormously increasing on a daily basis. On the other had, all available resources are exhausting rapidly. Therefore, the manufactured sand (MS) has become a viable alternative to RS. In granite factories, huge amount of granite powder (GP) waste is generated during the cutting and polishing process, and its disposal has become a serious impediment since it creates many environmental problems. Its diffusion pollutes air, water, and soil alike. This waste material has also been used in concrete as an alternative material to RS [1]. The strength and durability characteristics of concrete and mortar made with MS and GP waste have been studied by many investigators. Waste granite powder increases the volume of hydrated cement and improves performance of masonry mortar [2]. Lime powder used with MS fills the pore structures, strengthens interfacial transition zone, and accelerates cement hydration [3]. High surface roughness and lower crushing value of MS improves the abrasion resistance of MS cement concrete for pavements [4]. MS with a suitable production process exhibits better behaviour in concrete compared to RS [5]. Fines from manufactured aggregates affect rheological properties and increase the water demand [6]. Mix design based on the minimum paste theory has been suggested as a means to improve the volume stability and cracking resistance performance of MS concrete [7]. A mix proportion for ultra-high strength concrete with MS ensures high packing density, as well as smaller and homogeneous dispersal of hydration products [8]. During fire accidents, reinforced concrete structures are exposed to elevated temperatures. Mechanical properties of all common building materials deteriorate with a rise in temperature. The ductility, ultimate strength and yield strength of reinforced-steel bars are affected by fire. The severity depends on temperature level, rate of heating, period of exposure, and cooling rate. Either softening or hardening may take place depending on cooling methods [9]. To renovate such fire affected structures, the residual strength of the structure and structural elements such as concrete, reinforcement, and mortar, should be determined. Generally, the cover concrete renders protection to rebars against fire. After retrofitting and repairing, the fire affected structure may be used. Hence a thorough structural analysis is required before making a decision on whether the structure should be demolished or reused. Whereas a literature study reveals that a certain quantum of work has been carried out on the related areas of fire study, which include the effect of elevated temperature on surface hardness of reinforced concrete beams, the effect of prolonged high temperature exposure and thin cover on the strength of rebars, the effect of cover thickness on rebars exposed to elevated temperatures, shear behaviour of reinforced concrete beams exposed to elevated temperatures, nonlinear analyses of RCC columns during fire, performance of blended ash geopolymer concrete at elevated temperatures, spalling behaviour of fibre-reinforced high strength concrete at elevated temperatures, and deterioration of slag concrete at elevated temperature [10-17], only limited studies have been carried out vis-à-vis mortar and concrete made of RS substitutes such as MS and GP waste exposed to fire. To bridge this gap, the experimental study presented in this paper investigates the effect of high temperatures, methods of cooling and cover thickness on the mechanical properties of rebars embedded in mortars made with RS substitutes. The experimental results reveal that it is possible to determine the strength loss, predict the changes in the ductility performance of rebars, and study the spalling behaviour of mortar covers made with RS substitutes exposed to fire.

2. Materials and methods

2.1. Materials

The properties of materials used in this study, namely ordinary Portland cement (OPC), RS, MS and GP waste, have been described in detail in our previous report [18]. The RS and MS passing through a 4.75 mm sieve, having specific gravity of 2.54 and 2.57, respectively, were used. The water absorption was 0.032 % and the silt content was 2 %. The specific gravity and specific surface area of GP were 2.19 and 333 m^2/kg, respectively. The steel used in the experiment was the 12 mm diameter Fe 500 thermo-mechanically treated (TMT) ribbed bar that is commonly used as longitudinal bar reinforcement conforming to IS 1786: 2008 [19]. The rebars were embedded in RS mortar (RSM) control specimen, 100 % MS mortar (MSM) and 15 % GP mortar (G15M) which was an optimum percentage of RS replacement with GP waste [18]. The mixture proportions for casting the specimens and finding of optimum 15 % of replacement of GP waste for RS have been elaborated in our previous study [18, 20]. The chemical composition of the bars, given by the manufacturer, is given as follows: carbon, phosphorus, sulphurs and nitrogen content was 0.300, 0.055, 0.055, and 120 ppm respectively.

2.2. Specimen preparation

The mixture ratio of materials used in mortar specimens was 1:3 and the water cement ratio was 0.5. Mortars with 100 % RS (RSM), 100 % MS (MSM) and 15 % GP + 85 % RS (G15M) were produced in this experimental study. The water content of each mixture was kept constant. The rebars were embedded RSM, MSM and G15M to study the effects of fire, cooling methods, and cover thickness on the strength and ductility behaviour. Special cover blocks were used to provide a cover of 30 and 50 mm in thickness, which is the usual practice for rebars. The rebars were placed into the centre of mould-made frame works measuring 72 x 72 x 400 mm and 112 x 112 x 400 mm. They were filled with mortars in two layers with a vibration table so as to ensure that no voids are left in the mortars. One hundred and eighty specimens (5 different temperatures x 2 different cover thicknesses x 3 types of mortars x 2 cooling methods x 3 specimens) were cast so as to take into account the cover thickness (30 and 50 mm), mortars (100 % RS, 100 % MS and 15 % GP + 85 % RS), temperatures (room temperature, 200 °C, 500 °C, 700 °C and 900 °C), and cooling methods (natural air cooling and rapid water quenching). The specimens were demoulded after 24 hours, and then cured in water for 28 days. After curing, the specimens were kept at atmospheric conditions for 3 months for drying.

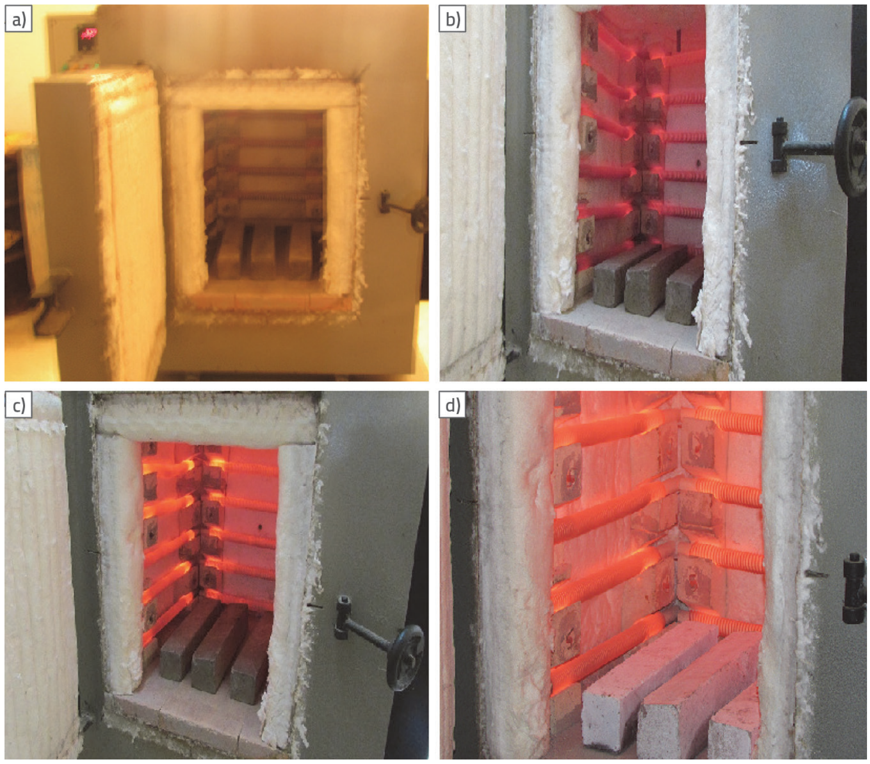

Figure 1. Specimens with rebars heated in high temperature muffle furnace to: a) 200 °C; b) 500 °C; c) 700 °C; d) 900 °C

2.3. Thermal treatment and methods

Three specimens from each group were kept at the same time after attainment of required temperature for 3 hours using a high temperature furnace. The specimens were slowly heated to the predetermined high temperatures (obtained from thermogravimetric analysis (TGA) as presented in our previous study [18] and as per ISO thermal loading) as shown in Figure 1. This was followed by a manual cooling process; the furnace was turned off and the specimens were cooled rapidly by plunging them into water for rapid cooling, after which they were kept aside for normal air cooling until they reached the atmospheric temperature. Then the rebars were removed from the specimens by breaking the mortar without any damage, and the specimens were labelled for the tests: RSM, G15M and MSM denote RS mortar, GP waste mortar (15 % GP + 85 % RS) and MS mortar (100 % MS), respectively. The numbers 3 and 5 denote 30 and 50 mm cover and A and W indicate normal air cooling and rapid water quenching, respectively. The mark PL denotes plain steel bars (not covered by mortar).

The yield strength, ultimate strength and percentage elongation of the rebars at failure were obtained in accordance with the provisions of IS1608:2005 [21] using a universal testing machine. The plain rebars were also exposed to these temperatures under the same conditions to investigate mechanical properties. Micro structural changes of tiny fragments of air cooled and water quenched mortar specimens were studied by scanning electron microscopy (SEM) JEOL JSM6390 model.

3. Results and discussion

Strengths and micro structures of RSM, GP15M and MSM at room temperature and elevated temperatures with different cooling regimes, namely normal air cooling and rapid water quenching, have already been reported by our group [18, 20, 22].

3.1. Mechanical properties of rebars embedded in fired mortars after air cooling

3.1.1. Yield strength

The results presented in Figure 2 are average results obtained on three specimens. The changes in yield strengths of RSM3A, G15M3A and MSM3A and RSM5A, G15M5A and MSM5A sets are shown in Figure 2a and 2b. The yield strengths of all the rebars reduce with an increase in temperature. There is not much reduction in yield strengths up to 500 °C, but a significant strength loss occurs above this temperature, as also reported in previous studies [23, 24]. The strength loss of exposed rebars was calculated by comparing the strength of rebars at ambient temperature. The yield strength loss at 700 °C varies from 8.29 % to 12.65 % for rebars embedded in mortars with 30 mm cover and 16.45 % for plain rebrs without thermal treatment at ambient temperature (PLA). While the yield strengths at 900 °C for RSM3A, G15M3A and MSM3A bars is in a closer range, there is a significant variation in the yield strength of PLA. The yield strengths loss varies from 22.28 % to 27.32 % for RSM3A, G15M3A, MSM3A and 38 % for PLA at 900 °C. It can be seen in Figure 2 A that the yield strengths of the rebars inside the RSM3A, G15M3A and MSM3A at 900 °C are better compared to that of the PLA. In line with these results, it might be stated that the 30 mm mortar cover obviously protects the rebars against high temperatures when they are cooled by normal air cooling. The yield strengths of all the rebars embedded in mortars with 50 mm cover also reduce with temperature as shown in Figure 3.b. It can be seen in figures 3a and 3b that the PLA and rebars embedded in mortars exhibit the same yield strengths values at 500 °C. The yield strength loss of RSM5A, G15M5A and MSM5A at 700 °C is around 6 % and, at 900 °C, it ranges from 6 to 12 %. According to these results, it can be inferred that the 50 mm cover reduces the yield strength loss more than the 30 mm cover and PLA by 6.65 % and 10.45 %, respectively, after exposure to 700 °C. At 900 °C, the 50 mm cover reduces the strength loss by 26 % compared to PLA. The mortar cover does give protection to the reinforcing bars by not allowing the complete transfer of high temperatures which occur at the surface of the specimens [25, 26]. The performance of RS, G15 and MS mortar covers is inconsiderable at all elevated temperatures.

3.1.2. Ultimate strength

The effect of elevated temperatures on the ultimate strength of the rebars embedded in mortars with 30 mm and 50 mm cover after air cooling is shown in Figure 2c and 2d. No appreciable reduction is seen up to 500 °C, i.e. the reduction starts to occur above this temperature. For rebars with 30 mm cover, the ultimate strength loss at 700 °C varies from 7.74 % to 12.9 %, and it is very negligible for rebars with 50 mm cover. At 900 °C, the ultimate strength loss for rebars in RSM3A, G15M3A and MSM3A and RSM5A, G15M5A and MSM5A ranges from 22.53 % to 25.43 % and 8.5 % to 15.6 % respectively. A major decrease in ultimate strength of about 17.4 % and 31.8 % is observed for PLA at 700 °C and 900 °C. These results show that the 50 mm cover offers 16.2 % higher protection than PLA. In rebars with cover, the high strength loss at temperatures of over 500 °C is accounted by the transformation of calcium hydroxide to anhydrous lime. Furthermore, due to consequent occurrence of a number of fractures in the mortar, the protective ability of mortars decreases and the rebars exhibit strength degradation at elevated temperatures [27]. Here again, the mortar covers give protection to the embedded rebars from direct exposure to high temperatures but the effect of RS substitute mortars is insignificant.

3.1.3. Percentage elongation

Relationships between the percentage elongation (PE) and temperature for RSM3A, G15M3A and MSM3A and RSM5A, G15M5A and MSM5A are shown in Figure 2. E & F. The deflection of reinforced cement concrete (RCC) members mainly depends on the ductility of steel. After fire exposure and air cooling, the ductility of steel increases resulting in an increased deflection of the member. There is no change in the PE of covered and plain steels exposed to temperatures below 500 °C. The increment in PE rises from 19.16 % to 24.73 % at 700 °C and 45.51 % to 49.70 % at 900 °C for rebars with 30 mm cover. The increment in PE was calculated by comparing the PE of rebars at ambient temperature. For rebars with 50 mm cover, the increment in PE increases from 10.4 % to 14.8 % at 700 °C, and from 22.2 % to 33.5 % at 900 °C. The PE increment is approximately 38 % at 700 °C and 64 % at 900 °C for PLA. The loss in the protection ability of mortars above 500 °C is attributed to the conversion of $Ca(OH)_2$ to free lime (CaO) and growing cracks and disintegration. When the specimens are exposed to 900 °C, the decomposition of hydration products and their conversion to calcite and calcium silicates [28, 29] take place, resulting in the formation of cracks as shown in Figure 3. All the mortars are affected in similar way when exposed to elevated temperatures.

3.2. Mechanical properties of rebars embedded in fired mortars after water quenching

3.2.1. Yield strength

The yield strength of all the rebars increases with an increase in temperature after water quenching as shown in Figure 4a and 4b. It can be observed that no noticeable increments are seen up to 500 °C for RSM3W, G15M3W and MSM3W and RSM5W, G15M5W and MSM5W. At 700 °C, the yield strength increases by 13.08 to 18.29 % for rebars embedded in mortars with 30 mm cover, and by 23.33 % for PLW. At 900 °C the yield strength is almost in a close range for RSM3W, G15M3W and MSM3W. The yield strength gain of the rebars is 8.8 to 14.2 % for the RSM5W, G15M5W and MSM5W at 700 °C. This strength gain grows up to 28.2 % and 37.02 % for rebars embedded in mortar with 50 mm cover and PLW, respectively, at 900 °C. Rapid cooling results in high strength but in low ductility [24]. Structural steel must have adequate ductility for better structural performance. Based on these results, it can be inferred that 50 mm cover thickness gives maximum of 9.13 % better protection than the PLA against the effects of high temperatures when heated specimens are cooled by rapid water quenching, but the effect of RS substitute mortars is insignificant.

3.2.2. Ultimate strength

The ultimate strength of rebars embedded in mortars exposed to different temperatures after water quenching is shown in Figure 4c and 4d. It can be seen that ultimate strength values increase with an increase in exposure temperature. With 30

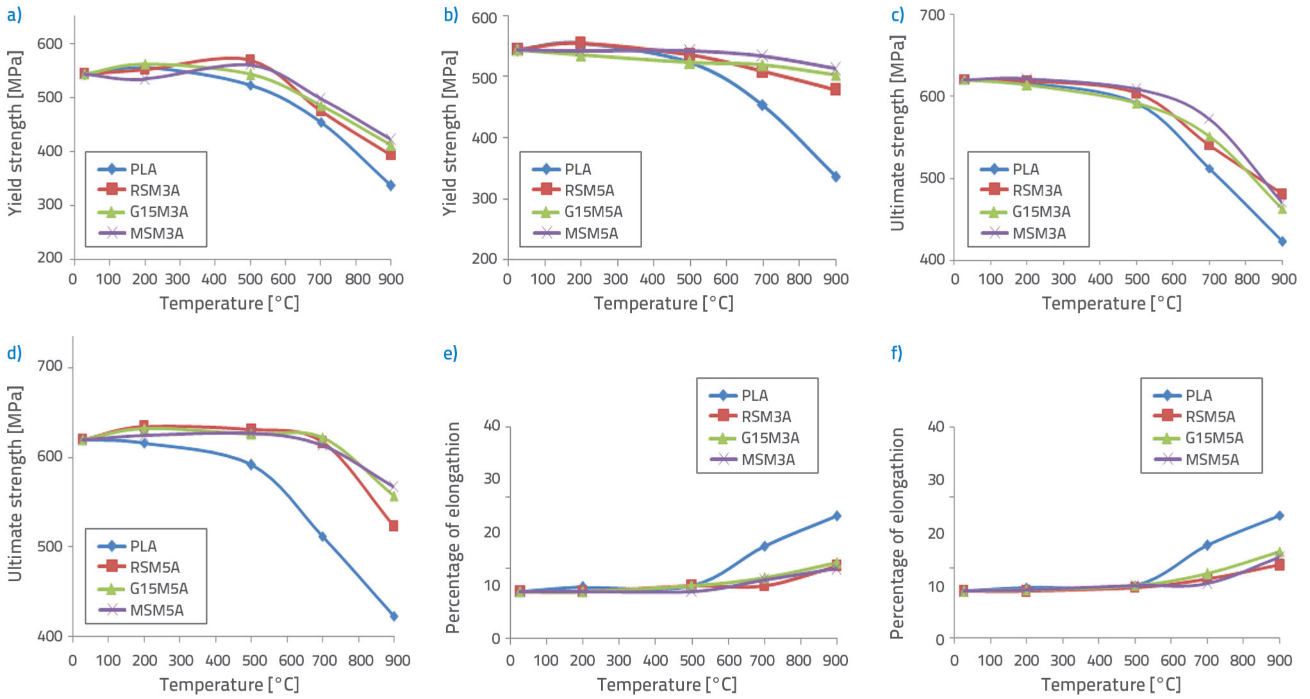

Figure 2. Effects of elevated temperatures on yield strength (a, b), ultimate strength (c, d) and % elongation (e, f) of rebars embedded in mortars with 30 and 50 mm cover after air cooling

mm cover, the increment is insignificant up to 500 °C. At 700 °C and 900 °C, approximately 9.52 to 11.13 % and 26 % strength increment is observed. At these temperatures PLW experiences 20 % and 36 % strength increment. Specimens with 50 mm cover gain 7 % and 21 % of ultimate strength at 700 °C and 900 °C, respectively. Based on the yield and ultimate strength results, it can be inferred that the 50 mm cover thickness gives maximum of 15 % better protection than the PLA against the effects of high temperatures and rapid water quenching.

3.2.3. Percentage elongation (PE)

Figure 4e and 4f. shows the effect of temperatures on PE of rebars embedded in mortars with 30 and 50 mm cover after water quenching. It is apparent that the PE of all the rebars decreases with an increase in temperature after water quenching. The decrease in PE ranges from 35 % to 38 % for RSM3W, G15M3W and MSM3W and 25 % to 27 % for RSM5W, G15M5W and MSM5W at 900 °C. 50

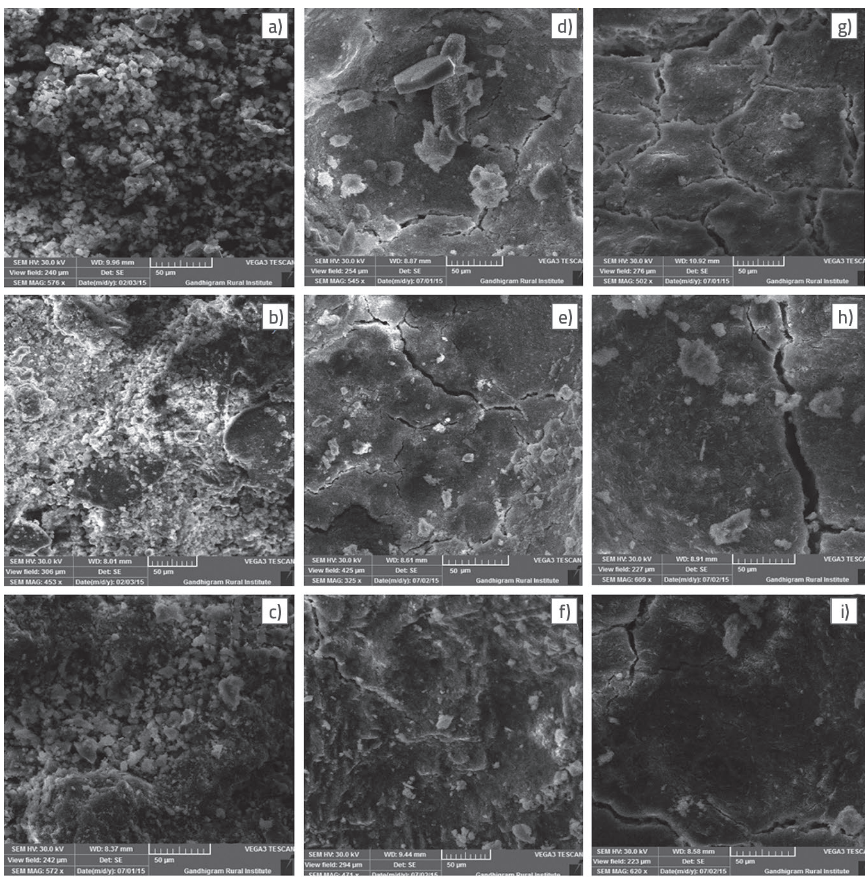

Figure 3. SEM images of RSM, G15M and MSM specimens at room temperature (a, b, c), after air cooling (d, e, f) and water quenching after exposure to 900°C (g, h, i)

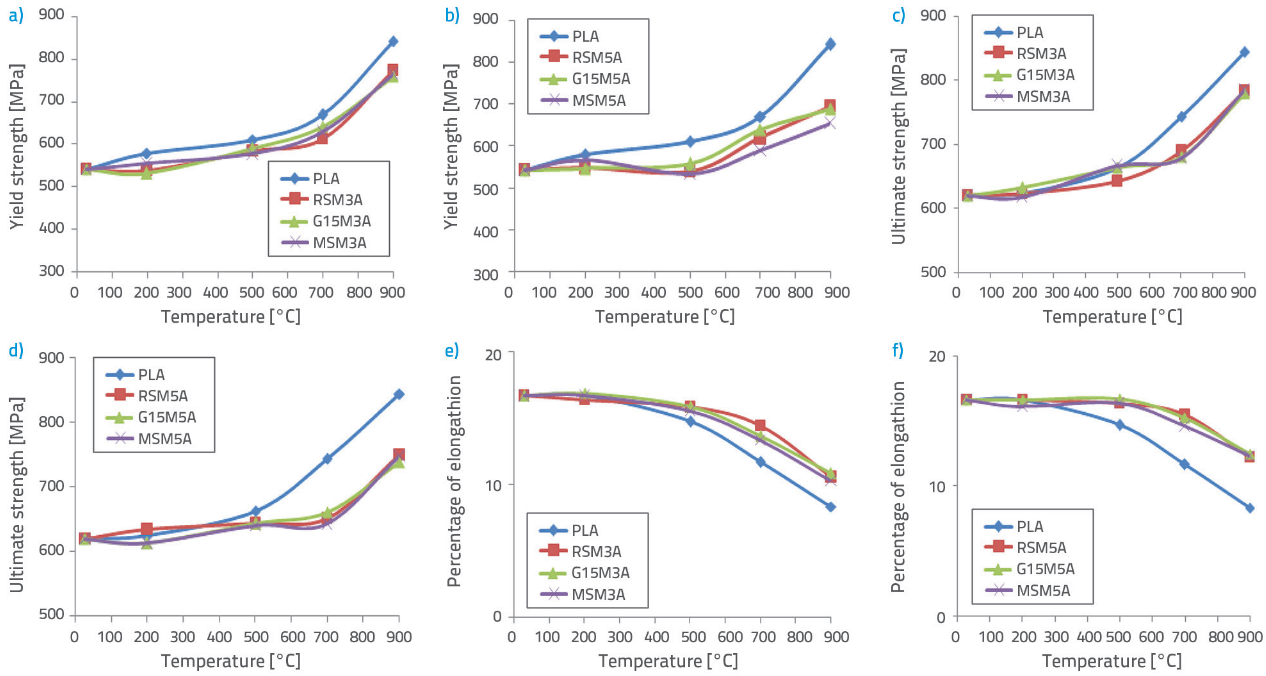

Figure 4. Effects of elevated temperatures on yield strength (a, bB), ultimate strength (c, d) and % elongation (e, f) of rebars embedded in mortars with 30 and 50 mm cover after water quenching

% decrease of PE was observed for PLW at 900 °C. Rapid cooling results in high strength but low ductility. The deflections of structural members mainly depend on the ductile behaviour of rebars [30]. The rebars become brittle with a decrease in elongation values and this behaviour is not desirable in RCC structures. Above 500 °C, calcium hydroxide is converted into quick lime by losing water. When the specimens are water quenched, the quick lime is rehydrated to calcium hydroxide, which is accompanied by volume expansion [31, 32]. Also, the mortars cooled rapidly by water quenching lose their strength due to large thermal gradients within the mortar specimens and the increment of water saturation. Both these phenomena lead to the formation of micro cracks as shown in Figure 3.

3.3. Colour change of mortar specimens

When specimens were heated to various temperatures, no colour change was observed up to 500 °C and, beyond this temperature, the grey colour faded away and turned into whitish grey at 900 °C as also reported in a previous study [33], as shown in Figure 1.

3.4. Spalling of mortar cover

Spalling is a physical process of breakdown of cover concrete. It is caused by high temperature or pressure. The pressure created by rapid changes in temperature by water quenching during fire-fighting operations causes spalling. If the concrete is reinforced with rebar, it may also be more susceptible to spalling, because the applied heat is absorbed at different rates by the metal and the surrounding concrete [34-36]. In this study, no spalling is observed up to 500 °C for all specimens.

Above this temperature, for specimens from the same batch, and under identical conditions, some spall while others do not, as is also reported in a previous study [37]. Beyond 500 °C, thermal stress induced random spalling of mortar cover (Figure 5.a) and, in most specimens, the spalling occurs along cover blocks, as shown in Figure 5.a and 5b. The sound of continuous surface spalling is similar to the sound of popping popcorn, but is somewhat sharper. The minimum and maximum spalling of 5 and 27 mm, respectively, are observed in G15M (Figure 5c), and 10 and 36 mm in RSM, which has also been observed by other authors [38] (Figure 5d) Only cracks are formed in MSM at 700 °C. Severe spalling was observed for all mortars at 900 °C (photographs not shown). Since the spalling observed is random, further analysis is required.

4. Conclusion

Experiments were carried out to study the effect of elevated temperatures on mechanical properties of rebars embedded in mortars made with RS substitutes, in relation to cover thickness and cooling regimes. The following conclusions were made:

- The changes in yield strength, ultimate strength and percentage elongation of the reinforcing TMT bars (Fe

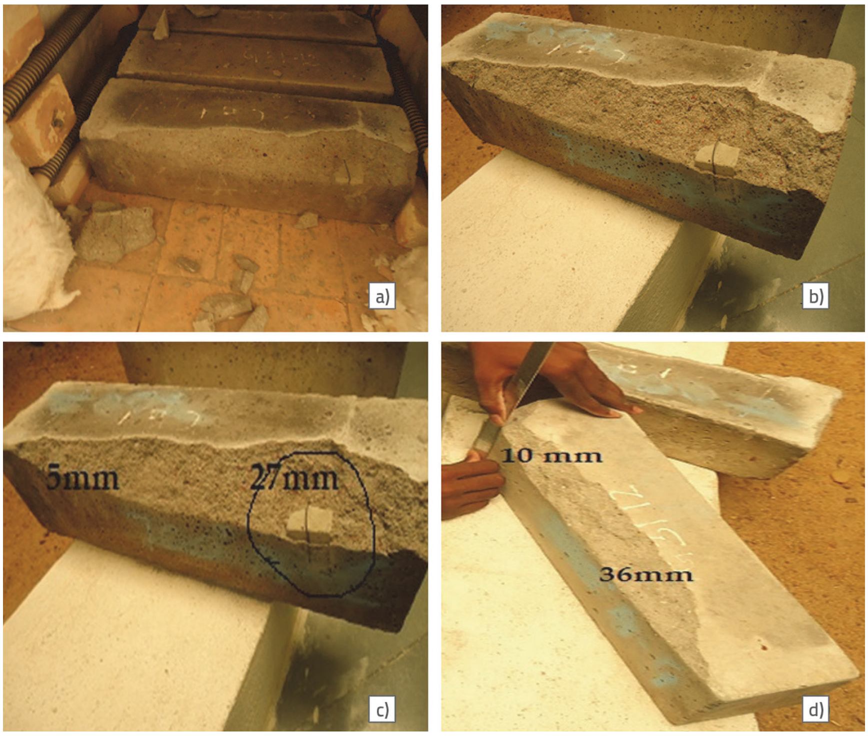

Figure 5. a) Random spalling; b) spalling along mortar cover; c) spalling of G15M; d) RSM

500, 12 mm in diameter) inside the mortar and the plain steel are similar, with close values for both air cooling and water quenching when the specimens are heated up to 500 °C.

- For reinforcing bars, 500 °C is found to be ceiling temperature, above which substantial damage is observed for both yield/ultimate strengths and percentage elongation.
- At 700 °C and 900 °C, the yield/ultimate strengths of rebars embedded in all mortars decrease and percentage elongation increases after air cooling. When exposed to maximum temperature of 900 °C, the rebar without cover loses an average of 35 % of its strength capacities compared to 26 % loss for the rebars with 30mm cover and 13.8 % for 50 mm cover. Percentage of elongation at failure is 64 % (maximum) for unprotected rebars.
- The yield/ultimate strength of rebars embedded in all mortars increases and percentage elongation decreases when exposed to 700 °C and 900 °C after water quenching. The maximum strength gain at 900 °C is around 26 % and percentage elongation is reduced by 38 % for protected steel bars.
- It is observed that both 30 and 50 mm mortar covers protect the rebars up to 500 °C only; these covers are insufficient when the structure is exposed beyond this temperature for the duration of three hours.
- No spalling is observed up to 500 °C for all specimens; beyond this temperature, thermal stress induced random spalling of mortar cover.
- Above 500 °C, the grey colour of mortar specimens fades away and turns into whitish grey at 900 °C.
- As far as the effect of cover thickness on the mechanical properties is concerned, all mortars behave in a similar fashion.

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