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Research Article

Investigation of mechanical properties of steel reinforcements in reinforced concrete structures as a result of exposure to fire

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ABSTRACT

In this study, it is aimed to investigate the properties of the most commonly used metal and alloy steel materials, which are used in our country and in the world as engineering materials, under the influence of fire of the rebar in the concrete. Inspection standard TS 708:2010 S420 quality 8 mm diameter ribbed construction iron bars for 90 minutes in resistant furnace, atmospheric environment at 600 °C, 800 °C and 1000 °C concrete inside and outside the concrete at the specified temperature fire simulation, the process was allowed to cool in air. With the protective environment created by reinforced concrete, the temperature directly affecting steel bars located outside the concrete under the same conditions, The variable properties of the sample, which are inside the concrete and outside the concrete, were evaluated comparatively. Surface images of the specimens prepared in metallography were taken at different magnifications. The tensile strength of rebar bars did not change significantly according to the environment, but the samples in the concrete showed a more ductile tendency than the samples outside the concrete. The hardness values of the steel bars in the concrete and the steel bars other than the concrete decreased as the temperature increased and this decrease was higher in the samples in the concrete.

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1. Introduction

It is known that iron and its alloys take the first place among the materials used in the field of engineering. Iron alloy steels constitute a large part of these materials.

The physical, chemical and mechanical properties of steels to be used are decided according to the working conditions. While commonly formed structures are selected according to these characteristics, exposure to high temperatures is generally ignored (Uysal 2004; Buzkıran et al. 2016). Mechanical properties of steel at high temperature, such as yield limit, ultimate strength, hardness, modulus of elasticity and thermal expansion coefficient, are the basic mechanical properties that determine the high temperature performance of steels (Ketabdari et al. 2019; Demirel and Özkan 2003). Fire is a serious threat to all building elements and causes loss of life and property. In this context, although steel structures or steel-containing structures show superior properties at room temperature, they are materials that show a significant decrease in their strength at high temperatures due to their metallurgical structures. (Köksal et al. 2004; Kodur and Aziz 2015; Cirpici et al. 2022). While steel structural elements have high strength and rigidity under normal conditions, these properties deteriorate rapidly at relatively high temperatures of 600 °C and above, and fire seriously reduces the load bearing capacity of the structure Yazici et al. (2022). Steel structures should not only have the capacity to carry the design loads at room temperature, but also maintain their strength in the face of difficult events such as fire in structural design. For this reason, fire resistant designs of these structures should be made so that the structures can maintain sufficient strength at high temperatures within the fire resistance period (Ergün et al. 2010). A large part of the building stock consists of re-

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inforced concrete and steel carrier systems added as carriers into the reinforced concrete structure. Because it is a semi-insulating material due to its structure and is more resistant to fire than steel, the concrete covering the steel creates thermal insulation for the steel (Buzkıran and Erten 2016).

Scientific studies are continuing on environmental coating with concrete and thermal swelling coating applications in order to use it as a thermal barrier against fire on structural elements and materials (Zhao et al. 1999; Ergün et al. 2010; Atashafrazeh et al. 2022). Steel and concrete are in the group of non-combustible materials in terms of flammability. Since they are non-combustible, there is no material loss in fire damage, but great decreases are observed in hardness values, yield limit and tensile strength in all post-fire steels (Tama 2012; Kodur et al. 2015). However, with the diffusion of nitrogen atoms in the microstructure at around 200 °C to the grain boundaries, a slight increase in the tensile strength and hardness of the steels is observed. However, when 300 °C is exceeded, the hardness and strength values begin to decrease. When the temperature rises above the critical threshold of 600 °C, the tensile strength falls below the safe mechanical values (Tama 2012; İplikçi 2006; Aliş et al. 2022).

In this study, the grain structures, tensile strength and hardness values of ribbed construction steels inside and outside the concrete were comparatively examined under the easily accessible temperatures of 600 °C, 800 °C and 1000 °C during fire. In addition, surface images were taken with a scanning electron microscope and their chemical compositions were examined.

2. Material and Method

Steel, which is the most widely used engineering material among metals, has some superior properties that make it advantageous compared to other building materials and highlight its use. Some of these are properties such as high strength and high modulus of elasticity of steels (Tama and Kaftan 2007).

Basically, fire consists of 5 phases: ignition, development, growth, full growth and extinction (İplikçi 2006; Korol et al. 2015). In a combustion event, the temperature relationship according to the fire stages is given in Fig. 1 (Yazıcı and Koşatepe 2020).

The variation in the temperature of protected and unprotected structural steels during fire is given in Fig. 2 depending on the time.

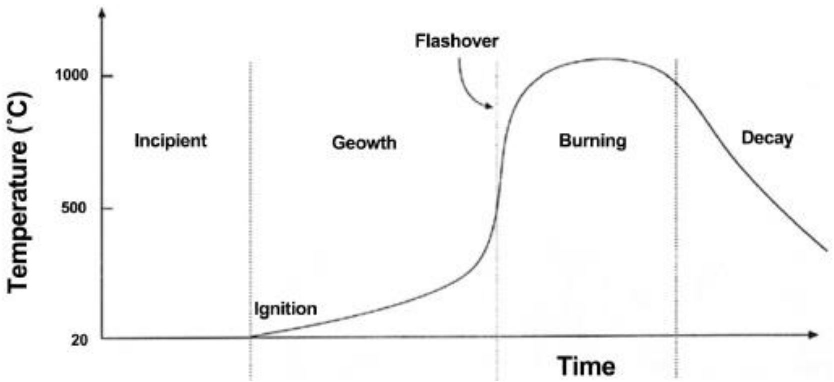

Fig. 1. Classic fire development curve (Polzin 2019).

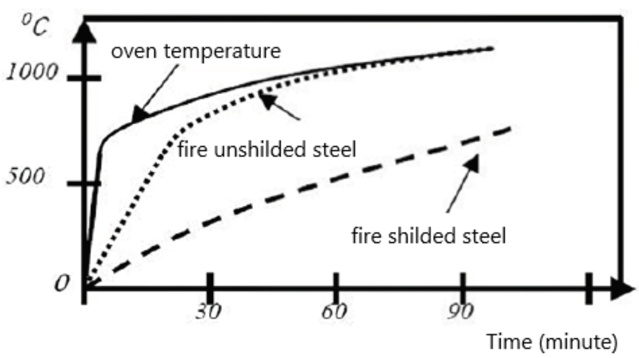

Fig. 2. Time-temperature relationship in structural steels (Lawson 2001).

In this study, TS 708:2010 standards and 8 mm diameter ribbed construction steel were placed in the concrete by leaving a 3 cm spacer. Then, the samples were kept at 600 °C and 1000 °C temperatures for 90 minutes and then allowed to cool. The temperature regulated furnace used to create an environment similar to the fire environment is given in Fig. 3. The samples were left to cool in the air after the fire as shown in Fig. 4.

Considering the fire conditions, 15 cm long and 8 mm diameter ribbed construction steel was embedded in the cement mixture (called C30) used in the structures. Then, 7 days were waited for the cement to cure. Concrete blocks containing steel in the form of molds were kept in the furnace for 90 minutes, being exposed to temperatures of 600 °C, 800 °C and 1000 °C separately. It was then removed from the furnace and left to cool in air for 24 hours. In this study, the samples inside the concrete will be called as "Intra-Concrete" (I.C.), and the samples outside the concrete will be called as "Non-Concrete" (N.C.).

I.C. and N.C. samples exposed to temperatures were classified for metallographic preparation. In order to obtain the surface images and measure the hardness values, it was cut into certain sizes and placed in the bakelite container. Then, it was sanded according to the appropriate abrasive sizes (240-2000 mesh) and polishing (crystal liquid containing 1 μm particles) processes were performed.

Fig. 3. Ash furnace providing desired temperatures.

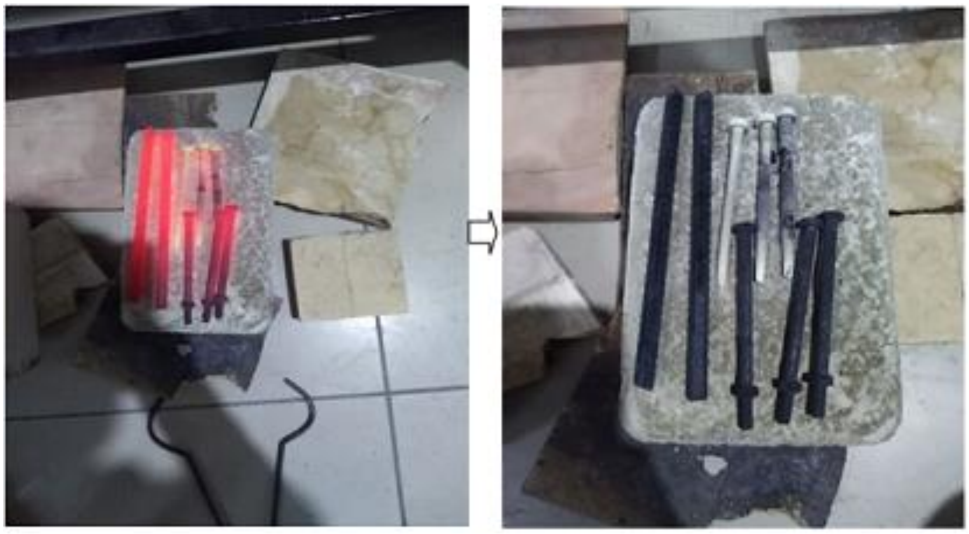

Fig. 4. Samples inside and outside the concrete that were left to cool in air.

Using a Nikon Eclipse LV150 metal microscope, surface images of samples subjected to sanding and polishing were obtained at magnifications of 50X, 100X and 200X. Then, the hardness values of the samples were measured under a load of 200 g using the Wolpert Wilson Instruments Vickers hardness tester. Using the SHIMADZU brand tensile device, the tensile strengths of the samples prepared according to ASTM E8:2016 standards were determined at a loading speed of 5 mm/min. Finally, using the Zeiss Sigma 300 SEM device, the surface topography of the samples was taken and the surface composition was examined with the EDAX software. The obtained results were examined comparatively in the form of in-concrete and out-concrete samples.

3. Experimental Results

Using a metal microscope, the surface images of the cross-sections of the concrete and non-concrete samples tested were obtained at the mentioned magnification ratios and are given in Figure 5 and Figure 6. Depending on the effect of temperature and cooling rate, it is clearly seen that an integrated structure is formed on the surfaces of both non-concrete (N.C.) and intra-concrete (I.C.) samples at various magnifications.

Considering the images taken from the sample at room temperature given in Fig. 5, it is seen that the porous structure seen on the surface decreases as the temperature increases at all magnification ratios in nonconc-rete samples. However, as seen in Fig. 6, the hollow structure seen on the surface of the steel sample at room temperature in the concrete samples decreases up to 800 °C, but after 800 °C is exceeded, it is observed that the hollow structure is more than the sample at room temperature.

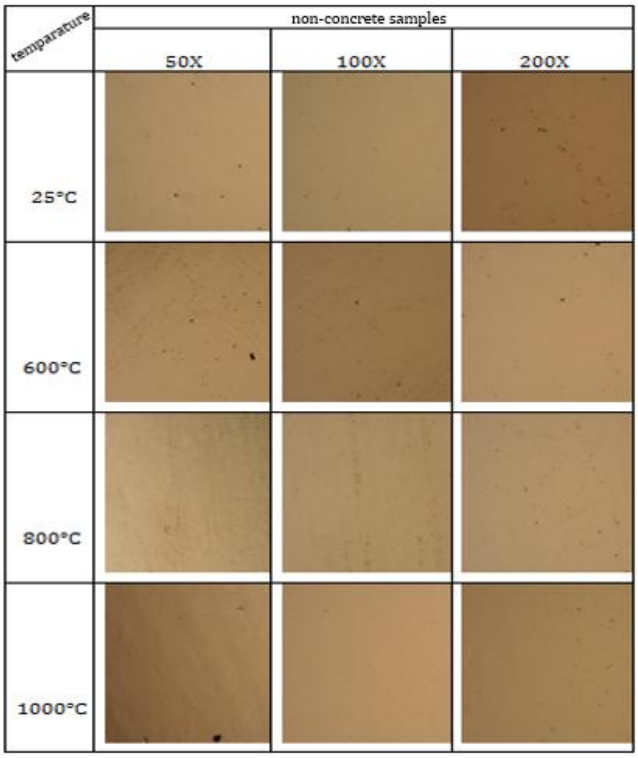

Fig. 5. Surface images of non-concrete samples taken under the metal microscope at the specified magnifications.

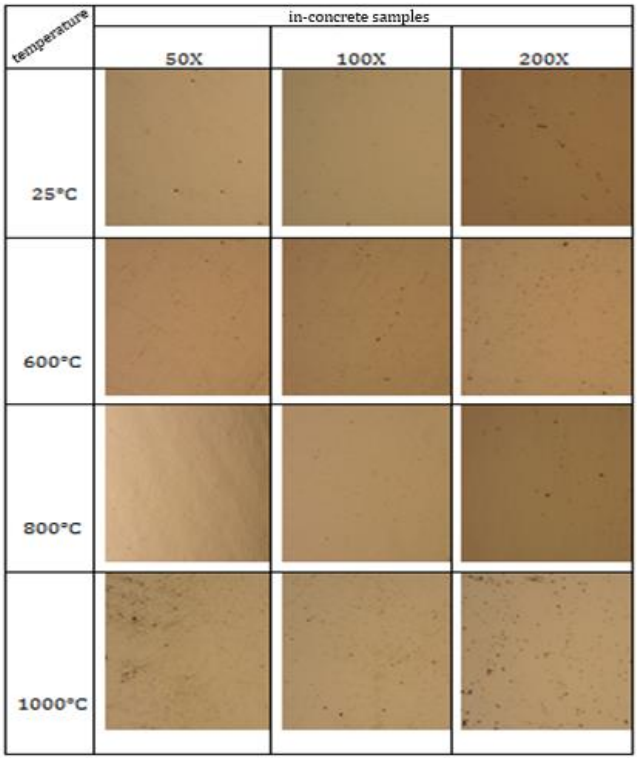

Fig. 6. Surface images of the samples in the concrete taken at the specified magnifications under the metal microscope.

Using a metal microscope, surface images of the samples inside and outside the concrete in case of fire were obtained. In addition, SEM images obtained at 100 µm size are given in Figs. 7 and 8. In the structures of the samples outside the concrete, it is seen that the number of voids seen on the surface decreases as the temperature increases and turns into a more integrated structure. In the samples in the concrete, it was observed that the voids decreased up to 800 °C, but it was determined that the voids increased again after 800 °C.

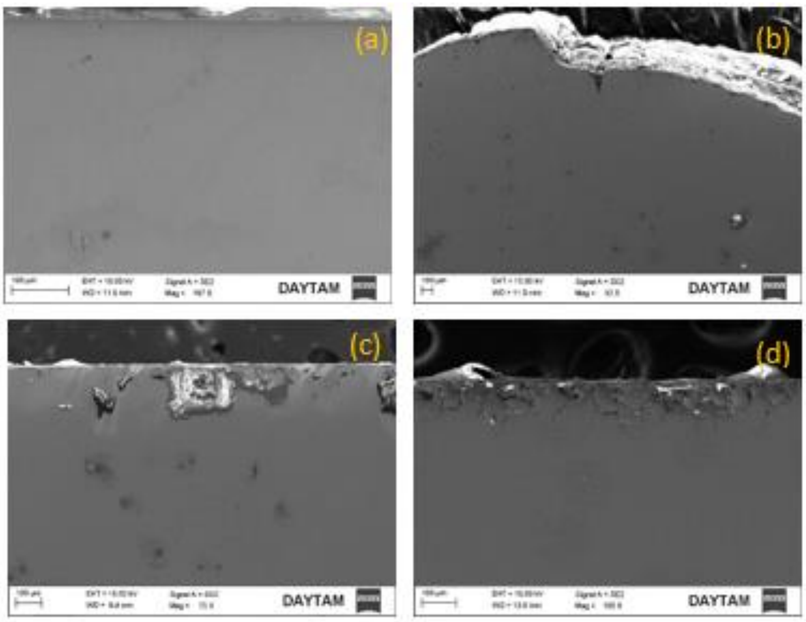

Fig. 7. SEM images of non-concrete samples: (a) at 25 °C; (b) at 600 °C; (c) at 800 °C; (d) at 1000 °C.

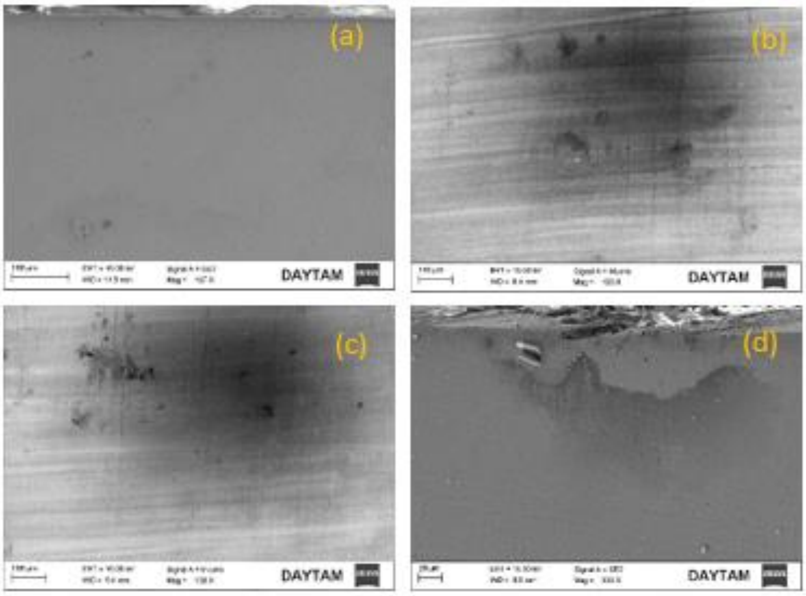

Fig. 8. SEM images of samples in concrete: (a) at 25 °C; (b) at 600 °C; (c) at 800 °C; (d) at 1000 °C.

Contrary to the heat treatments applied to steels, it is known that as a result of uncontrolled heating and cooling, the steel, both inside and outside the structure, loses most of its strength due to the high temperature.

As can be seen in Fig. 9, the hardness of steels decreases as the temperature increases and the cooling rate decreases. It has been determined that the decrease in the hardness values of the steels outside the concrete is higher than the decrease in the hardness values of the steels inside the concrete.

In Figs. 10 and 11, the samples subjected to the tensile test are handled separately as in-concrete and non-concrete. It is observed that the tensile strengths of both in-concrete and non-concrete samples do not change significantly up to 600 °C. However, at 800 °C and 1000 °C, a very significant decrease in tensile strength is observed for both in-concrete and non-concrete samples. Similarly, while there is no significant change in the ductility of the samples up to 600 °C, it is seen that the ductility values increase as the temperature increases. In the strength values parallel to the hardness properties, both the tensile strength of the in-concrete samples and the tensile strength of the non-concrete samples decreased. It was determined that the strength of the in-concrete samples decreased more than the strength of the non-concrete samples. Contrary to the hardness and strength values, the ductility values increased as the temperature increased.

As seen in Fig. 12, the steel sample outside the concrete melted locally at 600 °C. As given in Table 1, it has been determined that the oxygen rate seen on the surface is quite high. However, as can be seen in Fig. 13, it is seen that instead of regional melting, cavities are formed in the sample in the concrete. In addition, as seen in Table 2, it was determined that the oxygen ratio was low. Significant differences were observed on the surfaces of the in-concrete and non-concrete samples in terms of compositions.

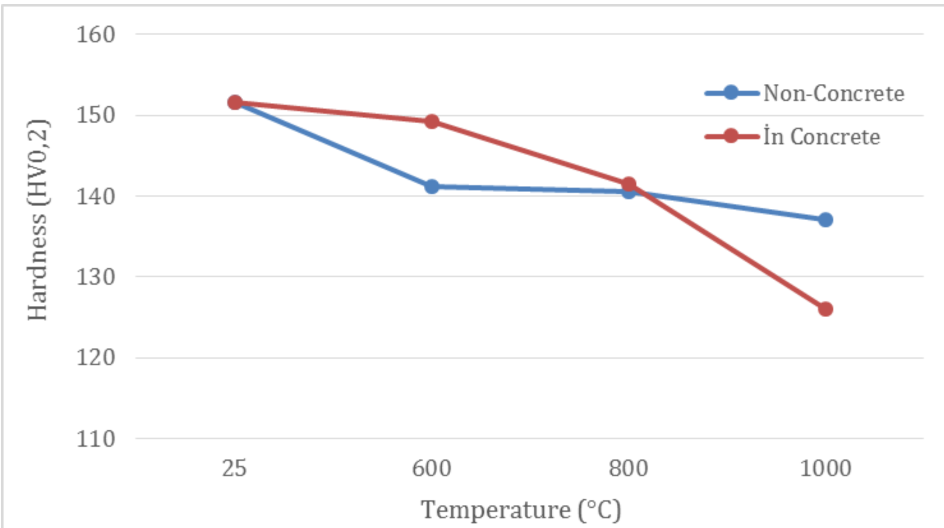

Fig. 9. Hardness values of samples inside and outside concrete.

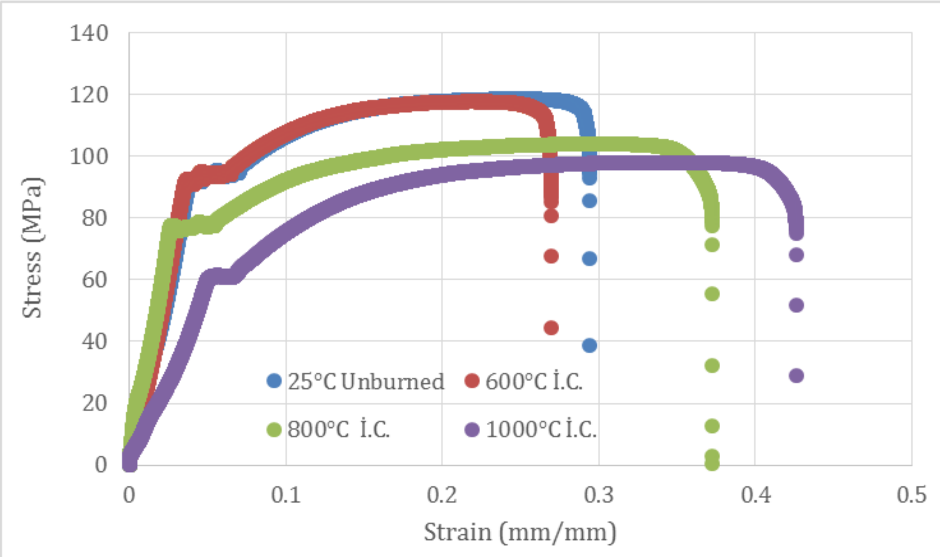

Fig. 10. Tensile curves of samples in concrete.

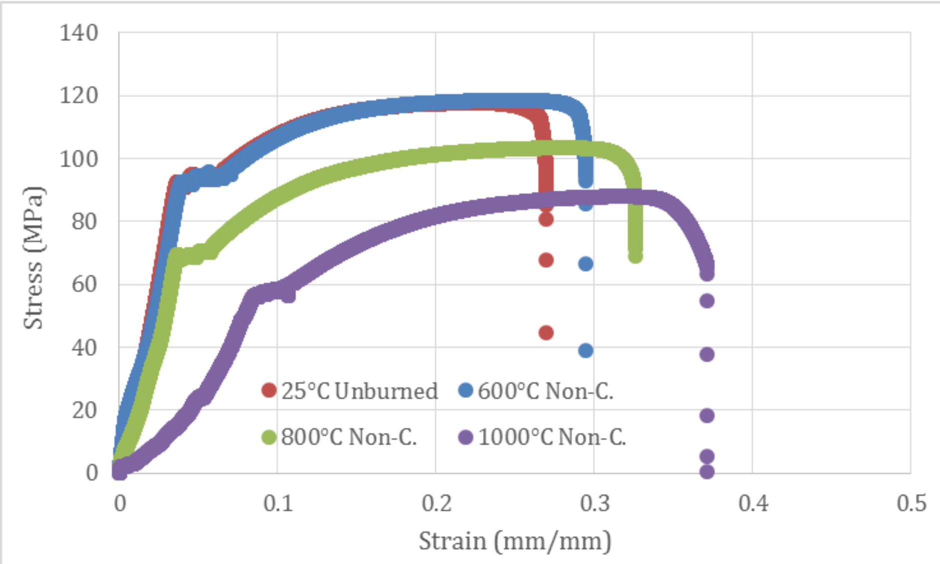

Fig. 11. Tensile curves of non-concrete samples.

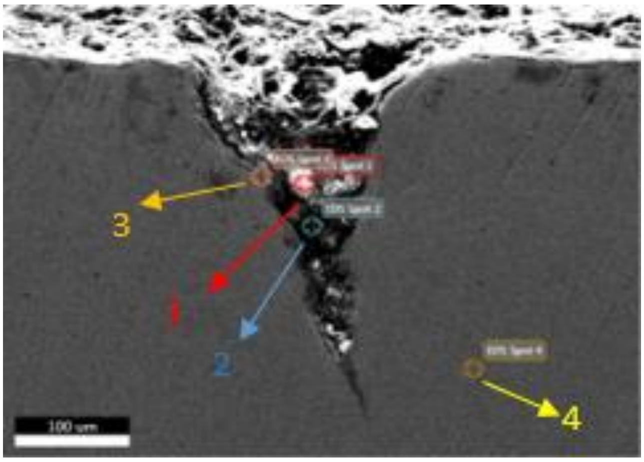

Fig. 12. SEM image of non-concrete steel at 600 °C.

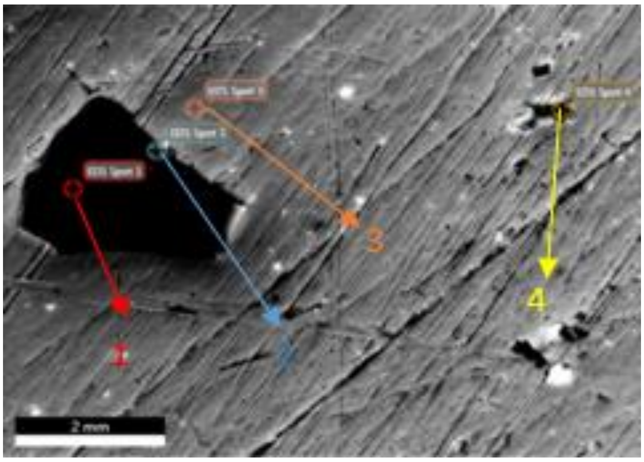

Fig. 13. SEM image of steel in concrete at 600 °C.

Table 1. Compositions of the regions in the SEM image of the sample treated on-concrete at 600 °C.

EDS Spot1		
Element	Weight %	Atomic %
C K	8.0	13.4
O K	48.4	61.1
NaK	2.5	2.2
MgK	0.6	0.5
AlK	1.9	1.4
SiK	9.4	6.8
FeK	1.9	0.7

EDS Spot2		
Element	Weight %	Atomic %
C K	46.8	63.0
O K	22.2	22.4
FeL	0.2	0.0
NaK	3.0	2.1
MgK	0.3	0.2
AlK	1.3	0.8
SiK	4.9	2.8

EDS Spot3		
Element	Weight %	Atomic %
O K	26.4	55.5
SiK	0.2	0.3
CaK	0.2	0.2
FeK	73.2	44.1

EDS Spot4		
Element	Weight %	Atomic %
C K	0.5	2.2
O K	2.5	8.2
SiK	0.2	0.3
FeK	96.8	89.3

Table 2. Compositions of the regions in the SEM image of the sample treated in concrete at 600 °C.

EDS Spot1		
Element	Weight %	Atomic %
C K	10.5	29.7
O K	6.0	12.9
AlK	0.2	0.3
SiK	10.3	12.5
FeK	73.0	44.6

EDS Spot2		
Element	Weight %	Atomic %
C K	32.8	63.8
O K	5.0	7.2
AlK	0.0	0.0
SiK	7.1	5.9
FeK	55.1	23.0

EDS Spot3		
Element	Weight %	Atomic %
O K	1.6	5.3
SiK	0.2	0.3
FeK	98.2	94.3

EDS Spot4		
Element	Weight %	Atomic %
C K	10.0	31.8
O K	3.7	8.8
CaK	0.9	0.9
FeK	85.4	58.4

In Fig. 14, it was seen that local melting and agglomeration were observed in the steel samples treated at 1000 °C other than concrete. In the composition samples taken from these regions, it was determined that the carbon atoms were gathered together as given in Table 3. It has been observed that both carbon and oxygen ratios decrease significantly towards the inside of the steel, where the oxygen ratio is high on the surface.

In Fig. 15, local melting and agglomeration were not observed in the sample placed in the concrete at 1000 °C. In Table 4, the element ratios in the inner sections of the steel are given. In this table, it is seen that the oxygen rate is very low.

The cavities formed in the steel exposed to the heat in the concrete are given in Fig. 16. Micro cracks and structural defects occurred in the cavity.

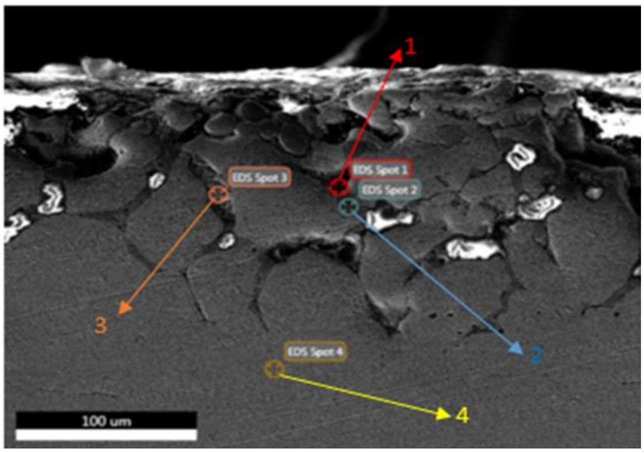

Fig. 14. SEM image of steel non-concrete at 1000 °C.

Table 3. Compositions of the regions in the SEM image of the sample treated non-concrete at 1000 °C.

EDS Spot1		
Element	Weight %	Atomic %
C K	10.6	26.2
O K	17.4	32.4
AlK	2.2	2.5
SiK	1.2	1.2
S K	0.7	0.6
CaK	3.6	2.7
MnK	7.4	4.0
FeK	56.8	30.3

EDS Spot2		
Element	Weight %	Atomic %
O K	29.9	59.7
CaK	0.3	0.2
MnK	0.6	0.3
FeK	69.3	39.7

EDS Spot3		
Element	Weight %	Atomic %
O K	17.9	41.3
MnL	0.7	0.5
SiK	0.1	0.1
S K	9.4	10.7
FeK	71.9	47.4

EDS Spot4		
Element	Weight %	Atomic %
C K	0.7	2.9
F K	4.2	11.1
SiK	0.3	0.6
MnK	0.5	0.5
FeK	94.3	84.9

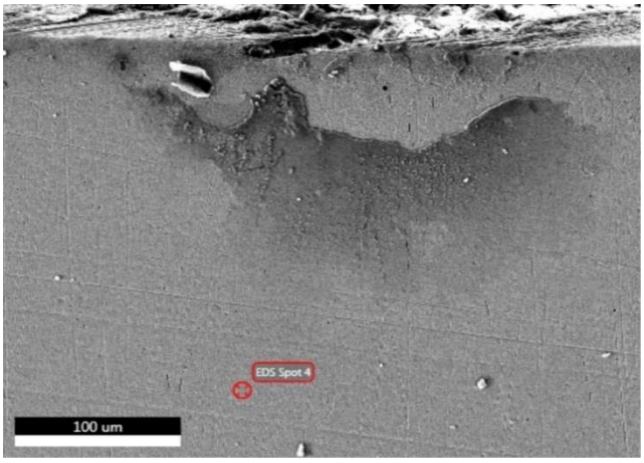

Fig. 15. SEM image of the sample treated in concrete at 1000 °C.

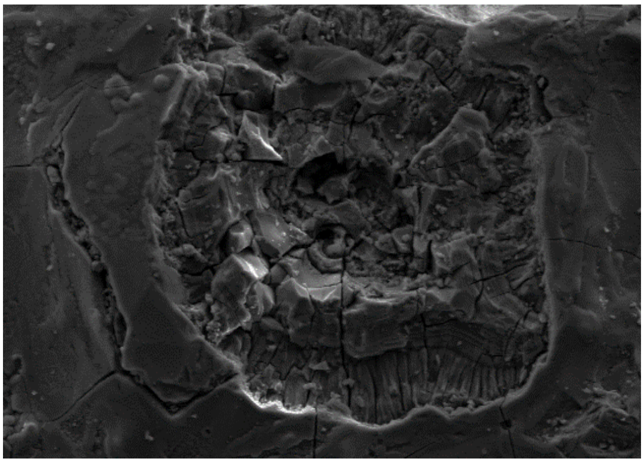

Fig. 16. SEM image of the cavity formed on the surface of the steel treated in concrete at 1000 °C.

Table 4. Composition of the region in the SEM image of the sample treated in concrete at 1000 °C.

EDS Spot4		
Element	Weight %	Atomic %
C K	0.0	0.1
F K	1.2	3.9
MnK	0.3	0.3
FeK	98.5	95.7

4. Conclusions

The following results were obtained in this research, in which the situations of the presence of ribbed construction steel exposed to fire in concrete (I.C.) and outside of concrete (N.C.) were studied comparatively. Microstructural, physical and chemical properties of the ribbed construction steels inside and outside the concrete are determined by the effect of temperature in the event of fire.

The steel embedded in the concrete heats up together with the concrete during the fire. The samples inside the concrete heat up and cool down more slowly than the samples outside the concrete. In this case, it was determined that the number of voids in the samples inside the concrete was higher than the samples outside the concrete. Similar to the studies in the literature, in this study, it is seen that the grains of the steels inside the concrete are larger than the grains of the steels outside the concrete, depending on the effect of temperature and the cooling rate. The high number of coarse grains reduces the number of grain boundaries in the structure. With the decrease in the number of grain boundaries in the material, the strength and hardness values of the material decrease. However, due to the slow cooling rate, it is seen that this decrease is more in the steels in the concrete. Grain growth, which caused a decrease in hardness and strength, also caused an increase in ductility, as expected.

In line with the information obtained from previous studies, it can be deduced that the reason for the high rate of oxygen in the composition samples taken from the areas close to the surface of the steels is that the temperature increase in the material accelerated the oxidation. In the steels in the concrete, the bond of the steel with the oxygen is relatively cut due to the protective atmosphere created by the concrete. Therefore, it is determined that the amount of oxygen on the surface of the steels in the concrete is quite low. In addition to the heat treatments applied to the steels, the pits formed on the surface of the steel material and in the steel material after uncontrolled heating and cooling reduce the strength and hardness of the material. It is very clear that the concrete and steel to be used in construction works should be designed by taking into account disasters such as fire. If the continuity of the structure is to be ensured after disasters, it is extremely important to evaluate it by taking these results into account.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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