A Review on Mechanical and Microstructure Properties of Reinforced Concrete Exposed to High Temperatures

Sharan Kumar Goudar, Santhosh Kumar Gedela, and B. B. Das

Abstract This paper presents the recent research progress on the response of concrete exposed to fire or high temperatures. The main highlight of this review paper is a compilation of previously reported data regarding the variations in mechanical properties and microstructure properties of concrete when exposed to high temperatures. The concrete structures get deteriorated at the macro- and microscopic levels due to high-temperature exposure. The macro-level damages can be measured with degradation in mechanical properties such as the reduction in compressive strength, weight loss, changes in elastic properties, reduction of bond strength in reinforced concrete, etc. The macro-cracks on the surface of concrete causes spalling which can be observed after exposing the concrete samples to more than 300 °C. The compressive strength of the concrete reduces slightly till 400 °C, and when the temperature increased to 600 °C, there was an exponential reduction in the compressive strength of concrete. Another important parameter is bond strength degradation, which plays a crucial role in durability issues. To understand the deterioration phenomenon and changes in mechanical properties, the changes at the level of the microstructure of concrete need to be understood. Dehydration of products causes deterioration of mechanical properties and weight loss of concrete when exposed to high temperatures. At different temperatures, the microstructure changes and the response of hydration products such as calcium hydroxide (CH), CSH gel, unhydrated cement and capillary water reported by previous researchers are compiled and discussed.

Keywords Microstructure · High temperature · Spalling · Dehydration · Bond strength · Compressive strength

S. K. Goudar (✉) · S. K. Gedela · B. B. Das
Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, India
e-mail: sgcr17@gmail.com

S. K. Gedela
e-mail: santu11112@gmail.com

B. B. Das
e-mail: bibhutibhusan@gmail.com

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1 Introduction

Fire, an accidental damage, is a dangerous threat to reinforced concrete structures. It is important to understand the response of reinforced concrete structures when exposed to fire or high temperature. The low thermal conductivity of concrete makes it one of the suitable materials to resist fire or high temperature [1]. However, high temperatures do affect the concrete structures but the response is better compared to other materials [2, 3]. When the concrete structures are exposed to fire or high temperature, there will be reduction in the mechanical properties and that affects the durability. When concrete are subjected to heat, due to non-uniformity of the cement and aggregate elements, changes in mechanical and microstructure properties of concrete are common. Both aggregate and cement elements react to heating in different ways. After cooling down of concrete, some of the reactions are reversible, while others are irreversible which causes a reduction in the strength of concrete [2].

When concrete are exposed to high temperature, until 400 °C, changes in compressive strength of concrete are minimal. During 400–800 °C exposure, the compressive strength of concrete decreases exponentially. The fibers aid to the reduction in compressive strength when exposed to high temperatures. The strength of the concrete also influences the rate of reduction of compressive strength, high strength (HSC) performs better compared to normal strength concrete [4]. There are numerous literatures available on compressive strength reduction of concrete due to the fire exposure. However, the degradation of bond strength due to fire exposure is limited. Few researchers studied only the bond strength degradation by pullout test, but proper microstructure justification for a reduction in bond strength was missing [5–7]. The need of the hour is a systematic study and proper explanation of microstructure changes occurring at the steel–concrete interface and also in bulk concrete.

The pore solution in capillary pores evaporates when the concrete structures are exposed to 100–140 °C and that creates a build-up pressure inside the concrete. This pore pressure is responsible for causing micro-cracks and spalling of concrete [8]. Spalling is a phenomenon where the cover of the reinforced concrete member gets separated from the original structure. The process of cracking is believed to be the same as the spalling phenomenon. Dehydration of the concrete causes the formation of fissures in concrete and causes further cracks [5, 8]. Calcium hydroxide (CH) decomposes at a temperature of 450 °C and converts to calcium oxide (CaO). When calcium oxide comes in contact with moisture after the fire exposure, it expands and causes micro-cracks which ultimately leads to severe cracking and spalling of concrete. The addition of mineral admixtures reduced the formation of CH and ultimately reduces the formation of CaO. When OPC and mineral admixed concretes were exposed to 600 °C temperature, visible cracks were noticed on the surface of OPC concrete, whereas the mineral admixed concrete showed very few micro-cracks on the surface [6, 7, 9, 10]. The mineral admixtures role can be explained in two ways. The first one being, reduction of CH which is consumed during pozzolanic reaction and second is the reduction of capillary pores and an overall improvement in the microstructure of concrete [11]. When concrete exposed to a high temperature of

750 °C, decarbonation occurs in concrete. The calcium carbonate ($CaCO_3$) at 750 °C converts into CaO and CO_2, this process is being termed as decarbonation. Due to the dehydration and decarbonation, CaO content will increase in bulk concrete, which finally expands when comes in contact with moisture and causes severe cracking [12]. The hydrates including CSH and CH will be converted to crystalline-like phase at 1000 °C of fire exposure and the pore system seriously expands which causes spalling of concrete [12]. The effect of high temperature on concretes mechanical and durability properties of concrete are discussed in this review paper.

2 Mechanical Properties of Different Types of Concrete Subject to Elevated Temperature

The main mechanical properties of the concrete structure are compressive strength and bond strength. For normal strength concrete (NSC), compressive strength starts decreasing from 400 °C. The strength of the concrete also influences the rate of reduction of compressive strength, high strength concrete (HSC) performs better compared to normal strength concrete. The fibers in fiber reinforced concrete (FRC) stops the cracks propagation which results in slightly lesser reduction of compressive strength when exposed to high temperatures. The results of different researchers were compiled and a plot of reduction in compressive strength versus exposure temperature was plotted in Fig. 1. The high-temperature exposure reduces the mechanical

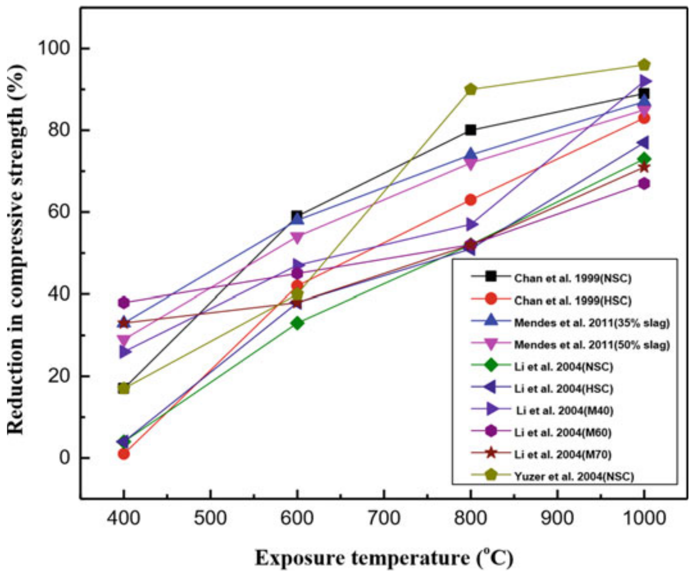

Fig. 1 Effect of high temperature on compressive strength of concrete

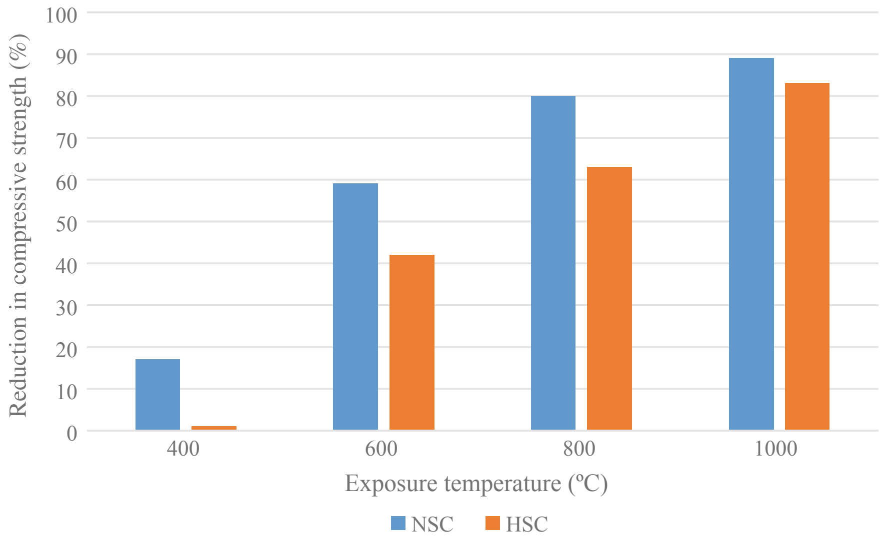

Fig. 2 Reduction in compressive strength of NSC and HSC at different temperatures

properties, reduction in compressive strength increases when exposure temperature increases. Up to 50% reduction in compressive strength was noticed during 400–600 °C exposure. As the exposure temperature increases beyond 600 °C, a severe reduction in compressive strength was observed. The pore solution in capillary pores evaporates and that creates a build-up pressure inside the concrete. This pore pressure is responsible for causing micro-cracks in the concrete structure. These micro-cracks will degrade the compressive strength. It can also be observed from Fig. 1 that HSC and FRC perform better compared to NSC.

Figure 2 shows the comparison of compressive strength reduction of HSC and normal strength concrete (NSC). Marginal strength of concrete was lost till 400 °C, up to 10% for HSC and 15% for NSC. The significant loss in compressive strength was lost in between 400 and 800 °C [1–4, 9, 11]. Some of the researchers also mentioned that the pore density in HSC was less compared to NSC, due to which the pore pressure in HSC concrete will be comparatively more. Because of the high pore pressure, slightly higher reduction of compressive strength was noticed in HSC as compared to NSC [9, 10].

The results of different researchers were compiled and a plot of reduction in bond strength versus exposure temperature was plotted in Fig. 3. The same trend of compressive strength can be noticed for bond strength of reinforced concrete also. As the exposure temperature increases, the percentage reduction of bond strength also increases [13–18]. The presence of calcium hydroxide degrades at a temperature of 450 °C which might cause a reduction in compressive strength. However, a clear explanation for microstructural changes at the steel–concrete interface for causing bond degradation is missing in the literature. The addition of steel fibers in concrete

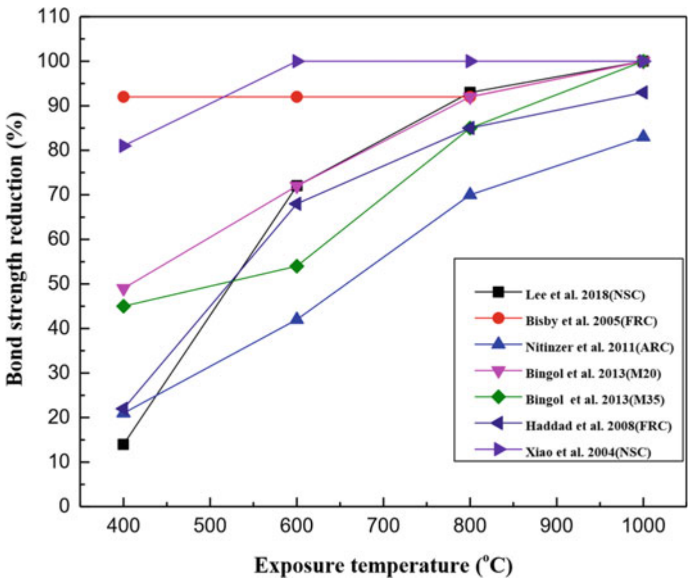

Fig. 3 Effect of high temperature on the bond strength of reinforced concrete

proves to be beneficial in terms of bond strength retention [19, 20]. However, the other fibers such as natural fibers were combustible at low temperatures which exerts expansive pressure which resulted in a slightly higher reduction of bond strength compared to NSC [13, 15]. Overall, the addition of fibers proves beneficial in terms of retaining bond strength as well as compressive strength [13, 16, 17, 20–23]. Figure 4 shows the comparison of reduction of bond strength for NSC and FRC at different

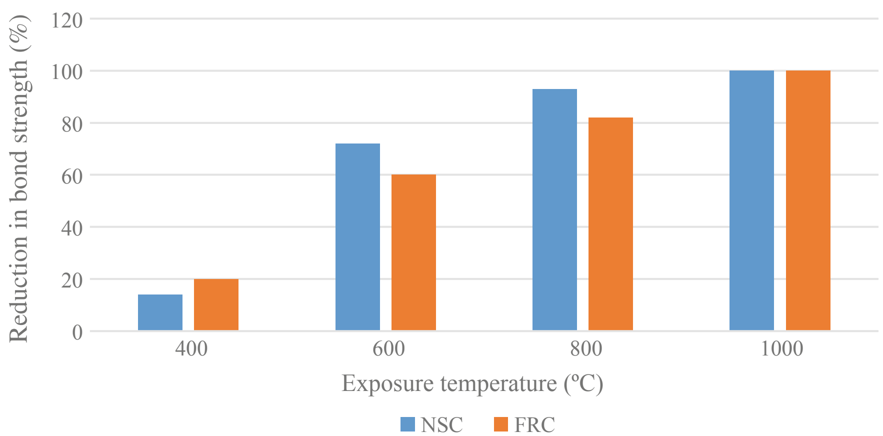

Fig. 4 Reduction in bond strength of NSC and FRC at different exposure temperatures

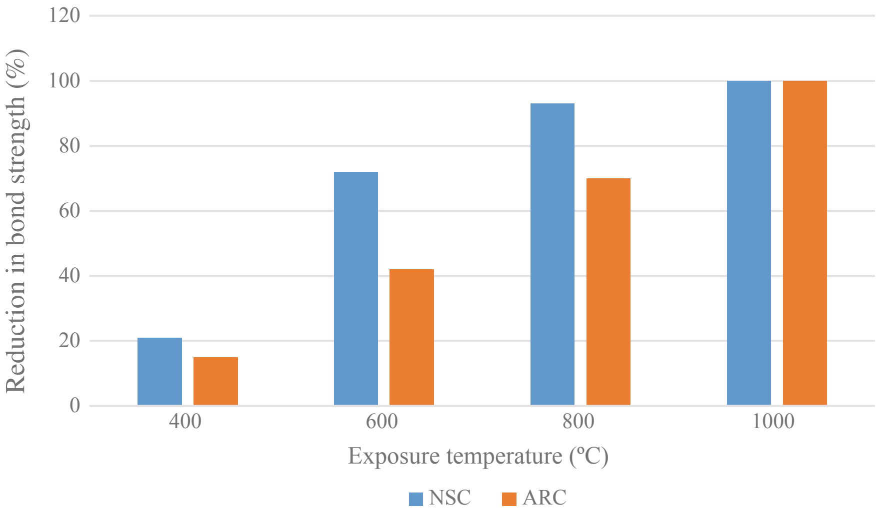

Fig. 5 Reduction in bond strength of NSC and ARC at different temperatures

exposure temperatures. The bond strength of NSC decreased up to 15%, while the bond strength of FRC decreased up to 20% for natural fibers. For the steel fibers, the scenario was quite the opposite. The addition of steel fibers proved to be beneficial in terms of bond strength retention. The spalling effect was reduced due to the addition of steel fibers [5–7].

The aggregate replacement also improved bond strength retention. Netinger et al. [3] reported that the addition of crushed bricks as a replacement of natural aggregates improved the bond strength retention in reinforced concrete. Many researchers [3, 4, 8, 17] reported similar findings and compiled data are shown in Fig. 5.

The addition of mineral admixtures (MA) proved to be beneficial in retaining the compressive strength of concrete when exposed to high temperatures [6, 8, 11, 12, 15, 24]. The mineral admixtures role can be explained in two ways. The first one being, reduction of CH which was consumed during the pozzolanic reaction and the second being reduction of capillary pores and an overall improvement in the microstructure of concrete [11, 19]. The data from several researchers regarding the significance of mineral admixed concrete toward the compressive strength retention are presented in Fig. 6. Mineral admixed concrete performed better when exposed to different temperatures when compared to NSC. It can also be observed that the replacement level of mineral admixtures also plays an important role. The high volume replacement of mineral admixtures had positive effect in terms of compressive strength retention when exposed to high temperatures.

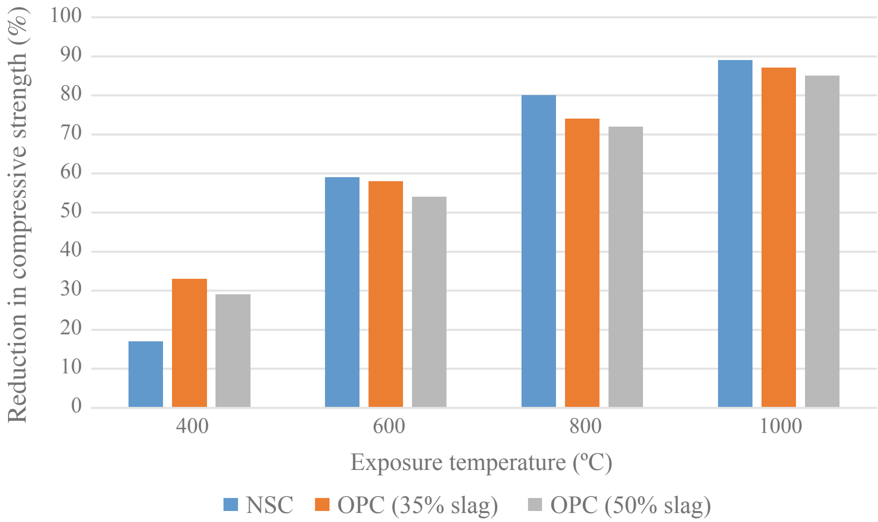

Fig. 6 Reduction in compressive strength of NSC, OPC (35% slag), and OPC (50% slag) at different exposure temperatures

3 Microstructure Properties of the Concrete Subject to Elevated Temperature

The microstructure of the concrete plays a crucial role in determining the mechanical properties. The hydration products undergo physical and chemical changes at high-temperature exposure. The pore solution in capillary pores evaporates when the concrete structures are exposed to 100–140 °C and a slight reduction in weight loss was noticed. The evaporated pore water exerts expansive pressure inside the concrete which leads to the formation of micro-cracks [8]. Calcium hydroxide decomposes at a temperature of 450 °C and converts to calcium oxide this phenomenon is generally known as dehydration. After the fire exposure when calcium oxide encounters moisture, calcium hydroxide is reforming, and the phenomenon is generally known as rehydration [11]. The reaction is shown in Eq. 1. Because of the rehydration, newly formed calcium hydroxide expands in volume which ultimately causes severe cracking. The dehydration of calcium hydroxide can be easily recognized from rapid weight loss and consequently analyzed by thermogravimetric analysis [25–27]. The thermogravimetric analysis provides a comparison of water loss of cement paste at different temperatures. The CSH gel also starts to crystallize slowly at 400 °C, which also aid to the cracking process inside the concrete.

Due to the atmospheric carbon dioxide, the concrete undergoes carbonation process, where calcium hydroxide is being converted into calcium carbonate (as shown in Eq. 2). The calcium carbonate at 750 °C converts into calcium oxide and carbon dioxide, this process is being termed as decarbonation (as shown in Eq. 3). Due to the dehydration and decarbonation, calcium oxide content will increase in bulk concrete, which finally expands when encounters the atmospheric moisture and causes severe cracking and spalling [12]. The spalling process generally starts to occur from 200 to 1000 °C depending upon the strength or grade of concrete [6, 11, 12]. The spalling process was faster in low-grade concretes and the high strength concretes showed comparably more resistance to spalling.

The hydrates including CSH and CH will be converted to crystalline-like phase at 1000 °C of fire exposure and the pore system seriously expands which causes spalling of concrete [12].

$$(OH)_2 \leftrightarrow CaO + H_2O \tag{1}$$

$$(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{2}$$

$$CaCO_3 \rightarrow CaO + CO_2 \tag{3}$$

4 Conclusions

The high-temperature effects on concrete mechanical and durability properties of concrete were discussed and the following conclusions can be drawn.

- High-temperature exposure of concrete structures results in degradation of mechanical properties. Up to 50% reduction in compressive strength was observed during 400–600 °C exposure and at 800 °C, only 10% of the original compressive strength was retained.
- The high strength concrete and fiber-reinforced concrete performed better compared to normal strength concrete when exposed to high temperatures.
- The bond strength between reinforcing steel and concrete is a sensitive to high temperatures. Significant reduction in bond strength was observed during 400–600 °C exposure and at 800 °C, only 5% of the original bond strength was retained.
- The bond degradation also follows the same trend of compressive strength, as the exposure temperature increases the percentage reduction in strength increases.
- A clear explanation for microstructural changes at the steel–concrete interface for causing the bond degradation is missing in the literature.
- Calcium hydroxide decomposes at a temperature of 450 °C and converts to calcium oxide, which in contact with moisture expands and produces micro-cracks and ultimately spalling of concrete occurs.
- When concrete exposed to a high temperature of 750 °C, decarbonation occurs in concrete. Due to the dehydration and decarbonation, calcium oxide content will increase in bulk concrete, which finally expands when encounters moisture and causes severe cracking and spalling.

- The hydrates including CSH and calcium hydroxide will be converted to crystalline-like phase at 1000 °C of fire exposure and the pore system seriously expands which causes spalling of concrete.

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