The effect of concrete cover thickness subjected to elevated temperatures

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Abstract. Concrete cover plays an important role in protecting the reinforcement from harmful environments and high temperatures. In this study, the effects of the concrete cover containing garnet and rebar prepared with cover thicknesses of 20 and 30 mm and subjected to temperatures of 20ºC, 200ºC, 400ºC, 600ºC and 800ºC for 1-hour duration were determined by conducting ultrasonic-pulse velocity and tensile tests. The results of the study show that concrete specimens with cover 30 mm protect steel completely before they disintegrate, almost up to 300ºC and by replacing sand with 40% of garnet, gives significantly better fire resistance than normal concrete.

1. Introduction
The concrete cover is needed to prevent corrosion and to protect the reinforcement in the event of a fire. In addition, the concrete cover also provides sufficient concrete surrounding the reinforcing bar to develop a good bond between the two materials [16]. Compared to other construction materials, concrete is durable against elevated temperatures [3,13] and thus, can be an effective protection against other materials such as reinforcement steel [4,21]. Nevertheless, concrete is a composite material and its dependence on moisture and porosity makes it a complex material when exposed to fire, compared to other construction materials [5].

Exposure of concrete to elevated temperatures affects its mechanical and physical properties. The behavior of concrete at elevated temperature is strongly affected by the type of aggregate. Quartz in siliceous aggregates changes at 570ºC, with a volume expansion and consequent damage, while in limestone aggregate concrete, CaCO₃ turns into CaO at 800–900ºC, and expands with temperature [2].
Shrinkage may also start due to the decomposition of CaCO$_3$ into CO$_2$ and CaO with volume changes, causing destruction [21]. Kong and Sanjayan studied the effect of elevated temperature on geopolymer paste, mortar and concrete [14]. It was shown the geopolymer concrete behavior under elevated temperatures was influenced by the size of the aggregates.

In a previous study regarding garnet used in concrete, Muhammad studied the effect of replacement of cement by 10%, 20%, 30% and 40% of garnet [17]. In his study, he found that 10% of garnet gives better results than normal concrete. Habeeb et al. studied the mechanical properties of self-compacting geopolymer concrete containing garnet as a fine aggregate [9]. They found that replacing 25% of garnet as fine aggregate in the geopolymer could be considered as optimum for mechanical properties and flowability. Garnet has been gradually replacing silica sand and mineral slag as a material in blasting since its chemical properties are relatively similar to silica sand and it does not have issues like the health risks in the inhalation of airborne crystalline silica dust [11]. Moreover, garnet sand is well suited for water filtration and treatment because it is relatively heavy and chemically stable, while garnet powders generally are used for glass/ceramic polishes, anti-slip paints, and anti-skid surfaces [18]. Large amounts of garnet waste generated from the work sandblasting ships in the southern part of Malaysia attract opportunities to use this garnet waste in the concrete mix.

The solid surface of high strength of concrete could spall and elements in the concrete could be distorted and displaced under certain conditions, due to the build-up of steam pressure at elevated temperatures [5]. Steel is exposed to hot gas at the beginning of a fire after the destruction of concrete [15, 21]. Thus, the exposure of the steel to the elevated temperature reduces the yield strength, ultimate strength, modulus of elasticity and ductility of reinforcing steel bars [8,13,15,19,20,21]. Previous studies have shown changes in the characteristics of the rebar steel after a fire. In their studies on the physical and mechanical changes of concrete, both Arioz and Hager [2,10] found that at temperatures above 400ºC, the expansion between the aggregates and cement paste, which undergoes shrinkage, prevails and results in the development of cracks.

Based on Eurocode 2, there are minimum requirements for concrete cover with regard to bond, durability, and fire [16]. In terms of fire resistance, the thickness of cover was determined based on the type of beams, side of column exposed, and thickness and type of slab. El-Hawary et al. studied the surface hardness of concrete using a Schmidt hammer after exposing the reinforced concrete beams with a different cover thickness to 650ºC for different time periods [6]. In their study, the use of this cover has significantly affected the strength of concrete and reinforcing steel under elevated temperatures. Ünlüoğlu et al. studied the concrete cover effect on reinforced concrete bars exposed to high temperatures by using steel bars embedded into mortar [7]. In their study, it was observed that 25 mm cover thickness was not sufficient to protect the mechanical properties of the reinforcing steel when the structure is exposed to temperatures over 500ºC.

Even though numerous studies have been conducted regarding concrete exposed to elevated temperature, there is still a gap to be addressed regarding the effectiveness of garnet concrete cover to protect the steel bars against fire. In this experimental study, the changes in the mechanical properties of garnet concrete and the steel reinforcements within the concrete with different thickness covers after being subjected to elevated temperatures were investigated.

2. Experimental
In this experimental study, to determine the optimum garnet percentage as a sand replacement, a compressive strength test was done with normal concrete as the control specimen and concrete containing 20%, 40%, 60%, 80% and 100% of garnet. The samples were tested at 7, 14 and 28 days. The optimum mixes of concrete containing garnet were prepared in the laboratory and rebars within the concrete were prepared in the laboratory with 20 mm and 30 mm thickness of concrete cover. The steel used in the experiment was plain steel with diameter R6 and length of 200 mm.

Formworks were prepared to provide concrete covers of 20 mm and 30 mm in thickness. The R6 diameter steel bars were placed with spacers into the center of the formworks with dimensions 46 x 46 x 240 mm and 66 x 66 x 260 mm. Then the concrete was poured in two steps with a vibration between
them to compact the concrete and to ensure that no voids were left in the concrete. The specimens were demoulded 24 hours after pouring in the concrete. After the demoulding, the specimens were cured for 28 days.

The concrete specimens with different cover thickness were exposed to elevated temperatures at 20°C, 200°C, 400°C, 600°C, and 800°C for 1 hour in an electrical furnace. After the heating, the samples were left to cool for some hours. After the cooling process, the samples were tested using ultrasonic-pulse velocity (UPV) and the reinforcing steel bars were removed from the specimens for the tensile test. Figure 1(a), and (b) shows the location of the rebar and spacer within specimen prepared and Figure 2. shows a schematic of reinforced the concrete specimen.

![Spacers](image1)

**Figure 1.** Covers of (a) 20 and (b) 30 mm with plain steel 6Ø mm were prepared before pouring the concrete

![Schematic drawings](image2)

**Figure 2.** Schematic drawings of reinforced concrete specimens

2.1 Materials of study

2.1.1 Sand
River sand that had 2651.88 kg/m³ unit weight with a 2.66 specific gravity was used for the normal concrete and garnet concrete specimens. The grading of the sand used in normal concrete is shown in Figure 3. Sand passing 4.75 mm in sieve analysis was used in this concrete mix.

2.1.2 Garnet
The X-ray fluorescence test of garnet is shown in Table 1. Garnet of 3635.87 kg/m³ unit weight with a specific gravity of 3.64 was used for the garnet concrete specimens. The grading of the garnet used in garnet concrete is shown in Figure 4. Garnet that passing 2.36 mm in sieve analysis was used in this garnet concrete mix.
Table 1. Chemical composition of garnet

| Chemical composition | Amount in percentage (%) |
|----------------------|--------------------------|
| SiO₂                 | 27.2                     |
| Al₂O₃                | 13.4                     |
| Fe₂O₃                | 25.5                     |
| CaO                  | 4.23                     |
| MgO                  | 5.79                     |
| Na₂O                 | 17.8                     |
| SO₃                  | 0.36                     |

| Chemical composition | Amount in percentage (%) |
|----------------------|--------------------------|
| K₂O                  | 0.04                     |
| TiO₂                 | 2.7                      |
| MnO                  | 0.89                     |
| Co₂O₃                | 0.1                      |
| ZnO                  | 0.56                     |
| ZrO₂                 | 0.51                     |

Figure 3. Grading curve of sand used in the normal concrete mix

Figure 4. Grading curve of garnet used in the garnet concrete mix

2.1.3 Water
The tap water used in this concrete mix followed the requirements of MS528: 1985 or BS3148: 1959, which means it was free from any contaminants and particles.
2.1.4 Cement
Ordinary Portland cement (OPC) was used in this study in both the normal concrete and garnet concrete mix.

2.1.5 Coarse aggregate
In this mix, the coarse aggregates above 10 mm and retained at 5 mm were used, following the BS882 grading limit.

2.2 Mixture proportions
In this experiment, to achieve 60 MPa strength of concrete, a water-cement ratio of 0.33 was used. 0.33% superplasticizer type rheobuild also was added to increase workability to get a slump of 60 to 180 mm. The material mixture proportions of the concrete specimens are given in Table 2.

| Ratio of garnet (%) | By weight (kg) | Cement | Sand | Garnet | Coarse aggregate | Water |
|---------------------|---------------|--------|------|--------|------------------|-------|
| 0                   |               | 757.58 | 709.51| 0      | 832.91           | 250   |
| 20                  |               | 757.58 | 567.61| 141.90 | 832.91           | 250   |
| 40                  |               | 757.58 | 425.71| 283.80 | 832.91           | 250   |
| 60                  |               | 757.58 | 283.80| 425.71 | 832.91           | 250   |
| 80                  |               | 757.58 | 141.90| 567.61 | 832.91           | 250   |
| 100                 |               | 757.58 | 0     | 709.51 | 832.91           | 250   |

3. Test results and evaluation

3.1 Mechanical properties of garnet
Figure 5. shows the compressive strength test for garnet as a sand replacement with amounts of 20%, 40%, 60%, 80% and 100%. It can be seen that when 20% and 40% garnet was added as the sand replacement, the compressive strength gave better results than normal concrete while adding 60% and 80% of garnet the graph gave lower values than normal concrete. For 100% of garnet, the strength was higher than normal concrete for early strength but significantly lower than normal concrete after 28 days. Thus, 40% of garnet was chosen as the optimum amount of sand replacement in the concrete mix.

![Figure 5. The compressive strength for garnet as sand replacement](image)

3.2 Ultrasonic-pulse velocity
The ultrasonic-pulse velocity test was performed for reinforced concrete (normal concrete and garnet concrete) exposed to elevated temperatures 200°C, 400°C, 600°C, and 800°C. It was observed that the
pulse velocity decreases as the exposure temperature increases. The velocities of the concrete were calculated using Equation 1, as shown in Figure 6. and Figure 7.

\[ v = \frac{l}{t} \]

Where:
- \( v \) = velocity
- \( l \) = length
- \( w \) = width
- \( t \) = time taken

**Figure 6.** Ultrasonic-pulse velocities for specimens with cover 20 mm that were exposed to high temperatures.

**Figure 7.** Ultrasonic-pulse velocities for specimens with cover 30 mm that were exposed to high temperatures.

It can be seen in Figures 6 and 7 that the velocity for both specimens, normal and garnet concrete, decreased when exposed to elevated temperature. For a cover of 20 mm, when normal concrete was exposed to temperatures of 200°C and 400°C, the velocity decreased by 10.28% and 16.26%, while for garnet concrete exposed to the same temperatures the velocity decreased by 11.44% and 15.94%. Moreover, the velocity decreased by 37.84% and 41.61% when normal concrete was exposed to 600°C and 800°C, while for garnet concrete when exposed to the same temperature the velocity decreased by 8.76% and 32.45%.

For cover 30 mm normal concrete exposed to temperature 200°C and 400°C the velocity decreased by .56% and 4.82% while for garnet concrete when exposed to the same temperature the velocity decreased by 1.68% and 5.15%. Furthermore, the velocity decreased to 10.87% and 20.83% when
normal concrete was exposed to 600°C and 800°C, while for garnet concrete when exposed to the same temperature the velocity decreased by 2.02% and 23.40%.

3.3. Rebar stress-strain relationship

A tensile test was done to plain reinforcing steel specimens (without cover) at room temperature as a control specimen. The average values for stress-strain relationship for concrete specimens with 20 and 30 mm cover are shown in Figures 8, 9, 10 and 11.

For cover of 20 mm, both concretes have a similar stress-strain pattern up to 400°C. However, when the temperature is raised to 600°C, the stress-strain curve for garnet concrete with 20 mm cover was slightly higher than for normal concrete.

For the cover of 30 mm, the stress-strain curve for garnet concrete was slightly higher than normal concrete. This indicates that, for the cover of both 20 and 30 mm, garnet concrete gives better results than normal concrete. This is because the size distribution of garnet is finer compared to sand. The finer size of garnet fills the empty voids between the course aggregate and cement paste. In addition, the smooth surface of garnet allows good mixing and decreasing interaction between particles.

![Figure 8. Tensile test result for normal concrete with cover 20 mm](image1)

![Figure 9. Tensile test result for garnet concrete with cover 20 mm](image2)
3.4. Ultimate tensile strength

Figure 12. shows the ultimate tensile strength of the normal concrete and garnet concrete with 20 and 30 mm cover, respectively. For normal concrete with cover 20 mm and garnet concrete with cover 20 mm the ultimate tensile strength was reduced to 6.92% and 6.90% when exposed to 200°C, while for normal and garnet concrete with cover 30 mm the values were reduced by 2.43% and 1.40% when exposed to the same temperature.

For a temperature of 800°C, for normal and garnet concrete with cover 20 mm, the values were reduced to 9.97% and 9.45% while for normal and garnet concrete with the cover 30 mm the reductions in value were 9.83% and 8.51%. It can be assumed that concrete specimens with the cover of 30 mm thickness protect reinforcing steel completely, before they disintegrate, almost up to 300°C.
4. Discussion and conclusion
In the experiments, the use of garnet as a sand replacement, with 40% of garnet, gives slightly better fire resistance to normal concrete. This is possibly due to the size distribution of garnet, which is fine compared to sand and the particles of garnet are uniformly graded where sand particles is uniform in shape. Thus, replacing sand with 40% of garnet can fill the empty void between the coarse aggregate. Moreover, the smooth surface of garnet allows good mixing and decreases interaction between particles.

Both covers of 20 and 30 mm can withstand elevated temperatures almost up to 300°C. This is because aggregate materials are thermally stable up to 300°C-350°C [12]. However, when further heating them up to 800°C, it was observed that for covers of 20 mm, the velocities decreased by up to 40% while for cover 30 mm the velocities decreased by up to 20%.

The reinforcing steel reduced in yield strength when exposed to the hot gas, due to the shrinkage of cement paste and expansion of the aggregate during heating, which is mainly due to loss of water. This leads to breaking the bond between the cement matrix and the aggregates [1]. Adding a thicker concrete cover will delay the fire or hot gas in penetrating the concrete specimen.

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