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# Mechanical properties of shielding concrete with magnetite aggregate subjected to high temperature

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**Abstract**

This paper presents an experimental study on the performance of shielding concrete with magnetite aggregate subjected to high temperature. Two concretes with magnetite aggregate and one ordinary concrete with natural aggregate were tested. Mechanical properties were studied at ambient temperature and after thermal exposure. Compressive strength and splitting tensile strength have been tested. For each test, the specimens were heated at a rate of 1°C/min up to different temperatures (300, 450, 600 and 800°C). In order to ensure a uniform temperature throughout the specimen, the temperature was held constant at the target temperature for 1 h before cooling. In addition, the specimen mass was measured before and after heating in order to determine the weight loss of tested samples. Studies have shown that use of magnetite aggregate can diminish the negative impact of elevated temperatures on mechanical properties of concretes.


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*Keywords*: magnetite; elevated temperature; heavyweight concrete; strength

## 1. Introduction

Concrete is one of the most popular and relatively cheap material used for radiation shielding in facilities containing radioactive sources and radiation generating equipment. Compared with other construction materials, concrete has a high shielding capacity against nuclear radiation and good long-term durability – Brandt and

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Niedźwiedzka [3], Fillmore [6] and Kharita et al. [10]. Heavyweight concretes (HWC), are the type of concretes which seem to be the most effective due to their properties and components. Kaplan [9] estimated that use of HWC enable to reduce the thickness of walls even by 40% while compared to ordinary Portland cement (OPC) concretes.

To produce HWC heavy weight aggregate containing high content of metallic phases (important for attenuation of fast neutrons) such as hematite, ilmenite and especially barite or magnetite is required – Oto and Gür [14]. Concretes containing magnetite and barite aggregate exhibit satisfactory shielding properties which is confirmed by Akkurt et al. [1], Akkurt et al. [2], Demir et al. [5], Mahdy and Speare [13], Oto and Gür [14] and are widely applied since 1950's (USA) – Henrie [7].

Factor which undoubtedly affects negatively the long-term durability of concretes is exposition to elevated temperature generated by nuclear facilities. The most affected is the inner face of the shielding concrete which is often exposed to direct heat from the reactor core. Concrete has a relatively low thermal conductivity, which makes it difficult to remove the heat generated in the shield. This results in non-uniform temperature distribution throughout concrete leading to arise of differential thermal stresses. Therefore, temperature changes in concrete cause differential volume changes in the ingredients, and these results in cracking and lower durability. The influence of temperature on processes occurring in concrete is precisely described by Lammond and Pielert [11] and Samarin [16].

Problems with significant decrease of strength can be noticed when samples are exposed to temperature around 350$^{o}$C. In that case concrete can decrease its strength by 40% percent. Studies held by Chan et al. [4] confirms that the most undesired temperature for concrete performance is within the range 400-800$^{o}$C. Concretes subjected to temperature above 800$^{o}$C loses its load capacity regardless of its initial strength. This phenomenon is associated with the processes occurring in cement paste while concrete is exposed to high temperature and its comprehensively described by Lee et al. [12].

Second important aspect, often omitted by researchers involves phase transformations and chemical decomposition of the concrete constituents under high temperatures – Jia et al. [8]. Iron oxides such as magnetite ($Fe_3O_4$), hematite ($Fe_2O_3$) or wustite (FeO). can transform to another phases when they are subjected to high temperature (or pressure) which can lead to undesirable changes of shielding properties of concretes.

There are few studies available related to the topic of barite aggregate concretes while in case of magnetite aggregate studies are limited and further studies need to be taken. The aim of presented study is to determine the mechanical properties of shielding concrete with magnetite aggregate subjected to high temperature.

## 2. Materials and mix proportions

Two types of high-strength shielding concretes containing magnetite aggregate were prepared. Concretes have been produced using Rapid Hardening Portland Cement CEM I 42,5 R and silica fume additive (10 %wt). Binder and water in each composition was constant and water-to-cement ratio (w/c) was set at 0.35. Concrete series designated as M1 contained river sand (fraction 0-2 mm) and magnetite coarse aggregate (from north Sweden) separated into two fractions, 2-8 mm and 8-20 mm. Mixture designated as M2 contained entirely magnetite aggregate in fractions, 0-2 mm, 2-8mm and 8-20mm. The maximum particle size of aggregate was kept constant at 20 mm in all mixtures. The bulk density of used magnetite aggregate was 4.7 kg/m$^3$. Reference series (R) contained river sand fine aggregate 0-2 mm and gravel coarse aggregate separated into two fractions, 2-8 mm and 8-20 mm. Grading curve was designed within the recommended grading limits in accordance with PN-B-06250 standard. To obtain reasonable workability of each concrete mixture (S3 – slump class), modified polycarboxylate ether based superplasticizer was employed as chemical admixture. Proportions of all mixture components were given in Table 1. Mixtures M1 and M2 due to their density value can be classified as a heavyweight concretes (HWC). Based on density values mixtures M1 and M2 can be classified as a heavyweight concretes (HWC).

Table 1. Mixture proportion of concretes, kg/m$^3$.

| Component | Unit weight [ kg/m$^3$] | | |
|---|---|---|---|
| | R | M1 | M2 |
| Cement CEM I 42,5 R | 450 | 450 | 450 |
| Silica fume | 45 | 45 | 45 |
| Water | 158 | 158 | 158 |
| River sand 0/2 | 705 | 888 | - |
| Gravel 2/8 | 701 | - | - |
| Gravel 8/16 | 301 | - | - |
| Magnetite 0/2 | - | - | 1055 |
| Magnetite 2/8 | | 769 | 871 |
| Magnetite 8/20 | | 330 | 374 |
| Superplasticizer [% m.c] | 2.6 | 3.6 | 3.2 |
| Density of concrete [kg/m$^3$] | 2395 | 2940 | 3720 |

## 3. Specimen preparation and test method

Concrete cubes with dimensions of 100 mm x 100 mm x 100 mm were prepared and tested for their mechanical properties at 5 temperatures: 20, 300, 450, 600 and 800°C. After 28 days of curing samples were weighed and kept in drying chamber at constant temperature 105°C for 7 days. Subsequently the density of concrete has been determined and specimens were subjected to elevated temperatures from 300°C to 800°C. Heating of the samples was performed using a medium-temperature furnace with thermostat allowing to regulate the rate of heating. Samples were set separately in the bottom of furnace chamber far from heating source to enable uniform heating distribution across the specimens (figure 1). Heating procedure conforms RILEM method [15]. In first stage a constant rate of heating, 1°C/min per minute, was maintained in the furnace. Then, the samples were left in the furnace for 1 hour, after reaching the desired temperatures.

Fig. 1. Specimens before (left) and after (right) thermal treatment.

For each testing temperature 6 cubic specimens have been prepared. Afterwards, to avoid any thermal shocks samples were slowly cooled with constant rate of cooling 1°C/min. Figure 2 presents the heating and cooling procedure. Cooled samples were visually observed to estimate the damage degree and weighed to determine the weight loss. Before determination of mechanical properties specimens were stored for 20 hours in laboratory conditions (50-60% RH at 20±22°C). The compressive strength and splitting tensile strength have been determined in accordance with PN-EN 12390-3 and PN-EN 12390-6 respectively. The age of tested samples was varied from

38 to 40 days due to the different heating time (dependent on temperature). The data obtained were compared with the results obtained for the control specimens which were stored at 20±2°C in the laboratory.

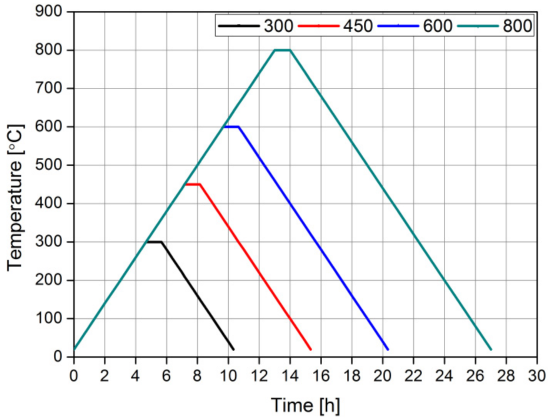

Fig. 2. Heating–cooling cycles chosen according to RILEM recommendations.

## 4. Test results and discussion

Figure 3 presents results of compressive strength determination. The compressive strength of reference sample (R) containing normal aggregate was decreasing with the increase of temperature. Compressive strength of samples containing magnetite aggregate (samples M1 and M2) increased after being exposed to 300°C and started to decrease at the temperature of 450°C. Nevertheless, the compressive strength of specimen was still higher than that of control mix. The highest strength increment in temperature between 300°C – 450°C was reported for samples containing mixed normal and magnetite aggregate (M1).

After being subjected to a temperature of 600°C and 800°C all tested specimens exhibited decrease of compressive strength. Residual relative compressive strength analysis which is depicted in figure 4 shows that reference samples (R) containing normal aggregate lost 60% of its initial strength after thermal condition at 600°C while samples containing magnetite aggregate lost 26% (M1) and 21% (M2) of their initial strength.

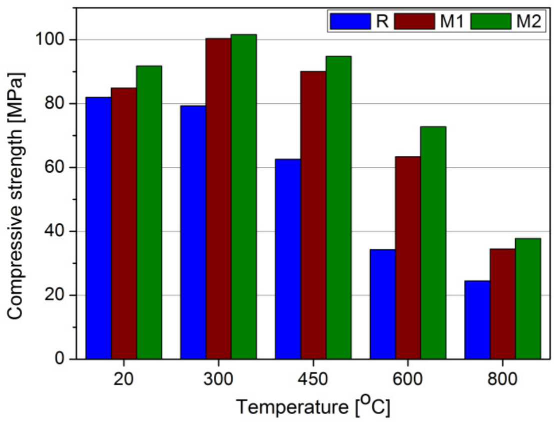

Fig. 3. Compressive strength of concrete after various temperature exposures.

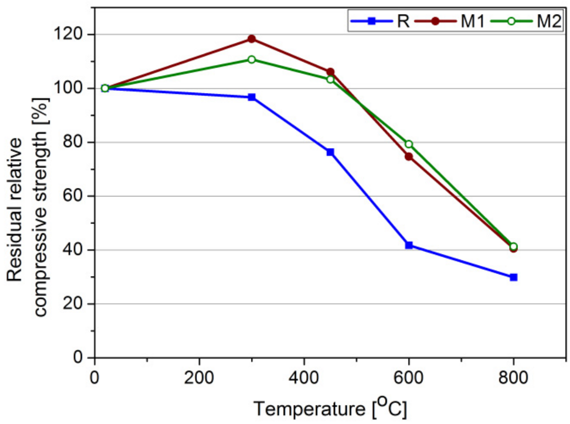


Fig. 4. Compressive strength variation of each concrete with respect to its value at 20$^{o}$C (before high temperature exposure).

Moreover, it was found that the strength was severely reduced while samples were exposed to 800$^{o}$C. Specimen R containing normal aggregate exhibited only 30% of its initial strength and samples M1 and M2 containing magnetite aggregate - 40%.

Splitting tensile strength of concrete samples subjected to high temperature are presented in figure 5. It was observed that the overall effect of subjecting specimens to high temperatures generally resulted in reduction in splitting tensile strength.

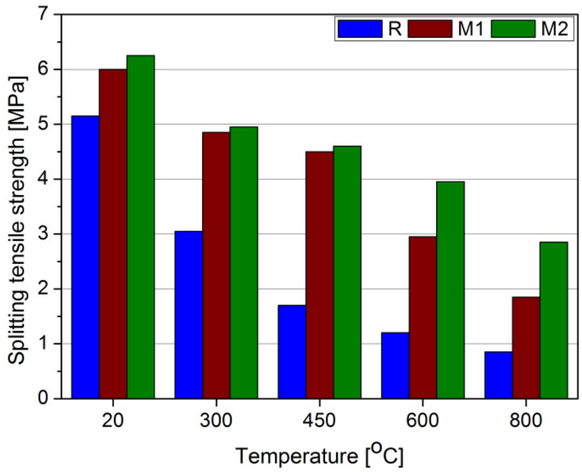


Fig. 5. Splitting tensile strength of concrete after various temperature exposures.

The lowest decrease of strength in the highest temperature was reported in samples containing magnetite (M2) – 54% of initial strength while reference mixture containing (R) normal aggregate exhibited only 16,5% of its initial strength (figure 6). Concrete specimen with mixed aggregate (M1) had 30% of its initial splitting tensile strength.

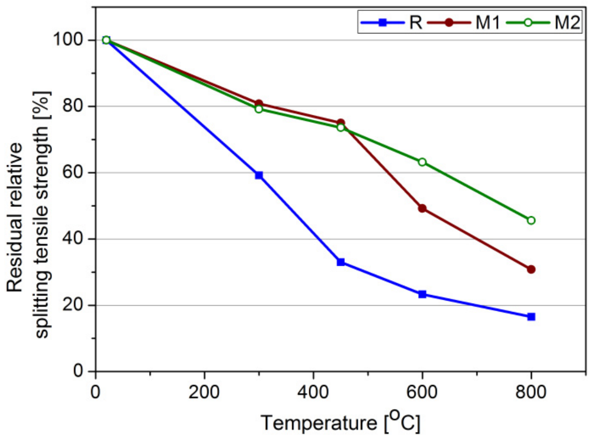


Fig. 6. Splitting tensile strength variation of each concrete with respect to its value at 20oC (before high temperature exposure).

Weight losses (in percentage) of the R, M1 and M2 specimens exposed to elevated temperature are depicted in Figure 7. It was observed that with the increase of temperature there were noticed systematic decrease of density. All the tested samples before being subjected to elevated temperature have been stored in drying chamber in constant temperature 105$^{o}$C in order to eliminate free water in the samples.

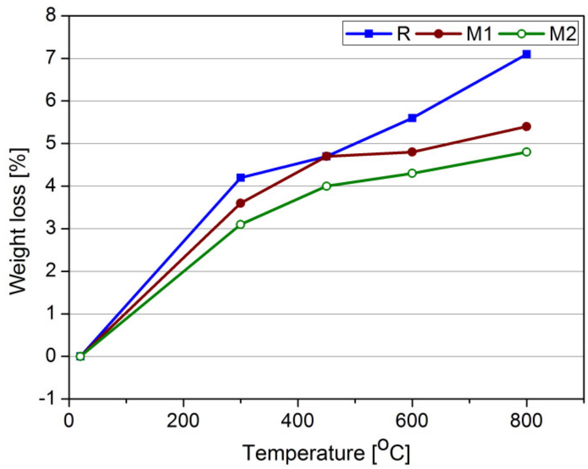


Fig. 7. Weight losses of tested mixtures exposed to elevated temperatures.

Density of specimens after being exposed to elevated temperature was still decreasing and the loss of weight was reported. It can be concluded that this phenomenon can be associated with the release of chemically bound water caused by high temperature.

During the tests the spalling has not been reported for any of tested samples. Visual inspection after exposition of samples at 600$^{o}$C reported cracks on the surface of samples containing normal aggregate and slightly less cracks on surface of mixtures M1. Cracks have not been noticed on the surface of M2 cubes. In addition, no damages on edges and corners of specimens exposed to 600$^{o}$C have been reported.


Fig. 8. Surface of tested specimens after exposure to 800°C (from left: R, M1, M2).

Reference specimen (R) after being subjected to high temperature changed the color from light grey to dark beige while samples containing magnetite changed their color from dark grey to light grey. In specimens exposed to 800°C the cracks where noticed in every type of sample, although the M2 was the least damaged. In addition, slight damage of the specimen edges and increased pores in cross-section have been reported.

## 5. Conclusions

Based on the experimental results presented in this paper, the following conclusions are drawn:

- Mechanical properties of concrete containing magnetite aggregate subjected to 300°C temperature resulted in the increase of compressive strength while compared to the sample cured in the ambient temperature. Concrete samples exposed to 450°C slightly decreased their compressive strength, however the strength was higher than the reference sample cured in ambient conditions,
- Further increment of temperature caused rapid decrement of strengths and after exposure to 800°C temperature samples containing magnetite aggregate exhibited only 40% of their initial strength,
- Increment of elevated temperatures caused systematic decrease of splitting tensile strength of tested concretes. However, the results showed that mixtures containing magnetite aggregate exhibited twice lower rate of deterioration than reference mixture containing normal aggregate,
- The use of magnetite aggregate in concrete mixture significantly improves mechanical properties when concrete is subjected to temperature up to 450°C. In higher temperature concretes containing magnetite decreased strength, nevertheless their performance were higher than the concretes containing normal aggregate.

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