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Effect of high temperature or fire on heavy weight concrete properties

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Abstract

Temperature plays an important role in the use of concrete for shielding nuclear reactors. In the present work, the effect of different durations (1, 2 and 3 h) of high temperatures (250, 500, 750 and 950 °C) on the physical, mechanical and radiation properties of heavy concrete was studied. The effect of fire fitting systems on concrete properties was investigated. Results showed that ilmenite concrete had the highest density, modulus of elasticity and lowest absorption percent, and it had also higher values of compressive, tensile, bending and bonding strengths than gravel or baryte concrete. Ilmenite concrete showed the highest attenuation of transmitted gamma rays. Firing (heating) exposure time was inversely proportional to mechanical properties of all types of concrete. Ilmenite concrete was more resistant to elevated temperature. Foam or air proved to be better than water as a cooling system in concrete structure exposed to high temperature because water leads to a big damage in concrete properties.

Keywords: Temperature; Mechanical properties; Physical properties; Aggregate; Concrete

1. Introduction

During the last few years, analytical and computation methods have been greatly developed in the field of concrete building exposed to high temperature or accidental fire. The transient heat flow within a fire-exposed structure is governed by the heat balance equation [1]. At elevated high temperature or accidental fire, concrete surfaces exposed to heat are significantly affected. At free surfaces, the heat flow is caused by convection and radiation [2]. A preliminary evaluation of the failure criteria showed that failure of heated concrete surface occurs most likely by crack formation parallel to the hot surface, degradation of concrete strength and pressurization of concrete pores [3].

The total strain can be divided into thermal strain, instantaneous elastic strain, plastic strain and also time- and temperature-dependent creep strain [4]. The behavior and the load-bearing capacity of concrete elements exposed to fire are the main tasks in fire engineering design. Simplifications using temperature-dependent stress/strain curves proved to be accurate [5]. Although the followed method is not complicated, it has been stated that stress and strain changes during the heating phase and the cooling down phase are still very complicated. However, the cooling phase usually does not need to be considered for determining the load-bearing capacity or the fire resistance time [6]. The generally accepted method for the fire safety design of load-bearing elements is based on a traditional classification system comprising a standard fire exposure and a standard fire resistance test. The required fire duration for exceptional structures, such as nuclear power plants or large traffic tunnels, is also very important [7].

The standard fire resistance test in the same or different furnaces may give significantly different results due to insufficiently specified test conditions (heat flow characteristics, test load and restraint conditions). Often, a rough idealization of the actual conditions in the structure is forced by the dimensions of the testing facilities (grading of structural elements is poor information, and is given on the actual response of a complete structure in a fire) [8].

A concrete shield is exposed to two sources of heat: heat transferred from the hot parts of the reactor systems and heat produced internally by the attenuation of neutrons and

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gamma rays [9]. Radiations attenuated by the shield do not have a significantly deleterious effect on the shield itself. Different types of concrete seem to hold up well, although if heated, they will lose water from crystallization, becoming somewhat weaker and less effective in neutron attenuation [10].

Energy captured from the slowed down fast neutrons and gamma rays entering the shield from a reactor core is deposited within the shielding material and liberated as heat. The total amount of heat generated in the shielding material is thus quite considerable. Its effect can be significant, especially that most of the heat is produced in the layers of the shield nearest to the reactor core. The determination of heat distribution and heat effect or thermal stress is an important aspect of the shield design [11]. In case of burning sodium pool reactors on a concrete surface, the heat transferred to concrete from the sodium pool will cause release of physically and chemically bound water from concrete leading to release of hydrogen and additional energy and may cause severe safety problems. The typical sodium–concrete reaction begins at a temperature of 400 °C; the temperature increases to reach more than 800 °C after half an hour from the beginning of the reaction [12].

Temperature of thick concrete sections used as prestressed concrete in the pressure vessels of nuclear reactors may reach as high as 400 °C. Kaplan et. al. investigated concrete structural properties of these sections and found that some deterioration in the structural properties would occur when mass concrete is exposed to high temperatures, but very little damage would occur if the concrete is heated indirectly at atmospheric pressure. They demonstrated that changes in physical properties of unsealed specimens exposed to low temperatures (70, 100 and 150 °C) were greater than those sealed specimens exposed to higher temperatures (250 and 400 °C) [13]. They also found that changes in concrete properties were mainly related to loss of water from the cement gel and the capillary pores in cement paste. Gluekler found that local failures at the surface of concrete structures (spalation) and significant water release have been observed when surfaces were exposed to elevated temperatures as in case of building fires. In liquid metal fast breeder reactors, spillage of hot sodium onto concrete structures could potentially cause such failure [3].

The aim of this work is to study the effect of accidental fire or high temperature (ranging from 25 to 950 °C) and gamma rays on physical, mechanical and radiation properties of different types of concrete (gravel, baryte and ilmenite concrete) used as shields in nuclear facilities. The study was extended to investigate the effect of fire protection painting material on concrete properties, and to determine the maximum permissible temperature of concrete shield of studied mixing composition, and also to study the effect of different methods of fire cooling on concrete properties.

2. Experimental

2.1. Materials

The fineness degree of the used portland cement was 2814 cm^2/g, initial setting time was 105 min, final setting time was 8.75 h, volume change is 15 mm and the compressive strength after 7 and 28 days were 21.0 and 33.0 MPa, respectively; these results were conformed to the Egyptian Standard Specifications (ESS 583-93).

The physical and mechanical properties of used aggregates, brought from natural mining in Egypt, were determined according to American Standard for Testing Material codes (ASTM; C-127, C-128, C-29 and C-33) and they are given in Table 1 [14].

The grain size distribution of used baryte and ilmenite was illustrated according to ASTM (C-637 and C-638) while that of used gravel was compatible with ASTM C-136, which is acceptable to ESS. The main chemical components of the used materials are given in Table 2 [14].

The used water for concrete mixing was tap drinking water, which is acceptable according to ESS no. 190.

FR2 viscous colorless fire protection painting material supplied from Chemicals for Modern Building [CMB LEYDE] was used as a concrete paint for protection from the effect of high temperatures.

2.2. Sample preparation

Trial mix was done using the absolute volume method to obtain denser concrete. The weight of used materials in the final mix design to obtain 1 m^3 of concrete is given in Table 3.

The mixing procedure was done according to ASTM C-39; to avoid segregation of heavy aggregate, smaller volumes of heavy material were used per batch.

Cubic specimens of dimensions $100 \times 100 \times 100$ mm were prepared to determine the density of the tested concrete (gravel, baryte and ilmenite concrete). Specimens of $150 \times 150 \times 50$ mm were used to investigate the absorption percent of different types of tested concrete and to study the compressive strength of concrete at different temperatures. Cylinders of 150 mm in diameter and 300 mm in height

Table 1
The physical and mechanical properties of used aggregates

Properties	Aggregate type		
	Gravel (or sand)	Baryte	Ilmenite
Specific gravity	2.6	4.0	4.2
Unit weight (t/m^2)	1.7	2.8	2.9
Void ratio (%)	38	28	31
Water absorption (%)	0.9	1.7	2.0
Crushing value	16.5	45	41.5
Hardness	–	3–3.5	4–5

Table 2
The chemical analysis of the used materials

Elements	Aggregate type			
	Cement	Gravel	Baryte	Ilmenite
TiO_2	0.01	0.02	0.38	21.4
Fe_2O_3	3.0	1.02	0.02	65.74
FeO	0.02	0.5	0.1	0.68
SiO_2	21.5	95.1	0.1	5.86
Al_2O_3	6.1	1.5	1.8	3.52
BaO	0.45	0.05	0.62	0.1
$BaSO_4$	0.1	0.04	90.1	0.05
SiO_3	0.01	0.02	4.8	0.74
CaO	63.5	0.1	0.05	0.2
MgO	3.8	0.2	0.05	0.1
L.O.I.	1.4	0.1	1.90	1.06

were poured to study the effect of different temperatures on the tensile and bonding strengths of tested concrete. Beams of 500 mm length and 100 × 100 mm in cross-section were prepared and used to investigate the bending strength of concrete samples.

Another group of all samples was prepared and then painted by fire protection material (FR2). All mechanical properties were determined for unprotected and protected concrete specimens.

A third group of only gravel concrete sample was prepared to study the effect of different types of cooling system (air, water or foam) on mechanical properties of protected and unprotected specimens at high temperature for different periods of time (1, 2 and 3 h).

For radiation test, special specimens of 200 × 200 mm in area but differing in thickness (20, 40, 60, 80 and 100 mm) were mechanically cut from the specimens of 200 × 200 × 200 mm to measure the resistance (attenuation coefficient) of different types of concrete to gamma ray penetration.

2.3. Test procedures

2.3.1. Heating exposure technique

Muffle furnace of big furnace chamber (400 × 600 × 400 mm) and maximum temperature of 1500 °C was used. Samples were placed unloaded in the cooled furnace chamber and the temperature was increased to reach certain degrees with ratting of 10 °C/min. After an exact period (1, 2 or 3 h), the furnace swatch off and left tills to cool, then the samples were tested. Other specimens removed from the furnace using a long clamping arm were cooled using water springier or foam until they are cool for testing.

2.3.2. Radiation test

Shielding tests of gamma rays were performed using cobalt-60 and cesium-137 point sources of 3.7×10^4 Bq (1 μCi) activities. Tests were carried out on different thicknesses using 4 in. in diameter of NaI (sodium iodide crystal) detector (this is a high-sensitivity material used to measure the gamma activity behind the shield) connected to a computerized Multi-Channel Analyzer (MCA). The different thicknesses of each specimen was subjected to Co^{60} and Cs^{137} point sources for 15 min to investigate the shielding properties to gamma radiation. The attenuation coefficient of studied samples was the average attenuation coefficient value of each tested thickness using the following attenuation equation:

$$I = I_o e^{-\mu x}$$

where I is the intensity of gamma rays after the shield material, I_o is the intensity of gamma rays before the shield material, μ is the attenuation coefficient factor and x is the thickness of shield material.

3. Results and discussion

The physical properties of studied concrete types are shown in Table 4. It can be observed that the differences in slump values can be attributed to the absorption of ilmenite aggregate (2%), baryte aggregate (1.7%) and gravel (0.9%). From the obtained results, it can be concluded that ilmenite concrete showed the highest density when compared to the other types of concrete. Its density was higher than gravel and baryte concretes by 47% and 6%, respectively. The difference in density can be attributed to the difference in specific gravity of the used aggregates. Ilmenite concrete showed the lowest value of water absorption. It was lower than that of gravel concrete by 33% while water absorption of baryte concrete was lower than that of gravel concrete by 25%. The difference in water absorption can be attributed to the difference in the void percent between gravel, baryte and ilmenite aggregates. It may be also attributed to the reduc-

Table 3
Proportional mix designs of different types of concrete

Type of concrete	Materials used				
	Cement content [kg/m^3 of concrete]	Fine aggregate (<5 mm) [kg/m^3 of concrete]	Coarse aggregate (5–20 mm) [kg/m^3 of concrete]	Mixing water (W/C = 40%) [l/m^3 of concrete]	Super plasticizer (sikament-163) [l/m^3 of concrete]
Gravel	400	750	1125	160	–
Baryte	400	1236	1510	160	1.5
Ilmenite	400	1041	1933	160	2.1

Table 4
Physical properties of different types of studied concrete

Type of concrete	Physical properties		
	Slump (according to ASTM C-149-90a) [mm]	Density after 28 days [kg/mm^3]	Absorption % after 28 days (ASTM C462-90)
Gravel	100–120	2.35×10^{-6}	3.75
Baryte	50–70	3.25×10^{-6}	2.8
Ilmenite	20–30	3.45×10^{-6}	2.5

tion in void percent of ilmenite concrete due to the chemical reaction between TiO_2 and hydrated cement producing gel which fills and reduces the void's volume [14].

The mechanical properties of different types of studied concrete at laboratory temperature (25 ± 3 °C) are given in Table 5.

It can be seen that ilmenite concrete, in general, has higher values of mechanical properties than baryte concrete, while gravel concrete has the lowest values of mechanical properties. This difference in mechanical properties can be attributed to difference in the shape and rigidity of the aggregates. Ilmenite aggregate was angular in shape while gravel was rounded. Angular aggregate produces concrete of higher strength than rounded aggregate. Moreover, ilmenite aggregate had a specific surface area of 23.3 cm^2/g, which is more convenient than the specific surface area of baryte aggregate (38.8 cm^2/g). Ilmenite concrete showed an increase in compressive strength of 16% and 8% when compared to gravel and baryte concretes, respectively. The highest values of indirect tensile, flexural and bond strengths was obtained by ilmenite concrete. The indirect tensile strength of ilmenite concrete was higher than that of gravel and baryte concretes by 38% and 24%, respectively, while its flexural strength was higher than that of gravel and baryte concretes by 57% and 22%, respectively. A pronounced increase in bond strength of ilmenite concrete was achieved; it showed an increase of 27% and 17% when compared to gravel and baryte concretes, respectively. The modulus of elasticity of ilmenite concrete was higher than that of gravel and baryte concretes by 66% and 19%, respectively.

Results of the maximum compressive strength (MPa) of different types of concrete, at different degrees of temperature for 2 h duration are given in Table 6. Exposure to different temperatures leads to reduction in compressive strength. The reduction in compressive strength of ilmenite concrete was less than that of gravel and baryte concretes, this being 16%, 59%, 85% and 100% for ordinary gravel concrete when exposed for 2 h to temperatures of 250, 500, 750 and 950 °C, respectively, and 7%, 40%, 68% and 86% for baryte concrete, while for ilmenite concrete, the reduction in compressive strength was 7%, 15%, 41% and 74% when exposed to the same degrees of temperature for the same duration. The reduction in compressive strength can be attributed to the driving out of free water and fraction water of hydration of concrete due to high temperatures. Dehydration of concrete causes a decrease in its strength, elastic modulus, coefficient of thermal expansion and thermal conductivity.

Table 6
Maximum compressive strength (MPa) of different types of concrete at different temperatures (°C)

Type of concrete	Temperature				
	25 °C	250 °C	500 °C	750 °C	950 °C
Gravel	44	36.79	18.2	6.58	0.0
Baryte	47	43.95	28.25	15.0	6.77
Ilmenite	51	47.58	43.2	29.92	13.44

The effects of heating duration at different degrees of temperature on mechanical properties of protected and unprotected gravel concrete specimens are given in Table 7.

The compressive strength of gravel concrete showed a minor reduction of 9% and 16%, and 5% and 11% when heated at 250 °C for 1 and 2 h in both cases of protected and unprotected concrete samples, respectively, but it was extremely affected (50%) when heated at 500 °C for 1 h in the case of unprotected ordinary concrete. On the other hand, the protected concrete was mildly affected compared with the unprotected concrete. The reduction in bending strength of gravel concrete was higher than that of compressive strength when heated at the same temperature and for the same duration. The bending strength of gravel concrete was extremely affected by exposure to heat at 250 °C for 2 and 3 h for protected and unprotected specimens, respectively. In general, when gravel concrete was exposed to temperatures of 250 °C for more than 1 h, the rate of loss of strength increased.

At temperatures above 500 °C, for 1 h duration, the high strength of protected and unprotected gravel concrete progressively lost its compressive strength, which dropped to more than 55% of the room temperature strength. Generally,

Table 5
Mechanical properties of different types of studied concrete

Type of concrete	Mechanical properties				
	Compressive strength (F_t) [MPa]	Tensile strength (F_t) [MPa]	Flexural (bending) strength (F_f) [MPa]	Bond strength (F_f) [MPa]	Modulus of elasticity [GPa]
Gravel	44	2.55	3.43	5.4	20.79
Baryte	47	2.85	4.42	5.89	29.03
Ilmenite	51	3.53	5.4	6.87	34.43

Table 7
Maximum mechanical properties (MPa) of protected and unprotected gravel concrete at different temperatures (°C) and different heating duration (h)

Mechanical properties of gravel concrete		Heating duration (h)	Temperature				
			25 °C	250 °C	500 °C	750 °C	950 °C
Compressive strength (F_t) [MPa]	Unprotected	1	44	40.2	22.1	13.1	5.89
		2	44	36.78	18.15	6.57	0.0
		3	44	28.93	9.81	0.0	0.0
	Protected	1	44	41.69	26.0	14.22	6.87
		2	44	39.24	23.55	7.85	0.0
		3	44	32.37	13.73	2.95	0.0
Tensile strength (F_t) [MPa]	Unprotected	1	2.55	1.96	0.98	0.59	0.11
		2	2.55	1.77	0.78	0.0	0.0
		3	2.55	1.37	0.39	0.0	0.0
	Protected	1	2.55	2.21	1.40	0.74	0.15
		2	2.55	1.91	1.0	0.42	0.0
		3	2.55	1.52	0.66	0.0	0.0
Flexural (bending) strength (F_f) [MPa]	Unprotected	1	3.43	2.71	1.01	0.30	0.10
		2	3.43	1.96	0.69	0.0	0.0
		3	3.43	1.21	0.59	0.0	0.0
	Protected	1	3.43	2.95	1.72	0.70	0.10
		2	3.43	2.45	1.42	0.30	0.0
		3	3.43	1.42	0.78	0.0	0.0
Bond strength (F_f) [MPa]	Unprotected	1	5.4	2.75	1.37	0.60	0.10
		2	5.4	2.35	0.98	0.15	0.0
		3	5.4	1.77	0.59	0.0	0.0
	Protected	1	5.4	2.95	1.67	0.80	0.15
		2	5.4	2.16	1.13	0.17	0.0
		3	5.4	1.47	0.69	0.0	0.0

the mechanical properties of concrete (compressive, tensile, bending and bonding strengths) were inversely proportional to heating temperatures (more than 500 °C) or firing time (more than 1 h).

The effect of different cooling methods on compressive strength of protected and unprotected gravel concrete for different heating durations at different degrees of temperature is given in Table 8.

The coating material had no significant effect on compressive strength in temperatures higher than 500 °C, but cooling by water led to more reduction in compressive strength of concrete than cooling by air or foam type,

Table 8
Maximum compressive strength (MPa) of protected and unprotected gravel concrete at different temperatures (°C) using different cooling methods

Gravel concrete cooling method		Heating duration (h)	Temperature				
			25 °C	250 °C	500 °C	750 °C	950 °C
Air cooling	Unprotected	1	44	40.2	22.1	13.1	5.89
		2	44	36.78	18.15	6.57	0.0
		3	44	28.93	9.81	0.0	0.0
	Protected	1	44	41.69	26.0	14.22	6.87
		2	44	39.24	23.55	7.85	0.0
		3	44	32.37	13.73	2.95	0.0
Water cooling	Unprotected	1	44	37.30	13.25	5.40	0.0
		2	44	32.40	10.80	0.0	0.0
		3	44	24.50	3.90	0.0	0.0
	Protected	1	44	38.25	14.70	6.87	0.0
		2	44	33.35	11.77	2.95	0.0
		3	44	26.0	4.90	0.0	0.0
Foam cooling	Unprotected	1	44	38.25	15.70	7.85	0.0
		2	44	34.35	12.75	4.90	0.0
		3	44	25.50	5.90	0.0	0.0
	Protected	1	44	39.25	16.68	8.34	0.0
		2	44	36.30	14.22	5.40	0.0
		3	44	26.50	7.85	0.0	0.0

Table 9
Attenuation coefficient percent (μ%) of tested concrete types at different temperatures

Type of concrete	Temperature (°C)	Attenuation coefficient percent (μ%)		
		Co^{60}		Cs^{137} (660 keV)
		1330 keV	1170 keV	
Gravel	25	12.72	12.21	7.33
	250	11.53	11.16	6.67
	500	11.01	10.55	6.28
	750	10.69	10.31	6.15
	950	9.55	9.18	5.50
Baryte	25	15.97	15.54	9.73
	250	14.53	14.14	8.94
	500	13.89	13.52	8.54
	750	13.25	12.91	8.15
	950	12.61	12.27	7.76
Ilmenite	25	16.59	16.22	9.81
	250	14.61	14.27	8.66
	500	14.27	13.95	8.46
	750	13.93	13.62	8.26
	950	13.61	13.31	8.1

because using water as a cooling system leads to a big damage in concrete properties.

The attenuation coefficient percent (μ%) of Co^{60} and Cs^{137} gamma sources of different types of concrete heated for 2 h duration at different degrees of temperature are shown in Table 9.

Results showed that the attenuation coefficient (μ%) slightly depends on temperature and decreased to about 16% for gravel concrete, 17% for baryte concrete and 16% for ilmenite concrete at 750 °C, compared to those attenuation coefficients at laboratory temperature (25 °C) for different energies (1330, 1170 and 660 keV).

Ilmenite concrete showed the highest attenuation of transmitted gamma rays. It was higher than gravel and baryte concretes by 32% and 4%, respectively, for Co^{60} and by 34% and 0.1% at Cs^{137} at laboratory temperature; this result can be attributed to the fact that ilmenite concrete has the highest density when compared to gravel and baryte concretes.

The attenuation coefficient (μ%) of ilmenite concrete was higher than that of gravel for Co^{60} by 31% and 33% and for Cs^{137} by 34%, respectively, while the attenuation coefficient (μ%) of baryte concrete was higher than gravel only by 26% and 27% for Co^{60} and about 33% for Cs^{137}. The reduction percent of gamma attenuation coefficient (μ%) of gravel concrete for Co^{60} and Cs^{137} at temperatures 250, 500, 750 and 950 °C was about 9%, 14%, 16% and 25%, respectively, while that of baryte concrete was about 9%, 13%, 17% and 21% at the same temperatures, respectively, and it was 12%, 14%, 16% and 18% at the same temperatures, respectively, for ilmenite concrete. The reduction of gamma attenuation coefficient (μ%) can be attributed to the effect of high temperature on concrete properties, especially density due to loss of water by evaporation.

4. Conclusion

From this study, it can be concluded that ilmenite concrete is more suitable as a shielding material than gravel or baryte concrete because of its high physical, mechanical and radiation properties. Ilmenite concrete is more resistant to elevated temperature than gravel or baryte concrete. It can be stated that ilmenite concrete is the suitable one to attenuate gamma rays as shielding material and there is a minor significance effect of high temperatures on concrete properties. It is recommended to use foam or air as a fire-fighting system in concrete structure exposed to high temperature or accidental fire compared to water, which leads a big damage to concrete properties. It is also recommended to use the fire protection material as a coating layer at temperatures lower than 500 °C to reduce loss of water at high temperatures and to insure the safety of concrete elements during any accidental fire. Moreover, it is necessary to employ special cooling arrangements in shielding concrete to limit the temperature effects on the shielding concrete properties; in addition, it is economic to employ more steel as an inner thermal shield and for reinforcement of the surrounding concrete shield.

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