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Heat transfer and thermal shock of recycled glass concrete

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Abstract. In this paper, an experimental study is carried out to investigate the effect of thermal shock on the mechanical properties of recycled glass concrete exposed to temperatures between 150 °C to 600 °C due to rapid cooling regimes, namely, natural cooling, spraying water, using CO_2 fire extinguishers, and immersion in water. The amount of waste glass replacement of fine aggregate resulting in optimal compressive strength is studied and then used in all specimens. The heat transfer in recycled glass concrete exposed to 600 °C for one hour using an electric furnace is studied, with the results validated via a finite element model. It is found that recycled glass can enhance the residual strength and reduce the severity of cracks in concrete subjected to thermal shock caused by rapid cooling from temperatures up to 600 °C to room temperature. Using recycled glass in concrete decreases temperature rise with time when exposed to elevated temperatures. The results obtained show that replacing 25 % of fine aggregate with recycled glass gives the maximum value of compressive strength. Compared with natural cooling, thermal shock generated by fast cooling regimes causes more severe damage to concrete, in terms of greater losses in compressive and tensile splitting strength and crack severity. Among the eight cooling regimes used in this study, natural cooling in air maintained a relatively higher value of residual compressive strength, while the highest reduction in strength was observed when using CO_2 fire extinguishers. Tensile splitting strength shows the same trend.

1. Introduction

Millions of tons of waste glass are being generated annually all over the world. In the concrete industry, recycled glass has received remarkable attention because of it being one such by-product. The world is encouraging the use of recycled glass in concrete not only for its environmental benefits, such as reduction of landfill space and consumption of raw materials, but also to reduce industry costs. Glass provides several beneficial mechanical properties when used in concrete. Hitherto, its implementation as a substitute for fine aggregate has demonstrated equivalent concrete strength. Using recycled glass as a concrete component is new technology that needs more study and investigation to promote this application and confidently introduce recycled glass to the construction market as an alternative to primary material [1]. Recycled glass can be used in many engineering applications, such as water filtration, grit plastering, sand cover for sport turf, and sand replacement in concrete [2]. Many studies have shown that recycled glass crushed to different sizes can be used as fine aggregate without compromising concrete strength.

Concrete design used to rely heavily on assuring a load bearing capacity, sufficient to withstand ultimate loading conditions, both short and long-term [3, 4]. However, as the concrete industry advances, concrete standards and design codes are shifting towards safety assurance and risk control. From this perspective, concrete to be used in structural applications must satisfy various fire safety requirements [5–7]. Providentially, concrete is a multi-phase material, that is, when its main constituent materials (i.e., cement and aggregate) are chemically combined, it forms an inert material with a marginal thermal conductivity, high heat capacity and, thus, an inherent resilience against fire [8, 9]. This allows concrete to be unsurpassed in fire resistance as a bearing structural material.

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Yet, owing to ever-imminent fire jeopardy as the most important risk for structures and their inhabitants, [10–12], and due to the ubiquitous use of concrete as a construction material, there is a growing demand to understand the effect of fire on concrete properties and behavior. Hitherto, several studies have shown that recycled glass can be used as fine aggregate without compromising concrete strength, but very little research has been carried out on the thermal properties of recycled glass concrete.

A significant amount of investigation has been carried out worldwide focusing on the recycling of waste concrete. An experimental study evaluated different proportions of crushed glass replacing fine aggregate in concrete in [13]. The results show that a 40 % proportion of glass as fine aggregate gives the highest compressive and tensile strength. The effect of using glass as a pozzolanic material in concrete using waste glass powder as a partial replacement for cement is studied by [14]. It is found that 10 % of cement replaced by waste glass yields the highest 28-day compressive strength compared to plain concrete. This percentage increases to 15 % for tensile splitting strength.

Most researchers have studied concrete failure, the mix design process, and concrete mechanical properties [15]. Only a few researchers have investigated the mechanical properties of recycled concrete at high temperatures. The authors of [16] were some of the pioneers who studied the residual compressive strength of recycled aggregate concrete at high temperatures. Another investigation done by [17] studied the effects of using recycled glass as a partial replacement for fine and coarse aggregates on the properties of concrete at elevated temperatures. They concluded that the compressive strength of recycled glass concrete decreased up to 20 % from its original value with elevated temperatures up to 700 °C. Concrete made with 10 % of coarse aggregate replaced by glass, as compared to natural coarse aggregate replacement, had better properties in the fresh and hardened concrete states at ambient and high temperatures than those with larger replacement percentages [18].

Many investigations have shown that the cooling process of concrete after exposure to elevated temperatures, followed by severe moisture loss, results in extensive micro-crack formation and propagation, which further decreases the residual strength. Therefore, it is evident that the residual strength of concrete is much lower than what appears in a hot-strength test [11]. For assessing post-exposure residual properties, the unstressed, residual-strength tests are considered more appropriate for simulating post-fire-extinguishment concrete properties [11, 19, 20]. It has since become customary to perform concrete strength experimentation subsequent to a sample's slow-cooling process. Hence, most of the extant research refers to experimental results of such residual-strength tests. The mechanical properties of engineered, cementitious composites subjected to elevated temperatures up to 800 °C using two cooling methods, quenching in water and cooling in air, are studied by [21–23]. The results show that the compressive and ultimate strengths increase up to a temperature of 200 °C and decrease beyond that temperature. The cooling regime of quenching in water aided the strength and stiffness recovery. The mechanical properties of concrete subjected to high temperatures and air-cooled are studied by [24]. The effect of cooling on high-strength/high-performance concrete (HSC/HPC) for a temperature range greater than 800 °C is studied by [25]. It was found that there is no effect at temperatures above 800 °C. The effect of thermal shock due to rapid cooling on the mechanical properties of fiber-reinforced concrete exposed to elevated temperatures is discussed in [20]. Natural cooling and quenching in water methods were used. The results from this experimental work show that thermal shock induced by water quenching causes more severe damage to concrete, compared to natural cooling. The difference in effect on the compressive strength of HPC between quick cooling (quenching) and slow cooling in air is done in [26]. Concrete was subjected to temperatures of 100 °C, 200 °C, 400 °C, and 600 °C. It was clear that the loss in compressive strength was more pronounced under quick cooling than slow cooling. The effect of quick cooling is dependent on a certain porosity of calcium-silicate-hydrate (C-S-H) gel. The degree of micro-cracking that exists after a certain temperature exposure is owing to the magnitude, duration, and rate of heating. Application of recycled glass as aggregate in concrete materials can offer significant economic and environmental benefits, provided that the alkali-silica reaction (ASR) of glass in concrete is properly controlled. Many papers discuss the use of glass sand in concrete and show that the reactivity of glass is influenced by its particle size. The use of waste glass in concrete has been avoided on the grounds that it is known to undergo a harmful ASR, but using glass as fine aggregate with particles smaller than 0.6 mm, passing the #30 sieve, does not produce deleterious ASR expansion within the time frame of the measurements [27]. In this study, most of the glass is very fine: 84 % of the glass used passes sieve #30 (0.595 mm).

To the authors' knowledge, there is no previous research showing the effects of thermal shock due to fast cooling, such as quenching in water, CO_2 fire extinguishers, and spraying water for different durations, on the residual mechanical properties of recycled glass concrete. In this paper, the effect of using recycled glass in concrete as a partial replacement for fine aggregate on heat transfer (through measuring the maximum temperature developed at different locations inside the concrete specimen) is investigated experimentally and validated using ABAQUS finite element modeling software. The FE model was also used to study heat flow inside the concrete specimens.

2. Methods

2.1. Experimental details

2.1.1 Raw materials

In this study, the concrete mixture used consisted of cement, fine aggregate, coarse aggregate, recycled glass as partial replacement for fine aggregate, and super plasticizer, to obtain the required workability. These materials were mixed at specific ratios to get a consistent mixture. The cement used in the production of all specimens was ordinary Type 1 Portland cement, manufactured in Jordan. The coarse aggregates used were brought from local suppliers. The coarse aggregate was of angular nature, with a 19 mm nominal maximum aggregate size. The fine aggregate was in the form of river sand. Super plasticizer with 1 %-2.5 % cement content was used as a water-reducing agent to maintain slump between 70 to 100mm. The specific gravity, absorption, and unit weight were obtained according to the ASTM C128-88 test method, as shown in Table 1. Glass in this experiment was collected from waste glass in Irbid, Jordan. The glass underwent crushing and milling in order to create a fine aggregate. The chemical composition of the waste glass aggregate can be seen in Table 2. The gradation of glass and fine aggregate is presented in Table 3.

Table 1. Physical properties of aggregate.

Properties	**Type of aggregate**		
	Coarse	**Fine**	**Waste glass**
Bulk Specific Gravity (BSG, Dry)	2.46	2.56	2.11
Fineness Modulus (FM)	-	2.99	2.42
Absorption (%)	0.58	0.45	0.4
Unit Weight (UW)	1455	1650	1320

Table 2. Chemical composition of waste glass.

Chemical composition of waste glass (%)								
SiO_2	Al_2O_3	Fe_2O_2	CaO	MgO	SO_3	Na_2O	K_2O	Cr_2O_3
68.5	1.66	0.52	13.15	2.45	0.43	11.99	0.8	0.5

Table 3. Sieving analysis of fine aggregate and recycled glass.

Sieve size	**Accumulated passing %**	
	Waste glass	**Fine aggregate**
4.75 mm	100	100
2.36 mm	94	97.25
1.18 mm	89	92.12
600 µm	53	45.25
425 µm	32	34.22
300 µm	22	25.25
150 µm	1.25	2.25
75 µm	0.35	0.78

2.1.2. Experimental procedures

The experimental procedures were divided into three main parts. The first part determined the optimum waste glass content as a partial replacement for fine aggregate based on 28-day compressive strength. This optimum value was then used for all specimens. The second part included the heating process and various cooling methods. The third part was testing, encompassing compressive and tensile strength measurement, and crack formation observation. Table 4 shows the mix proportions used in this study: the control concrete mixture (containing 100 % fine aggregate without any recycled glass) and the concrete mixture containing waste glass content of 5 %, 10 %, 15 %, 20 %, 25 %, 30 %, 35 %, and 40 % (by weight of fine aggregate) as partial replacement for fine aggregate. The waste glass content that exhibited the highest compressive strength was then used to investigate its resistance to thermal shock and compare its efficiency to the control mixture. The specimens were exposed to temperatures of 150 °C, 200 °C, 400 °C, and 600 °C in an electric furnace, as shown in Figure 1. The specimens remained in the furnace at the target temperature for 2 hours, to ensure that the centers of the samples reached the target temperature. This duration was chosen based on many experimental trials. All specimens were subjected to various cooling regimes, as given in Table 5, until reaching room temperature again. For each cooling method, three cubes, with dimensions of 150×150×150 mm, were tested for each compressive strength and recycled glass concrete content, and three cylinders with dimensions of 100 mm in diameter and 200 mm in height were used for tensile splitting strength determinations. After the specimens cooled to room temperature, compressive strength, tensile splitting strength, and crack dimensions were measured, respectively. It should be mentioned here that the value of strength obtained in this study is an average value of the three specimens. In order to analyze the visible cracks in the cube specimens, the face that had the highest severity of cracking was selected. Then, those surfaces were washed with water and dried in an oven at 50 °C for 8 hours. This temperature is used to avoid generating any new cracks or damage. A digital camera was used to take photographs of each of the selected faces. The last step aimed to calculate the distribution of cracks in each image by retouching the cracks in Adobe Photoshop using a pencil tool with a 4-pixel width to make crack recognition and detection easier.

Table 4. Mix proportions of concrete mixture containing waste glass.

Contents	Glass replacement percentage								
	0	5	10	15	20	25	30	35	40
Water (kg)	190	190	190	190	190	190	190	190	190
Cement (kg)	458	458	458	458	458	458	458	458	458
Coarse aggregate (kg)	952	952	952	952	952	952	952	952	952
Fine aggregate (kg)	750	712.5	675	637.5	600	562.5	525	487.5	450
Waste Glass (kg)	0	37.5	75	112.5	150	187.5	225	262.5	300

2.2. Temperature profile inside the specimens

The main objective of this work is to develop a model based on the finite element method using ABAQUS software in order to demonstrate the accuracy with which this model can predict the effect of using different percentages of recycled glass as a partial replacement for fine aggregate on the maximum temperature developed at different locations inside the specimen. The concrete specimens have dimensions of 150×150×150 mm. These specimens were exposed to a temperature of 600 °C for one hour. The temperature developed at the surface and at the centroid of the cube (7.5 cm in depth) were then measured. The geometry of the model and temperature measurement locations are shown in Figure 2.

Figure 1. Electric furnace.

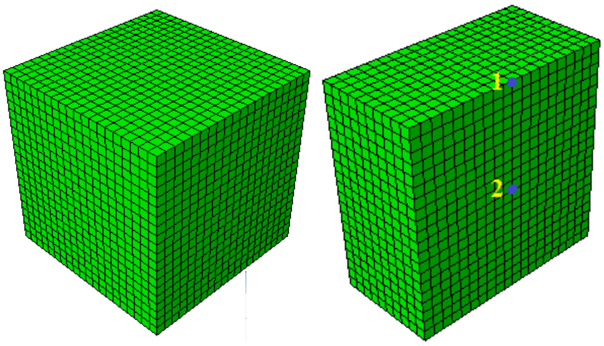

Figure 2. Finite element model and temperature measurement locations.

Table 5. Cooling regimes for heated concrete.

Cooling Regime	First stage	Second stage
CO_2 Fire Extinguisher	5 seconds 10 seconds 20 seconds	Natural cooling
Water Spraying	5 minute 10 minutes 20 minutes	Natural cooling
Water Quenching	24 hours	-
Natural Cooling at Room Temperature	Natural cooling	Natural cooling

The models were built using ABAQUS, version 6.14. The software offers a wide range of solvers: standard, coupled temperature-displacement, risk analysis, implicit, explicit, among others. In this work, the appropriate solver was the coupled temperature-displacement solver. The ABAQUS modeling space can be 2D or 3D, depending on the complexity of the case. Additionally, the software provides a wide range of shapes, such as, solid, shell, wire, and point. In this paper, the modeling space for all parts is 3D. The element type is C3D8R, which indicates a 3D solid element with 8 nodes per element.

This part presents experimental work and finite element modeling of concrete cubes that have the same properties as the specimens used in the thermal shock experiment, namely, normal concrete, and recycled glass concrete. The difference between the two types of concrete is based on the material properties. Table 6 shows the properties of both normal and recycled glass concrete.

The results of the analyses will be compared to the experimental results. The typical cube specimen with thermocouples is shown in Figure 3. Thermocouples were cast at the centroid of the cubes, i.e., at a depth of 7.5 cm. These results were compared to the finite element results.

Table 6. Properties of plain and recycled glass concrete.

Material	Recycled glass replacement percentage of Fine-Agg., %(By mass)	Compressive strength, N/mm^2 (Ksi)	Tensile strength, N/mm^2 (Ksi)	Thermal conductivity, W/mK (BTU/hr·ft·°F)	Coefficient of thermal expansion	Modules of elasticity, KN/mm^2 (Ksi)	Density, Kg/m^3 (pcf)
Plain Concrete, [28]	0	40 (6.1)	4.1	1.3 (0.75)	12*10-6	39.3 (5.7)	2450 (153)
Recycled glass Concrete, [29]	25	46 (6.5)	3.9	1.05 (0.61)	1.2*10-6	39.3 (5.7)	2385 (149)

Figure 3. Photograph of a typical cube specimen with thermocouple used at the surface and centroid of the cubes.

3. Results and Discussion

3.1. The optimum content of recycled glass

The optimum content of recycled glass as a partial replacement for fine aggregate was selected based on the maximum compressive strength after 28 days of curing in water. Different percentages of glass by weight of fine aggregate (5, % 10 %, 15 %, 20 %, 25 %, 30 %, 35 %, and 40 %) were used and tested. It can be seen from Figure 4 that the optimum value of recycled glass was 25 %, which gives a compressive strength of 46 MPa, compared to 40 MPa for plain concrete. This can be explained due to the angular nature of glass aggregate, which gives it a greater surface area than fine aggregate. When the glass percentage exceeded 25 %, the compressive strength decreased. This is because higher proportions of glass mean insufficient cement paste in the mix to facilitate bonding between particles, which creates microscopic voids, which adversely affect concrete strength [29]. This optimal percentage does not match that in the literature, [13], because 10 % crushed glass was used in the literature as a partial replacement for coarse aggregate. This percent was based on [14], who studied the effect of using recycled glass as a partial replacement for cement, while this study examines the effect of using recycled glass as a partial replacement for fine aggregate.

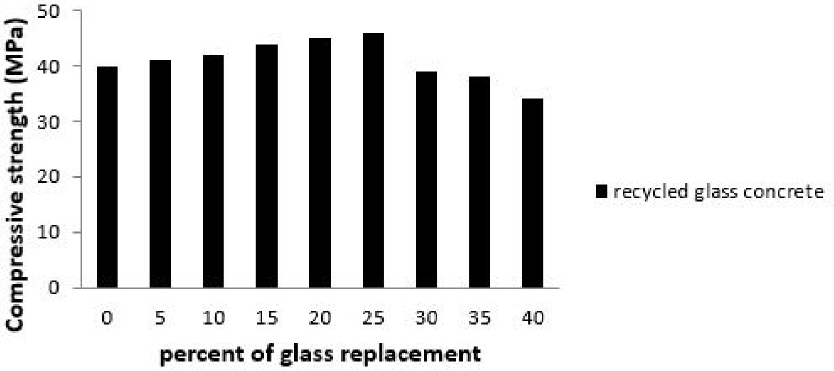

Figure 4. Compressive strength development of concrete containing recycled glass.

3.2. The effect of thermal shock on residual compressive strength

The compressive strength and reduction in compressive strength of recycled glass concrete and plain concrete exposed to temperatures between 150 °C and 600 °C for two hours, followed by different cooling regimes, fast and air cooling, is shown in Figures 5 and 6. For both types of concrete, the residual compressive strength of concrete was significantly influenced by the cooling regimen when the temperature exceeded 150 °C. Also, for all exposures, as the temperature increased from room temperature, the compressive strength increased up to 150 °C for all cooling regimes. It can be seen that at a temperature of 150 °C, the compressive strength of recycled glass and plain concrete are higher than those at room temperature, since additional hydration of residual cement is activated. The percent increase of the compressive strength of recycled glass concrete is more than that of plain concrete. As the temperature surpasses 150 °C, the strength decreases. This is due to a decrease in calcium hydroxide content, as well as the shrinking of an unhydrated area function, which is detrimental to the microstructure. At 200 °C, the compressive strength of plain concrete decreased for all cooling methods, except using natural cooling and spraying water for 5 minutes. The compressive strength was 46 and 42 MPa, respectively. The compressive strength of the recycled glass concrete decreased when the specimens were cooled using a CO_2 fire extinguisher for 10 seconds or more and by immersion in water, while the rest of the cooling regimes increased the compressive strength by percentages ranging from 3.5 to 20 %. From 400 °C to 600 °C, the residual compressive strength of the plain and recycled glass concrete specimens decreased for all cooling regimes. The highest reductions in compressive strength were caused by the use of a CO_2 fire extinguisher for 20 seconds, immersion in water, and a CO_2 fire extinguisher for 10 seconds, respectively. The results show that the reduction increases with an increase in the time of use of the CO_2 fire extinguisher. Also, it can be seen that the reduction in strength due to air cooling (natural cooling) for the two types of concrete is always lower than that due to fast cooling. It should be noted here that all the cooling methods can be classified as fast cooling methods, except air cooling (natural cooling). The reduction in compressive strength of recycled glass concrete was less than the reduction for plain concrete for all temperatures and for all cooling methods, since glass has a lower thermal conductivity than fine aggregate and absorbs less heat, due to its low specific heat. Also, the thermal incompatibility of the various components, initial moisture content, and permeability index of recycled glass concrete are higher than those of plain concrete. Using CO_2 fire extinguishers causes the largest reduction in compressive strength because the CO_2 is compressed at a very low temperature, generally –76 °C, which leads the thermal gradient to be very high, causing the concrete sample to undergo increased expansion.

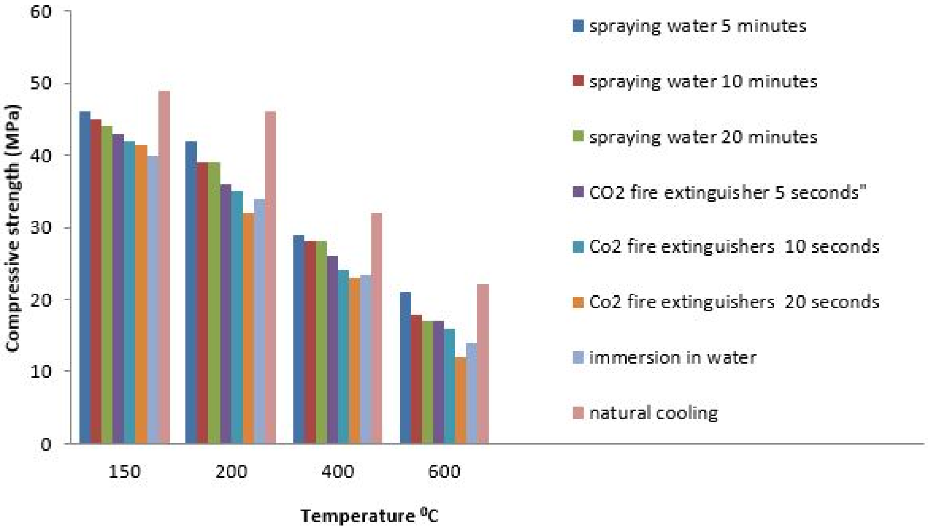

Figure 5. Bar chart for the residual compressive strength of plain concrete.

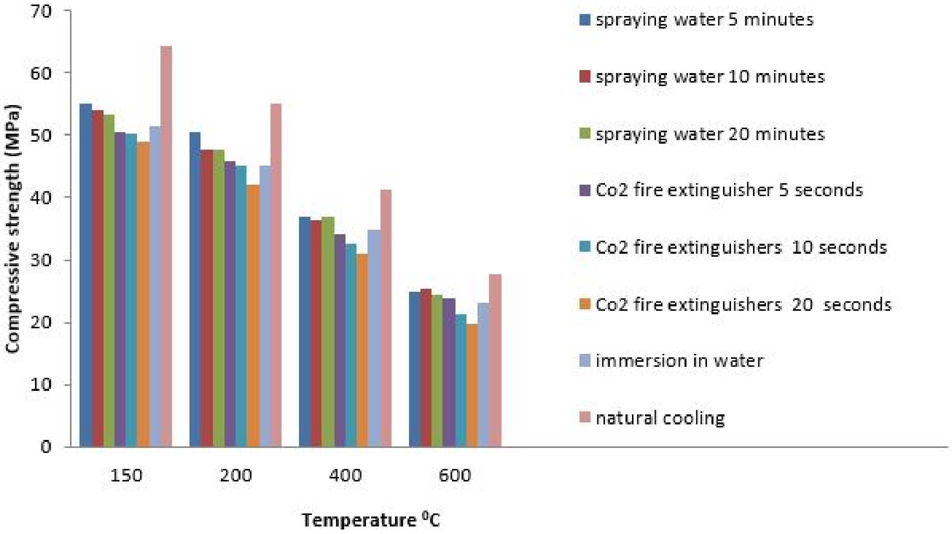

Figure 6. Bar chart for the residual compressive strength of recycled glass concrete.

3.3. The effect of thermal shock on residual tensile splitting strength

The residual tensile splitting results for the two types of concrete - plain and recycled glass concrete - subjected to elevated temperatures under various cooling regimes are presented in Figures 7 and 8. As previously observed, the residual tensile splitting strength due to natural cooling is higher than the other cooling methods for all temperatures for both types of concrete. Also, it is shown that, for all exposures, as the temperature increases from room temperature, the tensile splitting strength increases up to 150 °C, for all cooling regimes. At 200 °C, the tensile splitting strength of plain concrete for all cooling methods increased or remained constant by percentages ranging from 0 to 31 %, except when the specimens were cooled with a CO_2 fire extinguisher for 10 or 20 seconds. The tensile splitting strengths of those two cases were 3.2 and 3.1MPa, respectively, a decrease from the control sample of 8.5 % and 11.4 %, respectively. The tensile splitting strength of the recycled glass concrete decreased at 200 °C when the specimens were cooled with a CO_2 fire extinguisher for 20 seconds. The tensile splitting strength for this case was 4.11 MPa, a reduction of 2 %, while the rest of cooling regimes increased the tensile splitting strength from 0 to 36 %. For temperatures from 400 °C to 600 °C, the same conclusions can be made as in the compressive strength section. The reduction in tensile splitting due to fast cooling was more than natural cooling. This can be explained as in [30]: fast cooling produces residual stress between the outer and inner core of the concrete that creates micro-cracks in the core. It can also be seen that concrete containing recycled glass experienced less of a reduction in tensile splitting strength than plain concrete. This is because glass has a lower thermal conductivity than fine aggregate and sand.

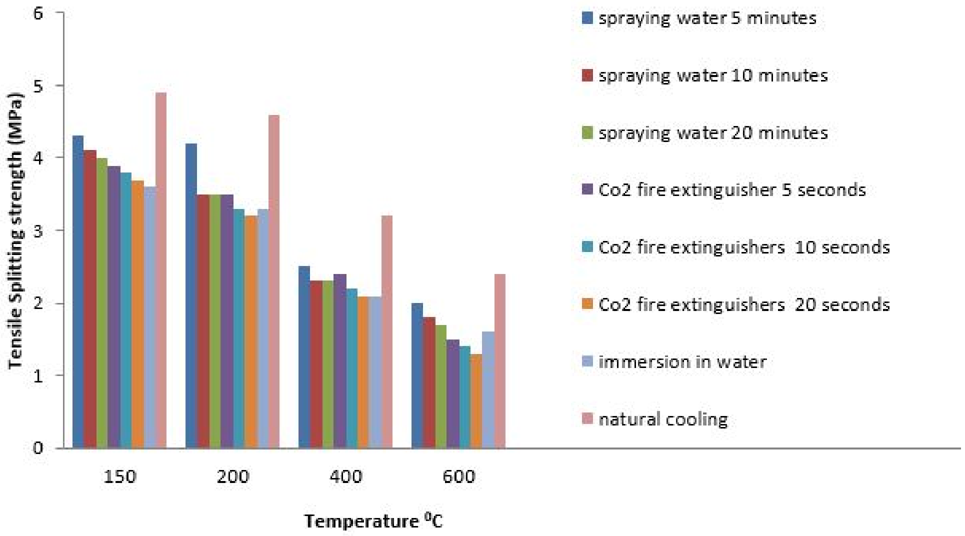

Figure 7. Bar chart for the residual tensile splitting strength of plain concrete.

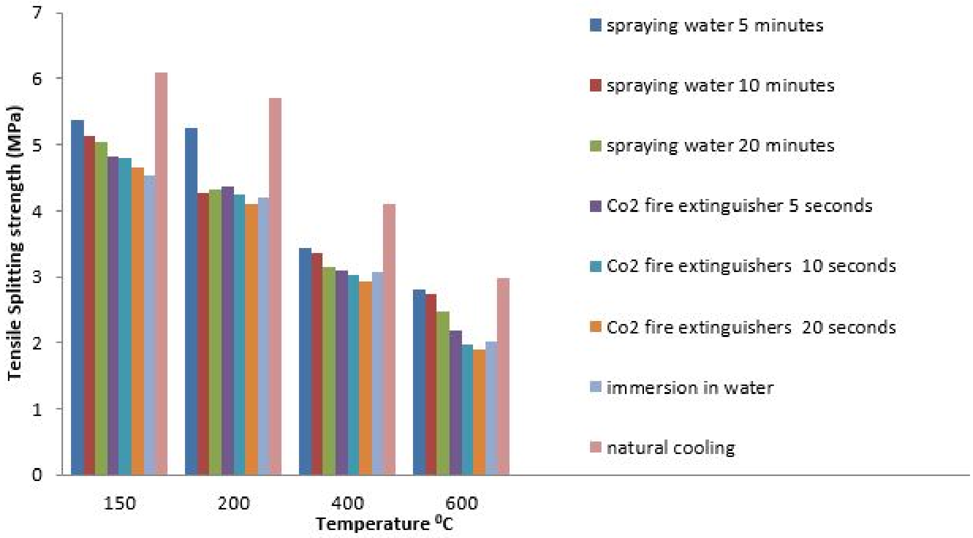

Figure 8. Bar chart for the residual tensile splitting strength of recycled glass concrete.

3.4. Crack formation

Figures 9, 10, and 11 show visible cracks in plain concrete and recycled glass concrete caused by heating and cooling processes for temperatures of 200 °C, 400 °C, and 600 °C, respectively. It is observed that there are noticeable effects on the crack length and density depending on the mixture. The cracks that were formed in the recycled glass concrete cube are less severe than those in the plain concrete for all exposure temperatures. Crack depth was not considered in this experiment. The severity of the cracks depends on the exposure to heat, with the effect of the cooling regime becoming obvious above 400 °C. The severity of the cracks at 200 °C for all cooling regimes is very low and increases with an increase in temperature, until reaching maximum severity at 600 °C. In terms of the effect of cooling methods on crack development, it can been seen that immersing the samples in water, spraying water for 20 minutes, and using a CO_2 fire extinguisher for 20 seconds cause more severe cracking than the other cooling methods. Natural cooling, spraying water for 5 minutes, and using a CO_2 fire extinguisher for 5 seconds cause less severe cracking. Cracks developed in the recycled glass concrete specimens are less severe than those in plain concrete for the same temperature exposure and same cooling regime.

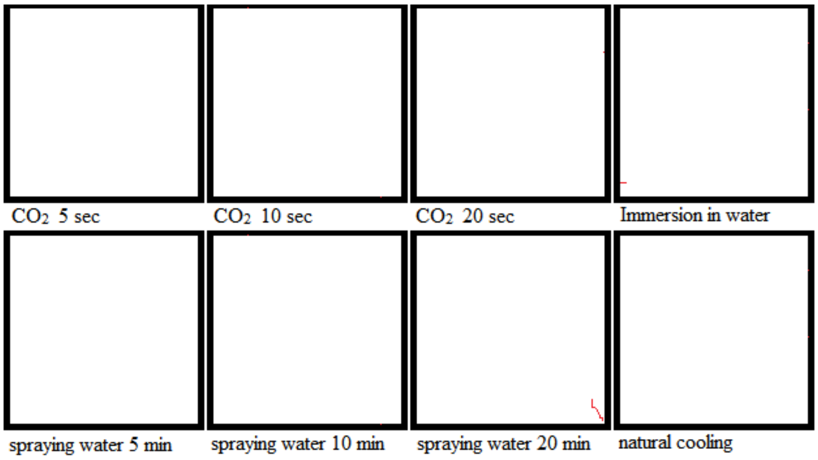

Figure 9(a). Retouched images of cracks developed at the surface of plain concrete specimens at 200 °C.

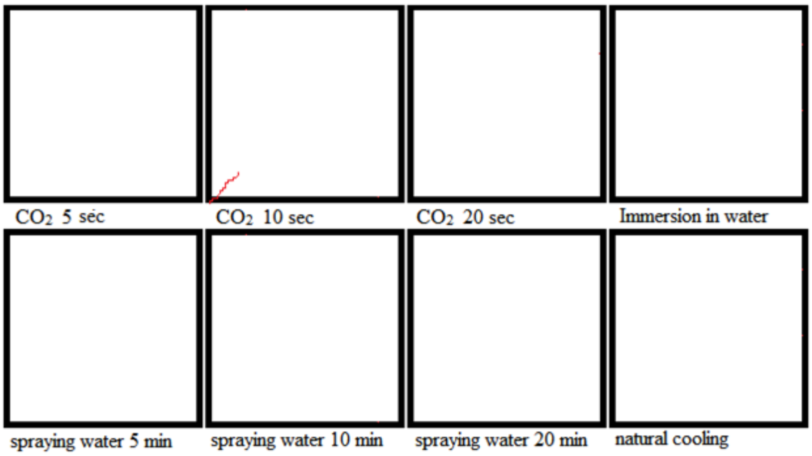

Figure 9(b). Retouched images of cracks developed at the surface of recycled glass concrete specimens at 200 °C.

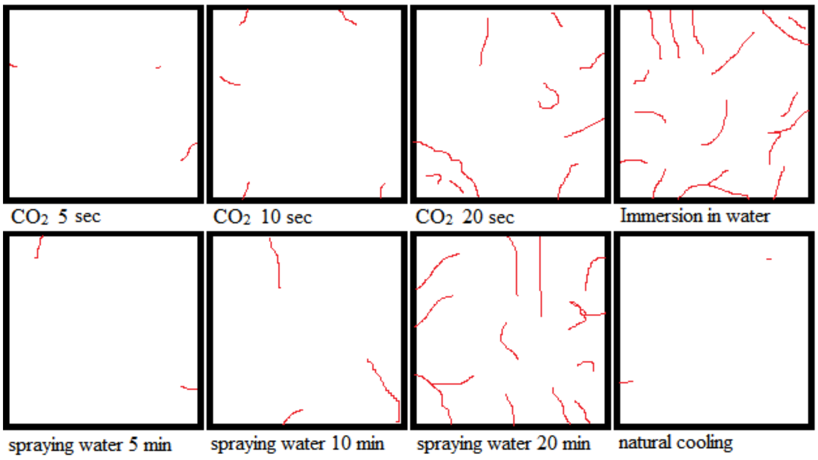

Figure 10(a). Retouched images of cracks developed at the surface of plain concrete specimens at 400 °C.

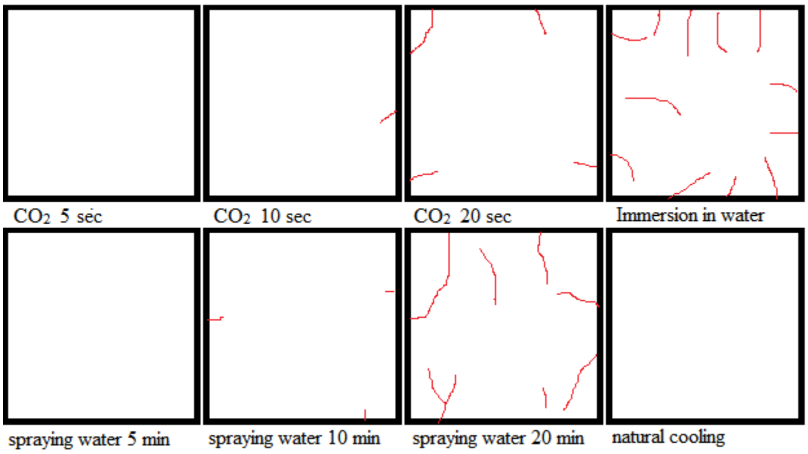

Figure 10(b). Retouched images of cracks developed at the surface of recycled glass concrete specimens at 400 °C.

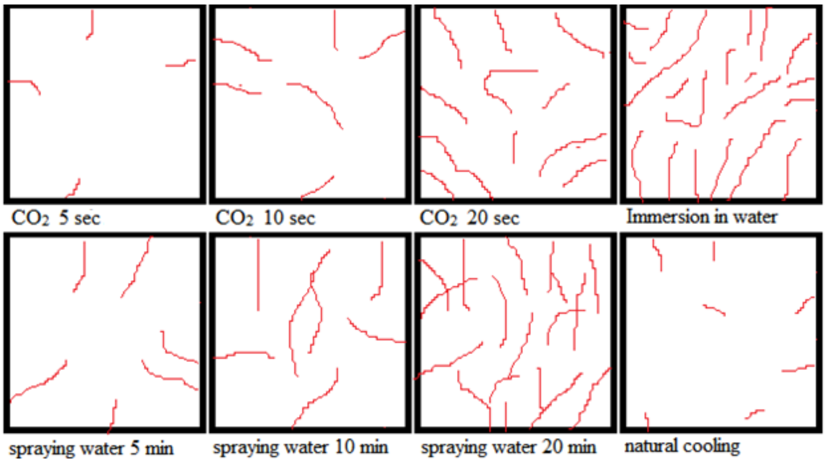

Figure 11(a). Retouched images of cracks developed at the surface of plain concrete specimens at 600 °C.

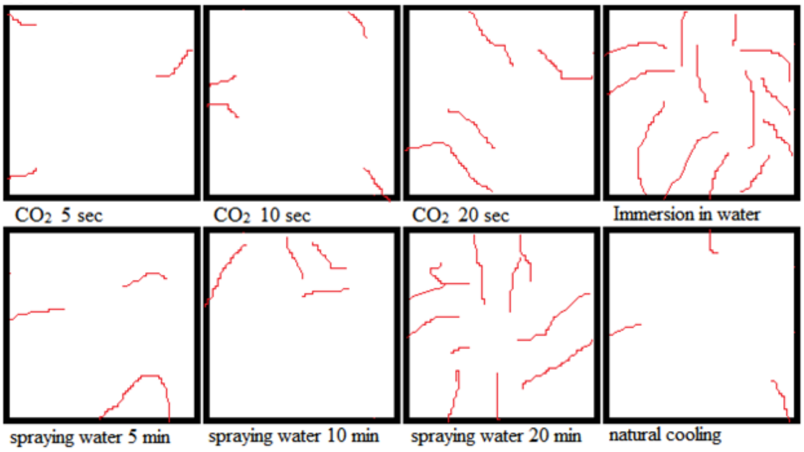

Figure 11(b). Retouched images of cracks developed at the surface of recycled glass concrete specimens at 600 °C.

3.5. Temperature profile over time

The temperature profile at the surface and at the centroid of the plain concrete specimen and recycled glass concrete are shown in Figures 12 and 13, respectively. It can be seen that the temperature rises more slowly at the surface and centroid of the recycled glass concrete specimens than plain concrete. This is because glass as aggregate exhibits better temperature stability, owing to a lower specific heat than sand and due to the pozzolanic activity of glass. In addition, the fine recycled glass concrete mixes have lower thermal conductivity coefficients when compared to normal concrete. The lower thermal conductivity of recycled aggregate concrete is due to the lower density and thermal conductivity of these aggregates.

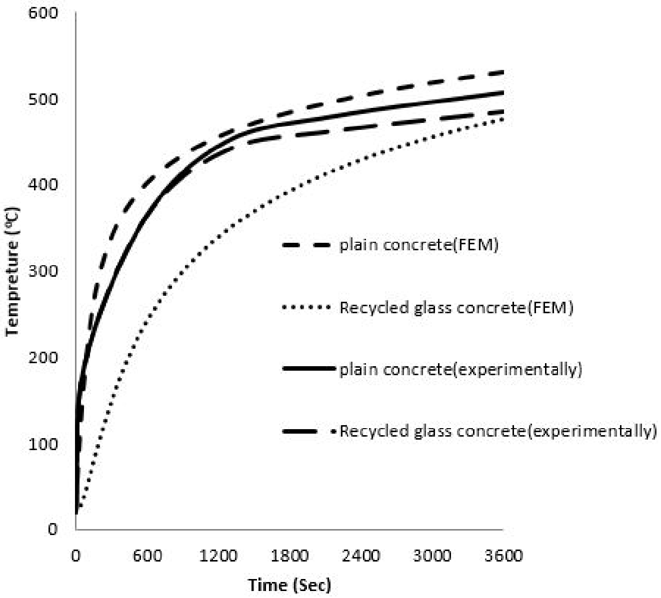

Figure 12. Temperature profiles over time at the specimen surface.

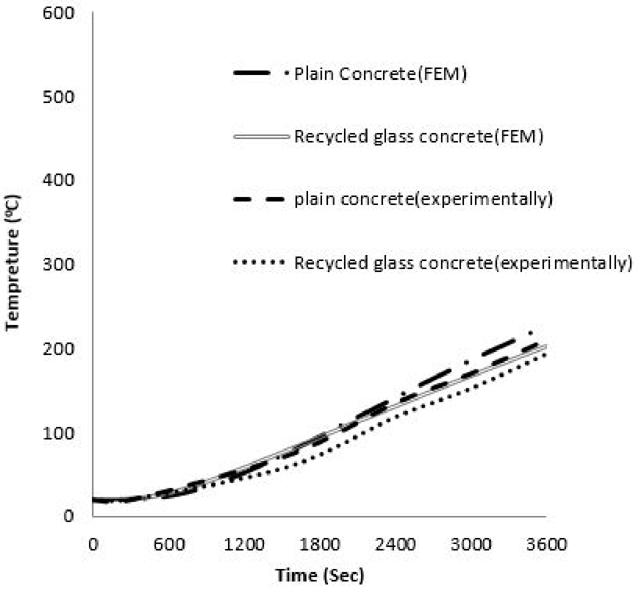

Figure 13. Temperatures profiles over time at the specimen centroid.

The maximum temperatures developed at the surface and centroid of plain concrete and recycled glass concrete after one hour were 515 °C, 226 °C, and 476 °C, 202 °C, respectively. The FE model predicted temperatures of 507 °C, 210 °C and 485 °C, 193 °C. The FEM curve and the experimental results for the two types of concrete generally agree.

4. Conclusions

This study was conducted in order to investigate the effectiveness of recycled glass as a partial replacement for fine aggregate on enhancing the resistance of concrete to thermal shock, as well as its effect on the thermal conductivity of concrete. To achieve this, a series of cubes and cylinders were cast and cured and exposed to high temperatures in an electric furnace, 150 °C, 200 °C, 400 °C, and 600 °C. The specimens remain in the furnace at the target temperature for two hours. After exposure to high temperatures, the specimens were subjected to various cooling regimes: CO_2 fire extinguishers, water spraying, water quenching, and natural cooling in room temperature, which is the control specimen. For each cooling method, six cubes were tested for compressive strength - three normal concrete and three recycled glass concrete. Six cylinders (three of normal concrete and three of recycled glass concrete) were tested for tensile splitting strength. In addition, the effect of using recycled glass as a partial replacement for fine aggregate on the maximum temperature developed at different locations inside a cube specimen heated in an electric furnace for one hour at 600 °C was investigated. The following conclusions are drawn based on the test results obtained:

1. The optimum replacement percentage of fine aggregate with crushed recycled glass aggregate was determined to be 25 %. For proportions exceeding 25 %, recycled glass negatively impacts compressive strength development.

2. The residual compressive strength increases with increasing temperature, up to 150 °C for all cooling regimes. Above this temperature, there was a reduction in strength and the effect of thermal shock becomes clear. The fast cooling methods lead to more damage in concrete specimens than the slow cooling method (natural cooling), with the highest reduction in residual strength being caused by CO_2 fire extinguishers.

3. In terms of cracking, the severity of cracks at 200 °C for all cooling regimes is very low, but worsens with increased temperature, with maximum severity occurring at 600 °C. The highest severity of cracking is caused by immersing samples in water, spraying water for 20 minutes, and using a CO_2 fire extinguisher for 20 seconds, while specimens subjected to natural cooling, spraying water for 5 minutes, and a CO_2 fire extinguisher for 5 seconds experience the lowest severity.

4. A finite element model was created with ABAQUS software to study the heat transfer inside the concrete specimens. This model was validated with the experimental results. The FEM results show reasonable agreement with the experimental values. The temperature developed on the recycled glass concrete specimens is slightly less than that on plain concrete. Recycled glass as a replacement for 25 % of fine aggregate in the concrete mix showed good results by reducing the maximum temperature developed after one hour by 4.3 % and 22.2 % at the surface and the centroid of the specimens, respectively.

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References

1. Taha, B., Nounu, G. Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. Constr. Build. Mater. 2008. 22. Pp. 713–720.
2. Carpenter, A., Cramer, S. Mitigation of Alkali-Silica Reaction in Pavement Patch Concrete That Incorporates Highly Reactive Fine Aggregate. Transp. Res. Rec. J. Transp. Res. 1999. Board 1668. Pp. 60–67. DOI: 10.3141/1668-09.
3. Kennedy, R.P. A review of procedures for the analysis and design of concrete structures to resist missile impact effects. Nucl. Eng. 1976. 37. Pp. 183–203.
4. Nilson, A.H., Darwin, D., Dolan, C.W. Design of concrete structures. 2010.
5. BS EN, 2004. Eurocode 2 : Design of concrete structures, British Standards Institution.
6. International Code Council, 2011. 2012 International Building Code, 2012th ed. ICC, Country Club Hills, IL
7. Japan Society of Civil Engineers. Standard Specifications for Concrete Structures, Concrete. 2007.
8. Gu, X., Jin, X., Zhou, Y. Basic Principles of Concrete Structures. 2016. Springer Berlin Heidelberg, Berlin, Heidelberg.
9. Mehta, P.K., Monteiro, P.J.M. Concrete: microstructure, properties, and materials, Concrete. 2006.
10. Chan, Y.N., Luo, X., Sun, W. Compressive strength and pore structure of high-performance concrete after exposure to high temperature up to 800 °C. Cem. Concr. Res. 2000. 30. Pp. 247–251.
11. Hertz, K.D. Limits of spalling of fire-exposed concrete. Fire Saf. J. 2003. 38. Pp. 103–116.
12. Netinger, I., Kesegic, I., Guljas, I. The effect of high temperatures on the mechanical properties of concrete made with different types of aggregates. Fire Saf. J. 2011. 46. Pp. 425–430.
13. Dinesh, S., Preetha, R., Subhi. M. Investigation on recycled glass as a replacement for fine aggregate in concrete. Int. J. Eng. Res. Mod. Educ. 2017. Pp. 105–108. DOI: 10.5281/zenodo.570519.
14. Anwar, A. The Influence of Waste Glass Powder as a Pozzolanic Material in Concrete. Int. J. Civ. Eng. Technol. 2016. 7. Pp. 131–148. ISSN: 2319-4847.
15. Xiao, J., Li, J., Zhang, C. Mechanical properties of recycled aggregate concrete under uniaxial loading. Cem. Concr. Res. 2005. 35. Pp. 1187–1194.
16. Teranishi, K., Dosho, Y., Narikawa, M., Kikuchi, M. Application on recycled aggregate concrete for structural concrete, Part 3 – Production of recycled aggregate by real-scale plant and quality of recycled aggregate concrete, Sustainable Construction: Use of Recycled Concrete Aggregate. London, UK. 1998.
17. Terro, M.J. Properties of concrete made with recycled crushed glass at elevated temperatures. Build. Environ. 2006. 41. Pp. 633–639.
18. Shi, C., Zheng, K. A review on the use of waste glasses in the production of cement and concrete. Resour. Conserv. Recycl. 2007. 52. Pp. 234–247.
19. Georgali, B., Tsakiridis, P.E. Microstructure of fire-damaged concrete. A case study. Cem. Concr. Compos. 2005. 27. Pp. 255–259.
20. Peng, G.-F., Bian, S.-H., Guo, Z.-Q., Zhao, J., Peng, X.-L., Jiang, Y.-C. Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures. Constr. Build. Mater. 2008. 22. Pp. 948–955.
21. Bažant, Z.P., Kaplan, M.F., Bazant, Z.P. Concrete at High Temperatures: Material Properties and Mathematical Models. 1996. Addison-Wesley, London.
22. Phan, L.T. Fire performance of high-strength concrete: State-of-the Art-Report. Gaitherburg. 1996. P. 105. Gaithersburg, MD.
23. Yu, J., Weng, W., Yu, K. Effect of Different Cooling Regimes on the Mechanical Properties of Cementitious Composites Subjected to High Temperatures. Sci. World J. 2014. Pp. 1–7.
24. Sidhu, S.H., Kumar, R.A., S.H., S., Sidhu, R.U. Effect of Thermal Shocks on Compressive Strength of Heated Concrete Cooled In Air. Int. J. Eng. Technol. Manag. Appl. Sci. 2014. 2. Pp. 37–40.
25. Luo, X., Sun, W., Chan, S.Y.N. Effect of heating and cooling regimes on residual strength and microstructure of normal strength and high-performance concrete. Cem. Concr. Res. 2000. 30. Pp. 379–383.

26. Balendran, R.V., Tang, W.C., Nadeem, A., Kamineni, P.R., Maqsood, T. Effect of cooling methods on residual compressive strength of high performance concrete (HPC) subjected to elevated temperatures. In: 28th Conference on Our World in Concrete & Structures: 28–29. Singapore, 2003. Pp. 23–24.
27. Rajabipour, F., Maraghechi, H. and Fischer Investigating the Alkali-Silica Reaction of Recycled Glass Aggregates in Concrete Materials. Journal of Materials in Civil Engineering. 2010. 22(12). Pp. 1201–1208.
28. Ali F., Nadjai A., Abu-tair A. Experimental and Numerical Study on Performance of Concrete Slabs Subjected to Severe Fire, Fire Saf. Sci. 2008. 9. Pp. 1255–1266. DOI: 10.3801/IAFSS.FSS.9-1255.
29. Adaway, M., Wang, Y. Recycled glass as a partial replacement for fine aggregate in structural concrete -Effects on compressive strength. Electron. J. Struct. Eng. 2015. 14. Pp. 116–122. ISSN: 1443-9255.
30. Nadeem, A., Memon, S.A., Lo, T.Y. The performance of Fly ash and Metakaolin concrete at elevated temperatures. Constr. Build. Mater. 2014. 62. Pp. 67–76.

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