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Review on Concrete Subjected to Elevated Temperature

Maya T M, PG Student
Department of Civil Engg,
M A College of Engg.
Kothamangalam
M.G University
Kerala
India

Nivin Philip, Asst Professor
Department of Civil Engg,
M A College of Engg.
Kothamangalam
M.G University
Kerala
India

Dr. Job Thomas, Asst Professor
Department of Civil Engg,
School of Engg.
Thrikkakkara
CUSAT
Kerala
India

Abstract: The main objective of this paper is to assess the effect of elevated temperatures on concrete. Studies are mainly based upon the comparison of the mechanical properties of concrete subjected to temperature and tested at ambient temperature. Type of concrete, replacement of aggregates and cement, duration of curing, maximum temperature, time of exposure to temperature, type of cooling are the major factors which influenced the properties of concrete after temperature exposure. In each study, the test results showed that there was a significant loss of weight and mechanical properties after temperature exposure. Also relative strength of concrete decreased as the exposure temperature increased. The replacement of aggregates with certain waste materials was justified, not only in terms of increased fire resistance than normal aggregate, but also in terms of responsible waste disposal.

Keywords: Aggregates; Elevated; Mechanical properties; Recycling; Replacement; Temperature

I. Introduction

During a fire, concrete material in structures is likely exposed to high temperatures. During these exposures the mechanical properties such as strength, modulus of elasticity and volume stability of concrete are significantly reduced resulting in undesirable structural failures. Therefore, the properties of concrete retained after a fire are of great importance the load carrying capacity and the serviceability of buildings. The chemical composition and physical structure of the concrete change considerably when exposed to high temperature.

Concrete is a composite material produced from aggregates, cement, and water. The thermal conductivity of concrete must be considerably influenced by the thermal conductivity of aggregates as aggregates represent a considerable proportion of volume in the concrete. With the use of different aggregates, the strength degradations of concretes are not the same under high temperatures which is due to different mineral structure of the aggregates. There is accumulation of water occurring at the paste-aggregate interface which creates porous zone in which cracking will be initiated and thus aggregate-matrix interface can therefore be considered as the "weak link" of ordinary concrete. And hence the selection of the type of the aggregate for the concrete also plays an important role and the aggregate should be able to sustain high temperature without much affecting the mechanical properties of concrete.

Also recycling construction material plays an important role to preserve natural resources. Sustainable reuse of waste materials reduces the environmental impact by recycling materials generated during building construction, demolition and renovation. The construction field is in real need for the alternatives for the concrete due to depleting nature of natural resources. The use of recycle aggregates and solid wastes from construction and demolition waste is showing a prospective application in construction and as alternative to primary and natural aggregate.

II. Research Development

The first recorded mixing of crushed brick and tile with Portland cement was in Germany from 1860 for the manufacture of concrete products. Systematic investigations have been carried out since 1928 on the effect of the cement content, water content, and grading of crushed brick and tile aggregates. Crushed brick and tile aggregate concretes have relatively lower strength at early ages than normal aggregate concrete. The compressive strength of crushed brick and tile aggregate concretes are approximately 7% lower compared to concrete made with natural aggregates. But as roof tiles are made at high temperatures, it was an assumption

that it may result in good fire protection and usually these roof tile aggregate concretes are used in casing of steel structures as a shield.

Husem (2006) examined compressive and flexural strengths of ordinary and high-performance micro-concrete which were exposed to high temperatures and cooled in air and water. For that according to the mix proportioning, they casted the specimens and after 28 days specimens were tested. Tests were performed at five different temperatures, 200, 400, 600, 800 and 1000 °C. They were removed 1 h after the desired temperature was reached. For each mix 36 samples were casted, in that 24 were subjected to temperature, in which 12 were cooled in water and others at room temperature, next 12 were tested at 23 °C. Experimental results indicated that concrete strength decreases with increasing temperature, and the decrease in the strength of ordinary concrete is more than that in high-performance concrete. Studies showed that experimental samples have been damaged to a great extent and they have lost their compressive strengths if high-performance concrete was cooled in water after being exposed to the temperature of 800 °C, and ordinary concrete was cooled in water after being exposed to the temperature of 600°C.

Terro (2006) studied about the effect of replacement of fine and coarse aggregates with recycled glass on the fresh and hardened properties of Portland cement concrete at ambient and elevated temperatures was studied. Percentages of replacement of 0–100% of aggregates with fine waste glass, coarse waste glass, and fine and coarse waste glass were considered. Soda-lime glass used for bottles was washed and crushed to fine and coarse aggregate sizes for use in the concrete mixes. Accordingly specimens were casted and cured for 28 days. Author heated the samples for 7-10 h in a furnace which can reach up to 1000 °C and left for cooling 15 h in furnace and 7 h in air before testing. Results showed that Concretes made with 10% aggregates replacement with waste glass possesses higher compressive strength than normal concrete at temperatures above 150 °C. The ratio of strength at elevated temperatures to that at ambient temperature for concretes made with waste glass was higher than that of the normal concrete at temperatures above 150 °C. In general, concretes made with 10% aggregates replacement with waste glass had better properties in the fresh and hardened states at ambient and high temperatures than those with larger replacement percentages.

Arioz (2007) investigated the effect of elevated temperatures on the physical and mechanical properties of concrete mixtures produced by different water/cement ratios and different types of aggregates. Four different concrete mixtures were prepared by using ordinary Portland cement, crushed limestone aggregate and siliceous river gravel. Casted cubes were cured for 28 days, air-dried for 6 days and oven-dried for 24 h. Specimens were subjected to elevated temperatures 200, 400, 600, 800, 1000 and 1200 °C for 2h and they were stored at room temperature for 2h until testing. From visual observation, it was noticed that the surface cracks became visible when temperature reached 600 °C. Cracks were pronounced at 800 °C and increased extremely at 1000°C. At 1200 °C specimens were completely damaged also weight of concrete significantly reduced as temperature increased and this reduction was gradual upto 800 °C but sharp reduction was observed beyond 800 °C. Relative strength of concrete reduced with increased temperature exposure and this effect was more pronounced for concrete mixes produced by river gravel aggregates and this was attributed to siliceous composition of river gravels.

Chen et al (2009) investigated the compressive and split tensile strengths of concrete cured for different periods and exposed to high temperatures. Accidental fires are known to occur during construction, causing concrete to be exposed to high temperatures when it is at an early stage. After casting, they were tested after different curing ages, 1, 3, 7, 14 and 28 days. The exposure temperatures were 200, 400, 600, 800 and 1000°C and these temperatures were maintained for 3h. The specimens were cooled both by air cooling and water spray cooling and cooling period varies between 20 min and 3h. After cooling the specimens were kept for another 28 days before the tests were conducted. Author observed that, for early-age concrete, 80–90% of its initial strength was recovered after exposure to high temperatures up to 800 °C also the recovered strength was higher than control specimens when temperature was only 200 or 400 °C. The order of the recovered strengths of the high-temperature exposed specimens was 3days > 7 days > 14days > 1 day. But while temperature reached than 1000 °C, the recovered strength of early age concrete was lower than concrete aged for 28 days. Compared with the compressive strengths a greater decrease was shown in the splitting tensile strength due to the more destructive microcrack and brittle microstructure formation that resulted from the tensile stress. For temperature being below 800 °C, for early age concrete, the recovered strength of specimens cooled by sprayed water was higher than that of specimens cooled by air, while for concrete specimens aged for 28 days, the converse was true. In the case of the maximum temperature being above 1000 °C, the recovered strength of all specimens cooled by air was higher than that of water-sprayed specimens.

Culfik and Ozturan (2010) investigated the effect of high temperatures, up to 250 °C, on mechanical properties of normal and high strength concretes with and without silica fume. They determined residual compressive and splitting tensile strength and static modulus of elasticity of the specimens by heating up to elevated temperatures (50, 100, 150, 200, 250 °C) without loading. For normal strength concrete compressive

and splitting tensile strengths and static modulus of elasticity reduction started at 100 °C but by using silica fume heat resistance of normal strength concrete was increased. And also the residual strength properties of high strength concretes were higher in comparison with normal strength concretes for all heating cycles, also high strength concrete specimens with silica fume showed no decrease in residual compressive and splitting tensile strengths for any temperature regime.

Demirel and Kelestemur (2010) investigated the effect of elevated temperature on the mechanical and physical properties of concrete specimens obtained by substituting cement with finely ground pumice at proportions of 5%, 10%, 15% and 20% by weight. The specimens were heated in an electric furnace up to 400, 600 and 800°C and kept at these temperatures for one hour. The unit weight of the concrete decreased when it was exposed to elevated temperature. This finding was due to the release of bound water from the cement paste and the occurrence of air voids in the concrete. The highest weight loss occurred in specimens with finely ground pumice and silica fume that were subjected to 800°C. The reduction in the compressive strength of concrete was significantly larger for samples exposed to temperatures higher than 600 °C. They concluded that this result was due to the lost water of crystallization resulting in a reduction of the $\text{Ca}(\text{OH})_2$ content, in addition to the changes in the morphology and the formation of microcracks.

Netinger et al (2011) studied about the effect of high temperatures on the mechanical properties of concrete made with different types of aggregates. They conducted the study on the presumption that all materials formed at high temperatures and usable as aggregates can improve the fire resistance of concrete. And materials used as fire resistant aggregates include diabase, steel slag, crushed bricks and crushed tiles. For the experiment all the mixtures were prepared with same water cement ratio 0.5 and the casted specimens were demoulded after 24hrs. The specimens were subjected to temperatures (200, 400, 600, 800 and 1000 °C) for 1.5h after 28 days curing. In this research the authors found that diabase ensures good mechanical properties of concrete at room temperature and better mechanical properties at temperatures up to 600 °C in comparison with the river aggregate and dolomite mixtures. And concrete made with brick industry waste showed satisfactory mechanical properties at room temperature, better fire resistance than the one made with river aggregates, and only slightly lower fire resistance than the one made with dolomite. Steel slag concrete shows similar fire resistance to the river aggregate mixture upto 400 °C, and much improved fire resistance at high temperature ranges. The fire resistance of these mixtures was lower than the fire resistance of the dolomite mixtures up to 800 °C, above which it increases considerably. According to these observations it can be concluded that the replacement of a river aggregate in concrete with steel and brick industry waste material can not only be justified in terms of fire resistance, but also in terms of waste management.

Vieira et al (2011) investigated the residual mechanical performance (compressive and splitting tensile strengths and elasticity modulus) of concrete made with recycled concrete coarse aggregates after exposure to high temperatures. For this four concrete mixes were produced: a conventional reference concrete and three concrete mixes with replacement rates of 20%, 50% and 100% of natural coarse aggregates by recycled concrete coarse aggregates. They casted specimens and cured for 28 days and the specimens were moved to a dry chamber for 21days. Specimens from all types of concrete, besides being tested at ambient temperature (about 20 °C), were subjected to the following three temperatures for a period of 1 h: 400 °C, 600 °C and 800 °C at age 49 days and, after cooling down to ambient temperature, 4 days later they were finally subjected to mechanical testing. The results showed that in spite of higher porosity and the different thermal properties of the matrix-aggregate interface of recycled concrete coarse aggregate when compared to reference concrete, the incorporation recycled aggregates does not influence the thermal response of the material. Accordingly, in terms of post-fire residual mechanical properties there are no limitations to the structural use of recycled aggregate concrete when compared with conventional concrete.

Xing et.al (2011) conducted an experimental study on concrete composed of three different types of aggregates: semi crushed silico-calcareous, crushed calcareous and rolled siliceous. For each aggregate type, two water/cement ratios (W/C), 0.6 and 0.3 are studied. Concrete specimens were subjected to 300, 600 and 750 °C heating-cooling cycles. They found that the residual mechanical behaviour varied depending on the aggregates. The silico-calcareous concrete presents severe cracking, and significant mechanical strength loss between 300 and 600 °C. Residual compressive strength of normal concrete of silico-calcareous concrete is 3 to 5 times lower than that of normal concrete of siliceous concretes and normal concrete of calcareous concrete respectively. The thermal instability of flints contained in silico-calcareous aggregates explains the higher damage of silico-calcareous concretes with the temperature increase. For calcareous concrete, lime coming from the decarbonation of calcite (between 600 °C and 750 °C) reacts with ambient humidity and forms Portlandite by multiplying its volume by 2.5 and leads to concrete disintegration. With a lower W/C ratio, the porosity of the paste-aggregate interface zone decreases, and bond strength between paste and aggregate was improved.

Yuksel et al (2011) examined the Influence of high temperature on the properties of concrete containing non-ground granulated blast-furnace slag (GBFS) and coal bottom ash (BA) as fine aggregate. GBFS and BA were

partially replaced with fine aggregate in different series. They casted specimens according to the mixes and cured in water for 28 days. Author's assessed losses in weights, variation of compressive strength and dynamic modulus of elasticity of concrete specimens before and after high temperature exposure. The first three specimens were exposed to high temperature; the remaining three specimens were kept in laboratory conditions. Specimens were subjected to high temperature of 800°C at the age of 90 days and they were cooled for 1 h in furnace itself, and then completely cooled down for 24 h in air.. Results showed that loss in weight due to high temperature effect was independent from the replacement ratio of GBFS or BA. Residual compressive strengths of specimens were lower than reference concrete strength for all series. BA showed better performance than GBFS as a replacement material for fine aggregate in terms of residual compressive strength. And concretes containing GBFS or BA performed similar or better properties as normal concretes with respect to investigated properties. Thus they concluded that concretes containing GBFS or BA can be used in practical field where the concrete will subject the high temperature effect.

Cakır and Hızal (2012) prepared Self consolidating lightweight concrete (SCLWC) mixtures by using two different lightweight coarse aggregates and by replacing normal weight crushed coarse limestone aggregate. All the mixtures were exposed to 300, 600 and 900 °C, respectively after being pre-dried for 24h at 105°C. Compressive strength and modulus of elasticity of the mixtures are affected from both the type of the aggregate and w/c ratio, while splitting tensile strength is mainly affected by the type of the aggregate, alone. They concluded that type and porosity of the aggregates and w/c ratio of the mixtures were the main factors that affect the porosity and thus, water absorption capacity of self-consolidating lightweight concrete. Also it was concluded that, concrete porosity adversely affects the resistance of self consolidating lightweight concretes to elevated temperatures. Even though the specimens were pre-dried at 105 °C for 24h before the exposure to elevated temperature, the pores in hardened concrete still acting as water reservoirs during exposure was attributed to be the main reason for exposure cracks.

Mathew and Paul (2012) conducted study on performance of laterized self compacting concrete under elevated temperatures. They evaluated mechanical properties such as compressive and splitting tensile strengths and elasticity modulus after fire. After the casting the specimens were kept in curing tank for 27 days and kept at room temperature for 24 h. On 28th day they were heated to temperature levels (200°C, 400 °C and 600°C). after heating, one set of specimens were allowed to cool to room temperature by air and another set by sprinkling water on its surface immediately after removing from the furnace. The entire specimens were allowed to cool for 24 h and tested on 29th day of casting. The compressive strength of laterized self compacting concrete reduced with increase in temperature and showed comparatively less strength reduction against self compacting concrete and air cooled specimens showed slightly higher strength than water cooled. Combined effect of both type of aggregate and fly ash content prevented the explosive spalling up to a temperature 800 °C. They concluded that laterized self compacting concrete could be considered as substitute fire protection material for conventional concrete.

Pathak and Siddique (2012) investigated the influence of fly ash as partial replacement of cement, and spent foundry sand as partial replacement of sand on the properties of SCC at different temperatures. Four mixes were prepared, accordingly the specimens were cast and left for 24 h and kept for curing. The specimens were heated to different temperatures 100, 200 and °C for 1h and cooled to room temperature. They examined mechanical properties like compressive strength test, split tensile strength and modulus of elasticity test at ages of 28, 91 and 365 days. They found that the compressive strength, splitting tensile strength and modulus of elasticity increased with a decrease in the percentage of the fly ash and the water to cementitious materials ratio. Results also showed that all the properties increased with age and with replacement of fine aggregate with spent foundry sand. There was a little improvement in compressive strength within the temperature range of 200 to 300 °C as compared to 27 to 200 °C and the slight increase in strength attributed to a modification of the bonding properties due to rehydration of the paste by the migration of water in the pores. But the rate of splitting tensile strength and modulus of elasticity loss was higher than that of the compressive strength loss at elevated temperatures and with the increase in percentage of fly ash. Porosity of the concrete specimens was increased with increase in temperature and increase in fly ash content due to the expansion of the pores diameters lead to increase in permeability.

Ergun et al (2013) assessed the effects of elevated temperatures and cement dosages on the mechanical properties of concrete. The concrete specimens were tested to failure to study the variation of the residual compressive strength, residual flexural strength and velocity of ultrasonic transmission with temperatures and cement dosages. Two concrete test series were cast and prepared, Series-I a cement dosage of 250 kg/m³ was used while for Series-II the cement dosage was set at 350 kg/m³. After casting the concrete specimens were cured in lime saturated water for 27days and the specimens were subjected to temperatures of 100, 200, 400, 600 and 800°C. After attaining the targeted temperature, it was maintained for 45 min and after which they were subjected to respective tests. The results indicated that the dehydration of CSH phase in cement paste of

concrete exposed to high temperature caused the deterioration in transition zone. Deterioration of the interface increased with the increase in the cement dosage. They concluded that, although the variation of cement dosage affects the strength and durability of concrete at ambient temperature, it does not affect the relative residual strength of concrete exposed to high temperature. The relative residual compressive and flexural strength–temperature relationships of concrete were found not to depend on the cement dosages used. The velocity of ultrasonic transmission test is found to be an effective tool to assess the degree of damage in concrete structure exposed to fire.

Karakoc (2013) studied about the residual compressive strength of concrete with expanded perlite aggregate and pumice aggregate after it was exposed to high temperature. The lightweight aggregates were first mixed, with water needed for dry surface saturated for half an hour before blending. After casting the moulds were removed after 24 h and kept for water curing for 28 days. Before testing the samples were subjected to a temperature of 700 °C for 1 h after reaching peak temperature and then the specimens were allowed to cool down by three cooling regimes. First cooling regime was furnace cooling. Second cooling regime was water cooling, i.e., the hot specimens at peak temperature was taken out of the furnace and immediately immersed in a fresh water tank. Last cooling regime was natural cooling, i.e., the hot specimens at peak temperature was taken out of the furnace and hold on laboratory conditions. The compressive strength of the concrete samples that were not exposed to high temperature and those that were subjected to high temperature were tested. Results showed that the compressive strength of concrete cooled in water cooling after being exposed to the effect of different mixture with 10%, 20% and 30% expanded perlite aggregate and pumice aggregate is higher than that cooled in natural and furnace. The compressive strength of concrete cooled in water, furnace and natural cooling decreased by an average of 78%, 81% and 83%, respectively, when compared to control samples. It was concluded that natural cooling caused only a bit more deterioration in strength than in the case of furnace cooling.

Marques et al (2013) investigates the effects of elevated temperatures on the residual mechanical performance of concrete in terms of thermal response and residual mechanical behaviour produced with recycled rubber aggregate. For the purpose, four types of concrete were produced: a reference concrete and three concrete mixes in which 5%, 10% and 15% of the total aggregate volume of natural aggregate were replaced by recycled rubber aggregate, using both fine and coarse particles. Specimens were cast and placed in a wet curing chamber after 24 h for 74 days and transferred to a dry chamber for 41 days. Specimens were exposed to heat at the age of 115 days and, 4 days later, after cooling down to ambient temperature, they were finally subjected to mechanical testing. The exposure temperatures were 400, 600 and 800 °C and the mechanical properties studied include compressive strength and split tensile strength. They obtained the results that, for exposure temperatures of 400 °C and 600 °C the loss in performance for recycled rubber aggregate concrete was roughly similar to that of normal concrete, but the recycled rubber aggregate with 15 % replacement suffered a steeper loss at 600 °C and large decline of residual strength took place at 800 °C and this is due to the decomposition of rubber aggregates at high temperatures. The loss in split tensile strength was greater in recycled aggregate concrete than in normal concrete. Despite the decrease in residual mechanical properties for recycled rubber aggregate concrete when compared to normal concrete after thermal exposure at higher temperatures (800°C), the relative reduction in performance is not relevant enough to prevent it from being used in structural applications, provided that low replacement rates are used.

Netinger (2013) investigated the use of slag as fire-resistant aggregate. Three groups of concrete mixes were prepared with the same cement content (400 kg/ m³) and water/cement ratio (0.43). Reference mixture was prepared with dolomite and other 2 mixes was prepared by slag as coarse aggregate. In one mix poly propylene fibres were included to reduce the possible slag expansion and to improve fire resistance and 20 % replacement of cement with fly ash to reduce thermal incompatibility between slag and Portland cement. Prisms were casted for testing and placed in water tank for 7 days and moved to a storage chamber for 28 days and kept in laboratory for another 28 days. After 56 days of curing the specimens were exposed to temperatures of 100, 200, 400, 600 and 800 °C for 1h. By the increase in temperature flexural strength of the specimens decreased. Reduction in compressive strength was less observable than reduction in flexural strength for all specimens. Modulus of elasticity value increased up to a temperature 100 °C after which it decreased. Weight loss was similar for all the specimens up to 100°C, due to evaporation of water. But when reached its maximum temperature (800 °C) dolomite specimen retained 78 % of initial weight and slag specimen retained 86 % while slag with fibres retained 84 % of initial weight. According to the investigation the authors concluded that the analysed slag can be considered as an aggregate for good fire resistance but it does not provide satisfactory concrete fire resistance if combined with Portland cement. This can be explained by a high coefficient of slag thermal expansion that causes the aggregate–cement paste contact to deteriorate during heating, which thus damages concrete integrity.

Table I: Details of work done by Authors

Author	Type of concrete/Replacement	Curing	Temperature	Time of exposure (h)	Type of cooling
Husem	Ordinary and High performance concrete	21 days in water rest 7 days at room temperature	200, 400, 600, 800 and 1000 °C	1	Water and air
Terro	Fine and coarse aggregates with recycled glass	28 days curing in 95 % RH	1000 °C	7-10	Left for cooling 15 h in furnace and 7 h in air before testing
Arioz	Ordinary Portland cement, crushed limestone aggregate and siliceous river gravel.	28 days, air-dried for 6 days	200, 400, 600, 800, 1000 and 1200 °C	2	Natural cooling for 2h
Chen	Normal concrete	1, 3,7,14 and 28 days	200, 400, 600, 800 and 1000°C	3	Water and air
Culfik and Ozturan	Normal and high strength concretes with and without silica fume	28	50,100,150,200 and 250 °C	3	Cooled in furnace
Demirel and Kelestemur	Substituting cement with finely ground pumice at proportions of 5%, 10%, 15% and 20% by weight	28	400, 600 and 800°C	3	
Netinger	Fire resistant aggregates include diabase, steel slag, crushed bricks and crushed tiles	28 days	200, 400, 600, 800 and 1000 °C	1.5	Natural cooling
Vieira et al	Recycled concrete coarse aggregates	28 days and moved to a dry chamber for 21days	400 °C, 600 °C and 800 °C	1	Natural cooling for 4 days
Xing et.al	Semi crushed silico-calcareous, crushed calcareous and rolled siliceous	90	150, 300, 450 600 and 750 °C	1	Natural cooling
Yuksel et al	Non-ground granulated blast-furnace slag (GBFS) and coal bottom ash (BA) as fine aggregate	Cured in water for 28 days and kept in air until 90 th day	800°C		Cooled for 1 h in furnace and cooled for 24 h in air
Cakır and Hızal	Self consolidating lightweight concrete	28 days	300, 600 and 900 °C	2	Natural cooling
Mathew and Paul	Laterized self compacting concrete	Cured in water for 27 days and kept at room temperature for 24 h.	200°C, 400 °C and 600°C	1	Water and air
Pathak and Siddique	Fly ash with cement, and spent foundry sand with sand	28, 91, and 365 days.	100, 200 and 300°C	1	Natural cooling
Ergun et al	Different cement dosages	27days	100, 200, 400, 600	45 min	Natural cooling

			and 800°C		
Karakoc	Perlite aggregate and pumice aggregate	28 days	700 °C	1	Natural, water and furnace cooling
Marques et al	Recycled rubber aggregate	74 days in wet chamber and 41 days in dry chamber	400, 600 and 800 °C		Natural cooling for 4 days
Netinger et al	Slag as fire-resistant aggregate	7 days in water tank, 28 days in storage tank	373, 473, 673, 873 and 1073 K	1	Natural cooling

III. Conclusions

In this paper a survey on how high temperatures effects the concrete strength is carried out. Most of the authors concluded that due to temperature exposure there will be a drastic reduction in the mechanical properties of concrete. The study about the influence of aggregates on thermal behavior showed that permeability of aggregates plays an important role in the thermal stability. Also the residual mechanical properties of concrete after exposure to temperature varied according to the type of aggregates. When normal aggregates are replaced by fire resistant aggregates the concrete was not only justified in terms of fire resistance but also in terms of waste management.

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