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POST-FIRE REDUCTION OF CONCRETE'S MECHANICAL PROPERTIES AND ITS IMPACT ON RESIDUAL LOAD CAPACITY

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Abstract. *This paper investigates the reduction of mechanical properties of four different light-weight concrete mixes containing expanded clay aggregate in a short time period after exposure to high temperature regime. The research has shown that compressive strength exhibits additional reduction up to 10-20%, 96 hours after being cooled down to ambient temperature. A numerical example of simply supported concrete column exposed to standard fire from four sides is given, illustrating the effects of post-fire strength reduction on residual load capacity. The results obtained indicate that the effect of short-term reduction of the compressive strength of concrete in real structures damaged by fire could have a significant effect on the post-fire load bearing capacity of structures and should be accounted for in the engineering building codes.*

1 INTRODUCTION

The post-fire reduction phenomenon of the compressive strength of concrete has already been noted by researchers [1-3]. Their results indicate the compressive strength tends to reduce and partially recover over a time period of 1-2.5 years. The reported researches regarding the post-fire behaviour have been conducted mainly for normal-strength (NSC), high-strength (HSC) and self-compacting concrete (SCC). However, the consequences of post-fire reduction of the compressive strength on the load bearing capacity have not yet been understood in entirety, nor has the influence of moisture conditions on the reduction process been investigated enough.

Post-fire reduction of the mechanical properties of concrete is governed by chemical and physical processes occurring in concrete after cooling. The most important ones are formation of calcium hydroxide and rehydration of cement paste [1]. The level of thermal damage (temperature level) and the moisture conditions following the cooling process represent the two most important factors which seem to affect the level of post-fire reduction of mechanical properties. Both processes generally govern the reduction of the compressive strength of concrete, whose strength minimum is usually reached within the time period of 1-6 months. After that, depending on the type of concrete, a partial or full compressive strength recovery is possible.

Regardless of the recovery process, the mechanical properties of concrete tend to reduce over a long time period. This reduction could have a substantial impact on the residual load capacity of concrete if the post-fire reduction level proves to be significant. It is noteworthy that the strength reduction of concrete after fire exposure is not taken into account explicitly in common engineering building codes [4,5] since it is generally considered that no significant strength reduction may occur in concrete after its exposure to fire.

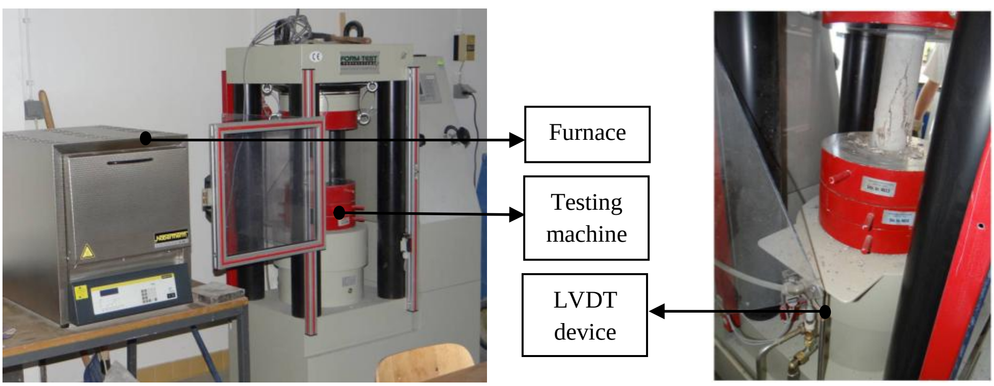
Most of the ongoing research concerned with the reduction of the mechanical properties of concrete has focused on concrete's hot and residual properties, which generally exhibit higher values than the post-fire properties. On the other hand, taking post-fire property values into consideration can be deemed as a more realistic approach in determining the compressive strength of fire exposed concrete. The results of a previously conducted research point out that the short-term strength reduction of HSC's compressive strength can be substantial [6] and that it should be accounted for in the analysis of the assessment of post-fire resistance of concrete structures. The objective of the proposed study is to further investigate the level of strength reduction in short time intervals (48 and 96 hours after exposure to high temperature) of four different LWC mixes in order to obtain further insight into post-fire behaviour of LWC and its level of post-fire reduction.

2 EXPERIMENTAL PROGRAMME

2.1 Equipment and specimen description

Determination of post-fire properties was conducted on cylindrical specimens with a Ø of 75/225 mm. Experimental programme included determination of the following concrete properties: compressive strength, stress-strain curves and dynamic modulus of elasticity.

Specimen dimensions were adopted according to the recommendations of the RILEM committee for compressive strength testing [7]. A 3000 kN FORM TEST testing machine was used to conduct the compressive test. To determine the stress-strain curve of a specimen, an LVDT recording the displacement of platens (Figure 1b) was mounted on the testing machine; while the increase of the pressure inside the machine was monitored by a pressure transducer SENSE STK131. Both devices were connected to National Instruments data acquisition card USB 6255. Heating of the specimens was conducted using programmable NABERTHERM L9/11/P330 furnace. A general view of the furnace and the testing machine is presented in Figure 1a.



(a) General view of the experimental setup (b) Rear view of the testing machine

Figure 1. Experimental setup – test machine and the furnace.

Temperature increase in the specimens during the heating stage was recorded with one NiCr thermocouple placed in the middle of the specimen during moulding. The thermocouple was connected into NI data acquisition card USB 6255.

2.2 Mix proportions

This paper accounts for a testing of 4 different mix designs of LWC in fresh and hardened states. The intention of the research was to test the amount of binder and type of admixture as variables influencing the reduction of the mechanical properties of light-weight concrete. In all of the mixes same cement, superplasticizer and aggregate were used, whereas admixtures were varied. The cement used was Portland cement of CEM I 42.5 R type that complies with the requirements of EN 197-1, having a specific weight of 3.14 kg/dm^3. The superplasticizer was the liquid PCE (poly-carboxylic acid-ether) with a specific weight of 1.06 kg/dm^3. A very light granulated product manufactured by expansion of natural clay was used as the light-weight aggregate. Concrete mixes contained two fractions, the fine light-weight aggregate of 0-2 mm and the coarse light-weight aggregate of 4-8 mm. Gradation of aggregate in the mixes was adjusted by using 70 % of coarse and 30 % of fine light-weight aggregate. Mixes LWC1, LWC2 and LWC4 were designed with the same amount of binder of 470 kg/m^3. LWC1 was prepared only with cement, LWC2 with cement and silica fume and LWC4 with cement and metakaolin. Characteristics of admixtures are given in Table 1.

Table 1. Admixtures' characteristics

Type of admixtures	Specific area according to Blaine (cm^2/g)	Specific weight (g/cm^3)
silica fume	> 15000	2.3
metakaolin	ca 24000	2.6

The LWC3 mix was prepared with the least amount of cement and the highest water-cement ratio. Mix proportions prepared in this study are given in Table 2.

Table 2. Mix proportions of LWC.

Concrete compounds (kg)	LWC1	LWC2	LWC3	LWC4
cement	470	420	350	420
w/c	0.40	0.42	0.50	0.45
water	188	177	175	190
silica fume	-	-	-	50
metakaolin	-	50	-	-
superplasticizer	4.7	4.7	3.5	4.7
FLA 0-2 mm	321	302	341	301
CLA 4-8 mm	750	727	819	723

The test results of fresh concrete mixes are given in Table 3. Slump, air-content and unit weight of fresh concrete mixes were determined in accordance with EN 12350-2, EN 12350-7 and EN 12350-6, respectively.

Table 3. Test results of fresh concrete mixes

Mix	Slump (mm)	Air (%)	Unit weight (kg/m^3)
LWC1	245	2.7	1915.2
LWC2	250	4.0	1859.0
LWC3	35	4.0	1841.4
LWC4	185	6.0	1810.9

2.3 Curing and storage conditions

Curing and storage conditions prior to heating were adopted from RILEM recommendations [6]. The specimens were kept in a mould for one day and moved afterwards into a curing room with a temperature of 20±3°C and a relative humidity of 95% for a period of 6 days. Following that, the specimens were taken into a chamber with an air temperature of 20±3°C and a relative humidity of 50% until testing. Testing programme was initiated when the specimens were three months of age. Prior to the heating cycle, the specimens were kept at a temperature of 100±5°C in a drying oven over a period of 24 hours so as to extract evaporable moisture content.

2.4 Testing procedure

Mechanical properties were determined by heating the specimens up to 200°, 400° and 600°C. They were calculated as the mean value of the results determined from the three tested specimens. Heating cycle consisted of heating the specimens with heating rates between 1-2.5°C/min up to the target temperatures. After reaching a target temperature, the specimens were kept at it for 2.5 hours. Subsequently, the specimens were cooled down slowly to ambient temperature. Some were tested immediately after cooling to ambient temperature (initial cooling).

In order to investigate a further reduction of concrete's strength, specimens were further tested 48 and 96 hours after the initial cooling. The specimens tested 48 and 96 hours after cooling were stored in laboratory conditions (temperature of 20±3°C and relative humidity 30%). Compressive test was conducted by loading the specimen with a stress rate of 0.5 MPa/s.

3 RESULTS

3.1 Post-fire reduction of compressive strength

In the following section a selection of the results of post-fire reduction are shown. Table 4. presents the results of the compressive strength of the four mixes at ambient temperature.

Table 4. Compressive strength at ambient temperature.

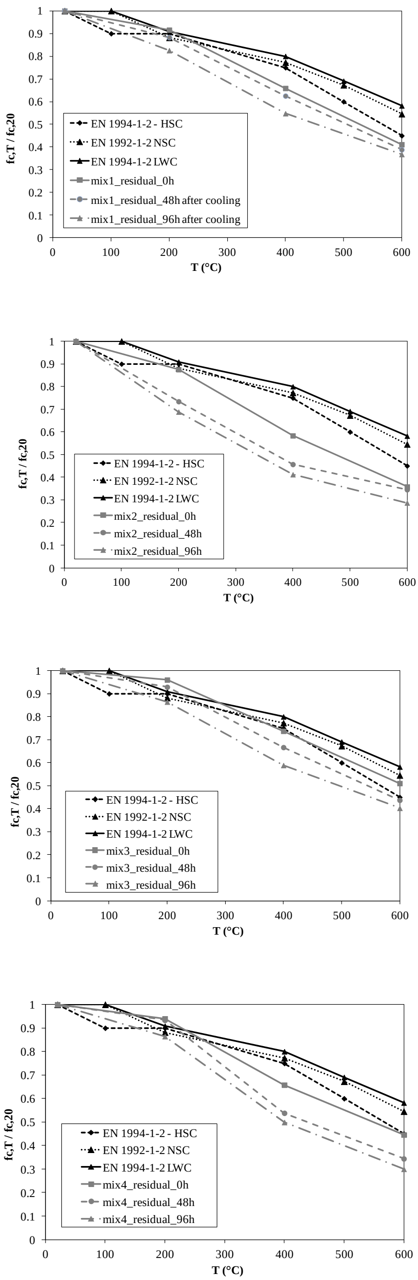
Compressive strength (3 months)	$f_{c,20}$ (MPa) LWC1	$f_{c,20}$ (MPa) LWC2	$f_{c,20}$ (MPa) LWC3	$f_{c,20}$ (MPa) LWC4
Specimen 1	52.9	54.4	53.4	55.7
Specimen 2	48.2	51.5	52.6	55.1
Specimen 3	49.5	53.9	54.3	53.9
Average	50.2	53.2	53.5	54.9
St. dev.	2.4	1.6	0.9	0.9

Table 5. presents the results of the post-fire reduction of compressive strength after exposing the specimens to a temperature of 400°C for all four mixes.

Table 5. Reduction of compressive strength after initial cooling. – 400°C

Test time after cooling (h)	$f_{c,400}/f_{c,20}$ LWC1	$f_{c,400}/f_{c,20}$ LWC2	$f_{c,400}/f_{c,20}$ LWC3	$f_{c,400}/f_{c,20}$ LWC4
0	0.66	0.58	0.74	0.66
48	0.63	0.46	0.67	0.54
96	0.55	0.41	0.59	0.50

Figure 2. presents a reduction of compressive strength of the mixes immediately after cooling and 48-96 hours after cooling. The results have been compared with the reduction factors taken from Eurocode 2 and Eurocode 4 for high-strength concrete, normal-weight concrete and light-weight concrete. The reduction factors from Eurocodes have been scaled by 10% because the original reduction values from Eurocodes are given for hot strength and are generally higher if compared to the initial residual strength.



(a) LWC1

(b) LWC2

(c) LWC3

(d) LWC4

Figure 2. Study results – post-fire reduction of compressive strength.

Figure 3 presents the mass change of specimens taken from LWC mix3 proportions in the period up to 96 hours after cooling for three temperature levels.

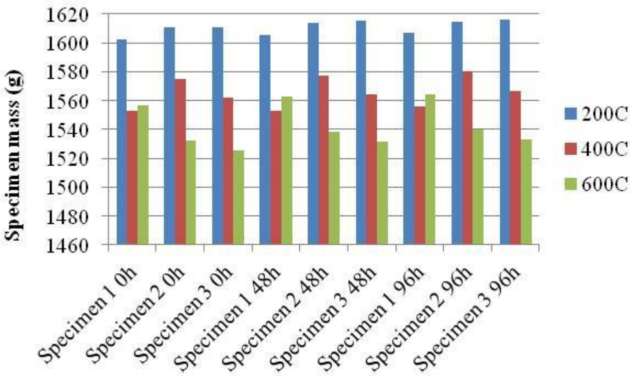


Figure 3. Mass change of specimens from mix3 during 96 hours after cooling.

3.2 An example of assessment of the residual load capacity

To illustrate the influence of post-fire strength reduction of LWC on the residual load capacity, a numerical example of a fire exposed concrete column with a rectangular cross-section of 30/30 cm was chosen. Temperature isochrones from Eurocode 2 [4] for columns exposed to 30 minutes of ISO fire from all four sides were used as a representation of fire exposure; as shown in Figure 4.

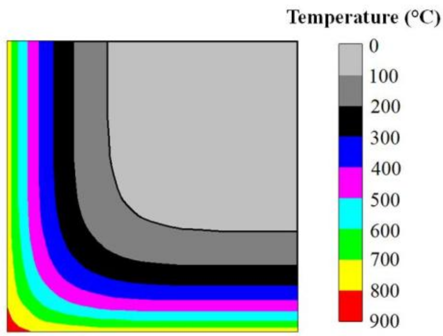


Figure 4. Temperature field in one quarter of a column after 30 minutes of ISO fire [4].

Following the exposure to 30 minutes of ISO fire and cooling of the column to ambient temperature, the axial load resistance of its cross-section was determined in relation to the maximum temperature exposure in the cross-section. The residual load bearing capacity was calculated immediately after cooling by using residual strength reduction factors from the presented experiment. Analogously, post-fire load bearing capacity was estimated by using post-fire reduction factors at a certain time after cooling.

Table 6. presents the results obtained by a numerical analysis of the axial resistance of the column using different levels of post-fire reduction for compressive strength of LWC from Figure 2.

Table 6. Post-fire reduction of residual load capacity of a column exposed to 30 min of ISO fire

$N_{fi,Rd}$ (kN)	LWC1	LWC2	LWC3	LWC4
Residual	3180.3	3250.0	3551.4	3528.1
48h after cooling	3069.2	3014.4	3419.9	3321.4
96h after cooling	3012.2	2914.3	3266.0	3230.9

4 DISCUSSION OF THE RESULTS

A comparison between Eurocode 2 reduction factors for LWC and the reduction factors obtained by testing the mixes indicates that the reduction factors for mixes 3&4 are close to the proposal of Eurocode 2. Some difference exists but can be attributed to the fact that the reduction factors given in Eurocode 2 were determined for a LWC with different type of aggregate than the one used in the study. However, reduction factor results for the analyzed LWC point out that the concrete mixes containing natural clay aggregate can be considered as a reliable construction product with adequate fire resistance up to 600°C.

Results from Figure 2 and Table 2 also indicate a distinctive reduction in the compressive strength of LWC (10-20%) in the short time period of 96 hours after cooling. The level of post-fire reduction of the compressive strength seems to vary depending on the composition of the mix. LWC mix3 has proved to have the highest fire resistance of all the mixes. In addition, mix3 has the lowest post-fire reduction factors for compressive strength as well. Both of these characteristics can be attributed to the proportions of the mix. The results show that a mix with the lowest amount of binder that includes all particles smaller than 0.125 mm has the lowest level of post-fire reduction factor. The three remaining mixes have a higher binder amount.

Levels of post-fire reduction of LWCs' residual capacity has been shown in Table 6 where post-fire load bearing capacity reduction amounts up to 7% for 48 hours and 10% for 96 hours after initial cooling. It can be noted that the calculated level of post-fire reduction is not negligible for concrete members exposed to all four sides. Level of post-fire reduction could be even greater than 10% if a concrete member was exposed to fire temperatures over a period longer than 30 minutes.

This points out to the fact that post-fire reduction of the mechanical properties of concrete should be accounted for in the assessment of residual capacity of concrete structures. It is important to note that storage conditions after cooling used in the study were chosen so as to exclude the influence of moisture absorption, which is known to contribute strength loss after cooling. Since a very small level of moisture absorption occurred during the storage period after initial cooling, mass gain of the specimens was negligible, as it is shown in Figure 3.

5 CONCLUSIONS

The discussion of the results points out that the effect of short-term reduction of light-weight concrete's compressive strength in real structures damaged by fire may have a significant effect on the post-fire load bearing capacity of a structure. This is due to an apparent reduction of the residual load capacity as illustrated on a simple example (section 3.2) where post-fire reduction of load bearing capacity amounts to approximately 10%.

Further research into these issues will include an analysis of post-fire reduction of mechanical properties over a longer time period after cooling so that the maximum reduction of the load bearing capacity that could occur in concrete structures after cooling may be assessed. Additionally, to capture more realistic moisture boundary conditions that can occur in concrete structures, the influence of storage conditions, i.e. moisture absorption on the strength reduction, is also planned in some future research.

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