Behaviour of Lightweight Expanded Clay Aggregate Concrete Exposed to High Temperatures

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***Abstract*—**This paper is concerning the issues of behaviour of lightweight expanded clay aggregates concrete exposed to high temperature. Lightweight aggregates from expanded clay are produced by firing of row material up to temperature 1050°C. Lightweight aggregates have suitable properties in terms of volume stability, when exposed to temperatures up to 1050°C, which could indicate their suitability for construction applications with higher risk of fire. The test samples were exposed to heat by using the standard temperature-time curve ISO 834. Negative changes in resulting mechanical properties, such as compressive strength, tensile strength, and flexural strength were evaluated. Also visual evaluation of the specimen was performed. On specimen exposed to excessive heat, an explosive spalling could be observed, due to evaporation of considerable amount of unbounded water from the inner structure of the concrete.

***Keywords*—**Expanded clay aggregate, explosive spalling, high temperature, lightweight concrete, temperature-time curve ISO 834.

I. Introduction

FOR assessment of fire resistance of lightweight concrete with lightweight aggregates is important to evaluate characteristics of row material and even more significant is the evaluation of concrete as a unit. Lightweight aggregates from expanded clay have suitable properties in terms of volume stability, when exposed to temperatures up to 1050°C [1]. Amount of concrete moisture content in lightweight concrete is relevant. The two most important factors in case of fire resistance of lightweight concrete are the mixing procedure and conditions to which is the construction exposed.

There are two possibilities how to dose lightweight aggregate for producing lightweight concrete:

1) in soaked state, which is positive for workability of concrete and internal curing. The higher moisture content is brought into concrete structure and continuously released while curing of concrete. Time for releasing of water is based on environment conditions. This technological process is suitable for ready-mix concrete, high performance lightweight concrete and in road constructions. Lightweight concrete prepared by this technological process has moisture content up to 20 % after 28 days of curing.
2) in dry state, this technological process is more often used in prefabrication, because moulding of the concrete is fast (within 10 minutes). There is no time for aggregate to soak up mixing water and reduce workability of the lightweight concrete. Lightweight concrete prepared by this technological process has much lover moisture content (from 3 to 5% after 28 days of curing).

The moisture content in concrete is fundamental factor which cause explosive spalling while thermal loading. Due to water evaporation, the pores are loaded by additional pressure. If the pressure of vapour is higher than the flexure strength of cement paste, the cement paste breaks and the microcracks or explosive spalling is occurring [2]. The changes of chemical components are accompanied by volume changes which also contribute to destruction of the microstructure of concrete. The dehydratation of CSH-gels starts at temperature 100°C, decomposition of portlandite take place at temperature 400°C and is producing water and free lime and other decomposition of hydration products and changes of aggregate due to thermal load [3], [4]. The pore system in structure is major for fire resistance of concrete. The more complex the pore system is, the easier it is for the water vapour to escape out of concrete element. The system of the pores could be created artificially by addition of fine fibres (the most common are polypropylene or cellulose fibres). The fine fibres depredate by the thermal load and create pore system [5], [6].

Based on previous tests [7] was declared that lightweight expanded concrete with lightweight aggregate concrete has a good fire resistance. For instance the prefabricated ceiling slabs in thickness of 150 mm made from concrete LC 25/28 D 1.6, tested according to standard EN 1365-2 [8] has very good fire resistance according to the standard REI 180. The moisture content of tested slab prior to testing was 9.04 %. The length of the slab was 5 750 mm, in between supporting walls 5 625 mm. The test slab was loaded by burdens which evocate the flexure moment equal to uniform load q = 2.39 kN/m^2. The test carried out in accredited laboratory was stopped after 186 minutes. Even at this time (186 minutes) the test slab reached the criteria for attaining the limit state capacity, wholeness and insulation according to standards. There were no damages of the test slab during the test (see Figs. 1 and 2) [7].

The aim of the experimental part described in this article is the assessment of behaviour of lightweight concrete with higher content of moisture loaded by high temperature.

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Fig. 1 Test slab after the 186 min of fire resistance testing

Fig. 2 Test slab after the 186 min of fire resistance testing – surface loaded by the high temperature

II. Experimental Part

A. Mix Design and Testing Plan

The behaviour of lightweight concrete with lightweight aggregate exposed to high temperatures was verified. Concrete mixture contains cement CEM II/B-S 32.5 R, fine basalt aggregates fraction 0/4 mm, lightweight expanded clay aggregate fraction 0/4 mm and 4/8 mm. For better workability and reduction of water the polycarboxyl ether-based plasticizer was added in dosage 0.8% from cement amount. To improve fire resistance of the concrete, the polypropylene fibres (PP-fibres) were used in dosage 2 kg/m^3. The lightweight aggregate were stored in water for 48 hours prior to testing. The mix properties of lightweight concrete are given in following table, concrete class LC 20/22 D 1.6. Test samples of dimensions 100×100×400 mm and slabs in dimensions 100×300×1050 mm were moulded.

The density of the fresh concrete L was 1650 kg/m^3 and fresh concrete LF was 1655 kg/m^3, specified by EN 12350-6 [9]. Consistency of fresh lightweight concrete was specified by cone test according to EN 12350-2 [10] degree S1. Density of harden concrete was determine on samples 100 × 100 × 400 mm according to EN 12390-7 [11], afterwards the samples were tested for compressive strength according to EN 12390-3 [12] and flexural strength according to EN 12390-5 [13].

TABLE I
MIX PROPERTIES L AND LF FOR 1 M^3

Materials:	L	LF
CEM II/B-S 32.5 R [kg]	375	375
Aggregate 0/4 mm basalt [kg] density 3050 kg/m^3	500	500
Lightweight aggregate 1/4 mm/625[m^3] density 1050 kg/m^3	0.17	0.17
Lightweight aggregate 4/8 mm/650 [m^3] density 1150 kg/m^3	0.4	0.4
Water [kg]	135	140
Plasticizer Chrysofluid Optima 208, 0.8% m_c [l]	3.0	3.0
PP-fibres [kg] diameter 18 ± 10 % , length 12 ± 10 %	0.0	2.0
Water cement ratio w = v/c	0.36	0.37

L = Lightweight concrete
LF = Lightweight concrete with PP-fibres

B. Monitoring of Physical-Mechanical Prosperities of Lightweight Concrete on Test Samples (Prisms) 100 × 100 × 400 mm Thermally Loaded in Furnace

Test samples were thermally loaded according to standard temperature-time curve ISO 834 [14]. After thermal treatment compressive strength according to EN 12390-3 [12] and flexural strength according to EN 12390-5 [13] was determined. As a referent were used samples mixed from the same concrete mixture stored in laboratory conditions.

There were no significant damages observed on the test samples of dimension 100 x 100 x 400 mm after thermal load according to standard temperature-time curve ISO 834.

TABLE II
DENSITY OF CONCRETE WITHOUT AND WITH THERMAL TREATMENT

Sample	Density [kg/m^3]	Decrease of density %
L	1740	13.8
LT	1500	
LF	1780	18.5
LFT	1450	

L = Lightweight concrete
LT = Lightweight concrete after thermal treatment
LF = Lightweight concrete
LFT = Lightweight concrete with PP-fibre after thermal treatment

TABLE III
COMPRESSIVE STRENGTH, FLEXURE STRENGTH AND FLEXURAL STRENGTH WITHOUT AND WITH THERMAL TREATMENT

Mixture	Concrete label	Compressive strength [MPa]	Decrease of compressive strength %	Flexural strength [MPa]	Decrease of flexural strength %	Tensile strength of concrete surface layers [MPa]	Decrease of tensile strength of surface layers %
L	L	30.2	49.1	7.5	91.5	2.8	31.6
	LT	15.4		0.6		1.9	
LF	LF	30.9	54.5	4.7	87.4	3.6	69.5
	LFT	14.1		0.6		1.1	

L = Lightweight concrete
LT = Lightweight concrete after thermal treatment
LF = Lightweight concrete
LFT = Lightweight concrete with PP-fibre after thermal treatment

C. Monitoring of Explosive Spalling of Lightweight Concrete Slabs 100 × 300 × 1150 mm, One Side Thermal Loaded According to Standard Temperature-Time Curve ISO 834

For one side thermal treatment and monitoring of explosive spalling were prepared slabs in dimension of 100 × 300 × 1150 mm. The thermocouples (type TFE-K-24) were set in concrete slabs in height 20 mm, 40 mm and 80 mm from the bottom of the mould.

The slabs were cured in laboratory conditions (23 °C, 80 % RH) for 3 months and prior to testing the concrete moisture content was determine. The moisture content was 19.0 %, surface moisture was 9.5 %. Test slabs were thermally loaded according to standard temperature-time curve ISO 834 for 60 minutes. The temperature changes in slabs were monitored by thermocouples.

TABLE IV
MAXIMUM RECORDED TEMPERATURE ON INDIVIDUAL THERMOCOUPLES

Thermocouple	Time [min]	Temperature [ºC]
L20 (20 mm)	40.78	443.32
L40 (40 mm)	55.03	99.11
L80 (80 mm)	107.92	43.50
Surface	124.15	26.10

The first explosive spalling occurred at 21.2 min after starting the test. The big piece of concrete was released from the surface and the thermocouple L20 was exposed straight to the fire and temperature rose by 230ºC immediately. Subsequent explosive spalling was observed during the whole testing. Releasing of the light weight aggregates from the structure of the concrete was accompanied by loud crackle. The speed of thermal changes in concrete was relatively fast during 20 to 40 minutes. The temperature on heated surface sharply rose at 33 minute and kept rising for 7 minutes. After this reaction the temperature started to fluctuate for the next 16 minutes and afterwards the temperature decreases fluently. Fluctuate of temperature was probably cause by evaporation of bigger amount of water from whole volume of slab. The extensive explosive spalling was caused by high concrete moisture content. Water vapour was escaping by the cracks (max. size 0.12 mm) formed by thermal treatment on the surface of the no heated sides of slab.

The key moments described in previous paragraph are very similar to the one from ceiling slab testing [7] according the EN 1365-2 [8]. At time 20 minutes from the beginning of test the first cracks occurred and small scale explosive spalling (small piece of concrete was released from slab). At 29th minute the cracking was audible and at 33th minute the vapour was escaping from the concrete and the water occurred on the surface of the slab. There were no any radical changes, besides the deflection of the slab starting at 134th minute until the end of the test (186th minute). The test was ended because the adequate results were achieved, not because of the failure of the lightweight concrete slab [7].

In comparison with testing of the slab with moisture content 19.0 % which was completed in our experimental testing, the water vapour was continuously evaporating from the slab after completion of the heating. The cement paste starts to peel off from lightweight aggregate on the top surface of the slab. Entire surface of the slab was full with cracks and some cracks enlarged to 0.15 mm while cooling. The cracks on the bottom surface of the slab were spread through the cement past but also through lightweight aggregate. From entire heated surface the 3.5 dm^3 of concrete spalled. The temperature on thermocouple L80 and surface of the slab was rising even after the heating of the slab finished (heating time 60 minutes, test time 120 minutes).

Fig. 3 Surface of the slab after thermal treatment – evaporation of water

Fig. 4 State after testing – spalled concrete

Fig. 5 State after testing – crack in cement past and lightweight aggregate

III. CONCLUSION

The experiment showed the need to conduct tests not only on the small samples (prisms 100 × 100 × 400 mm) but always proceed form smaller test samples to bigger dimension test samples. There was detect decrease of physical-mechanical properties of lightweight concrete with and without PP-fibres while thermal load testing of samples with dimension 100 × 100 × 400 mm. There was not detection of explosive spalling on the surface of samples after thermal loading. The test samples were heated from all directions in same test oven and with the same heat regime as the slabs with dimension of 100 × 300 × 1050 mm.

Explosive spalling on the slab (19 % moisture content) occurred while thermal loading according to standard temperature-time curve ISO 834 [12] for 45 minutes. Light-weight aggregates were soaked up for 48 hours prior to testing and therefore the moisture content of the light-weight concrete is high and causes explosive spalling. The addition of PP-fibres in dosage of 2 kg/m^3 had no positive influence on thermal resistance of the light-weight concrete.

Based on previous results it is possible to conclude this:

1) The compactness and bearing capacity of light weight concrete with higher moisture content was disrupt at temperature 700°C which is equalled to 20 minutes of fire.
2) If the moisture content is lower than 10% of weight the fire resistance of lightweight concrete LC [7] is not influenced.
3) The fire resistance of the lightweight concrete is rapidly decreasing with decreasing moisture content. This assertion is valued for moisture content from 10 to 20%. In further studies could be defined exact limit for moisture content.
4) The results should be taken in account when using lightweight concrete in environment or construction with requirements of fire resistance (tunnel lining, industrial spaces with high humidity etc.).
5) The type of technological process of preparing lightweight concrete influences the fire resistance of the concrete in first weeks or months of curing. In this period the fire resistance could not be sufficient.

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