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EVALUATION OF DISRUPTION OF CONCRETE CAUSED BY EXPOSURE TO HIGH TEMPERATURES BY INITIAL SURFACE ABSORPTION TEST

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ABSTRACT

If a concrete structure is exposed to high temperature, inner structure of concrete degrades. Level of permeability of the surface layer is important for evaporation of water vapour from the whole bulk of the structure. If permeability of the surface layer is low, explosive spilling can occur and steel reinforcement can be uncovered. One of methods of measuring permeability of the surface layer of concrete is the Initial Surface Absorption Test (ISAT). The paper states results of experimental determination of permeability of the surface layer of concrete before and after thermal load. Tested concretes contained basalt aggregate and lightweight expanded clay aggregate. Results of the measurements showed that structure of surface layer in case of concrete with lightweight expanded clay aggregate is less porous than the structure of concrete with basalt aggregates. Damages caused by exposed to high temperature were recorded on both tested mixtures but concrete with lightweight expanded clay aggregate resists better.

Keywords: initial surface absorption test, high temperatures, clay aggregate, basalt aggregate, normative heat curve ISO 834, fire risk.

INTRODUCTION

Quality of the surface layer has considerable influence on permeability of concrete for both gaseous and liquid substances. Permeation of these media into the structure of concrete considerably influences durability of concrete (for example the process of carbonation caused by CO_2, degradation caused by change of phase of water after cyclical freezing, degradation caused by chemically aggressive substances). Likewise, if surrounding corrosive influences act on concrete, the surface layer is damaged first and consequently the degradation process progresses into the bulk of concrete. If concrete structure is exposed to high temperature or a fire, surface of the structure is loaded with high temperature first and very often the damage of the surface is more serious than damage of inner structures of concrete. Information about water permeability of the surface layer of concrete can be obtained through Initial Surface Absorption Test. The principle of the test is determination of time in which a defined amount of water is absorbed by the surface layer of concrete on specified area. The paper presents results of experimental measurements of concrete before and after thermal load by use of the Initial Surface Absorption Test Method.

METHODS OF INITIAL SURFACE ABSORPTION TEST

The Initial Surface Absorption Test (ISAT) is specified by the British Standard BS 1881 Part 5 Methods of testing hardened concrete for other than strength (BS 1881, 1970). The ISAT specifies volume of water (measured by marks on calibrated glass capillary), which is absorbed by a specified area of concrete under constant pressure of 200 mm (~ 0.02 bar). The measurement data provide information about water permeability of the initial surface of concrete on a flat specimen. The measurement is time dependent and shows capability of concrete to resist absorption of water (Torrent *et al.* 2008).

Moisture content or water content of test specimens can have negative influence on measured results and the results of the tests of various types of concrete are then not comparable (Reiterman *et al.* 2012). Water content reduces water valve absorbing capacity and therefore it is advisable to dry test specimens prior to the test in a drying furnace at the temperature 105 °C for 48 hours. After drying, test specimens are cooled down for another 24 hours in laboratory environment (temperature 20 ± 2 °C).

Description of measuring apparatus

The apparatus consists of two stands connected with a bearing polymeric board, to which a capillary tube with diameter 1.81 mm and length 327 mm is attached. The capillary tube is calibrated; each scale unit corresponds to 0.01 ml water absorbed on 1 m^2 of surface layer of concrete in the time of 1 second. Position of the capillary tube and a funnel reservoir can be vertically adjusted, which makes it possible to keep constant pressure of water column at the value 200 mm above the surface tested concrete. Funnel reservoir is intended only for initial watering of the system and/or topping up water during the test. The reservoir is connected with acrylate cup, which provides contact of water with concrete over a closing valve. The cup with diameter 85 mm is fitted with rubber sealing and has two gratings. One is for initial watering of the system from the funnel reservoir, the other one leads water from capillary tube during measurement (Stavař, 2013). Measuring apparatus is pictured on Figure-1 and Figure-2.

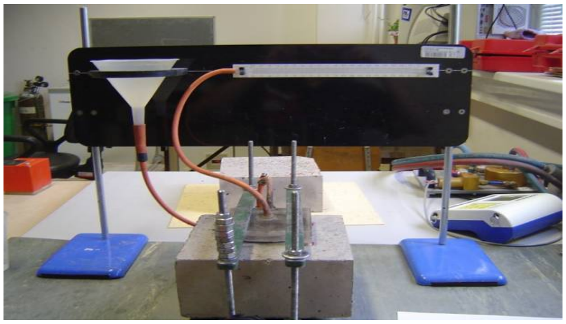

Figure-1. Measuring apparatus, ISAT Method.

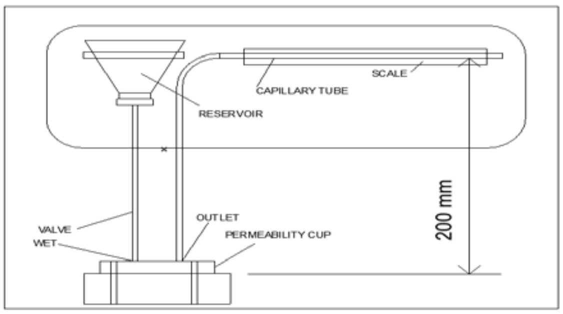

Figure-2. Sketch of ISAT apparatus.

Measurement procedure

It is necessary to check cleanness of test apparatus before testing, because impurities on the surface of the capillary tube may increase surface friction and alter the rate of water passage.

The acrylate cup is fastened to the surface of tested concrete by steel clamps. To ensure perfect sealing of the cup on the concrete surface, it is advisable to cover the rubber sealing with a thin layer of silicone. The capillary tube is set in a horizontal position 200 mm above tested surface and the funnel reservoir is filled with distilled water. Then the closing valve is opened, which starts the test. As soon as the capillary tube is filled with water, the closing valve of the funnel is closed. After 5 seconds, the value of the dropped meniscus of the water (or better – retracted meniscus of the water – the tube is horizontal) is read on the scale of the capillary tube. Based on the decrease of the value of meniscus of the water on the capillary tube after 5 seconds, the intervals of indication of water level in the capillary are set on 30, 60 or 120 seconds. One test specimen is subjected to three subsequent measurement cycles: after 10, 30 and 60 minutes from watering the system.

Calculation of water permeability of concrete

Individual scale units on the capillary tube express rate of water flow through the concrete surface depending on certain time. The computational relation is expressed in the formula:

$$ISA = 0{,}6\ D / \delta t \qquad (1)$$

Where

ISA = Rate of water suction [$ml.m^{-2}.s^{-1}$]

D = Number of scale units covered by the retraction of the meniscus

δt = Time taken for the meniscus to move D scale units of the capillary tube [s] (BS 1881, 1970).

If the rate of water suction after 5 seconds is higher than 30 units, it means that permeability is 3.60 $ml.m^{-2}.s^{-1}$ and it is not advisable to carry on in the measurement because of high surface permeability of concrete (the method is not intended for concrete with high porosity). After evaluation of measured values, the concrete samples are classed in accordance with Table-1.

Table-1. Classification of „Concrete“Absorption Based on ISAT-Values. (BS 1881, 1970).

Concrete absorption	ISAT results [$ml.m^{-2}.s^{-1}$]			
	Time after starting test			
	10 min	30 min	60 min	120 min
High	>0.50	>0.35	>0.20	>0.15
Medium	0.25 - 0.50	0.17 - 0.35	0.10 - 0.20	0.07 - 0.15
Low	<0.25	<0.17	<0.10	<0.07

EXPERIMENTAL DETERMINATION OF ISA VALUE

For this experiment two mixtures were design, one with natural basalt aggregate and second with natural basalt aggregate and expanded clay aggregate. These concretes were chosen to have absolutely different characteristics of the testing concrete in order to have various results from ISAT.

The main criteria for selection of input raw materials was minimal or no change of properties at higher temperatures. Authoritative values were linear thermal expansion coefficient and thermal conductivity coefficient (Bosnjak *et al.* 2013), (Minho *et al.* 2015), (Schneider *et al.* 2007). Cement which was used for preparation of mixtures was CEM II/B-S 32.5 R. This kind of cement content Portland cement clinker (65 – 79 %) and slag (21 – 35 %) which is decreasing thermal expansion of cement past matrix which is $15 \times 10^{-6}\ K^{-1}$ (Nováková, 2014). The basalt aggregate was selected because of its thermal stability up to the 900 °C. Coefficients of thermal expansion for basalt is 3.6 - $9.7 \times 10^{-6}\ K^{-1}$ which is lower in comparison to other rock up to $4 \times 10^{-6}\ K^{-1}$ (Bodnárová *et al.* 2013). There are no any chemical changes of chemical composition of basalt caused by high temperatures or by cooling down aggregate (Sitek *et al.* 2015) Bulk density of basalt aggregates was in average 2965 kg/m^3 (for each fraction bulk density slightly changes) (Bílčice, 2012). The lightweight expanded clay aggregate was chosen for more reasons. Positive characteristic of expanded clay aggregate is resistance to temperatures up to 1000 °C this is ensured by burning process (around 1200 °C) during production. Low thermal conductivity is provided by high porosity of aggregate and

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it is positive for slower expansion of the heat into the construction (Sokol *et al.* 2012). Higher absorptivity is one of disadvantages of expanded clay aggregate. This kind of aggregate is mostly added to concrete mixture in soaked up state. The moistness of aggregates reminding high and in case of fire this moisture has to be evaporate and causes damages of the concrete. To avoid this situation is possible to mix expanded clay aggregates in dry state but this mixing should be very fast (used in prefabrication production). Bulk density of lightweight expanded clay aggregate fraction 0 – 4 mm is 500 kg/m^3 and for fraction 4 – 8 mm 600 kg/m^3 (Hela *et al.* 2006). To reduce slightly the amount of mixing water, dosage of 0.8% by weight of cement of superplasticizer was used. Composition of the mixtures is showed at Table-2.

For measurements of permeability of the surface layer by ISAT were manufactured 6 test cubes with dimensions 200 × 200 × 200 mm. After reaching sufficient strength (7 days), the samples were cut into two identical blocks with dimensions 200 × 200 × 100 mm. Three cubes or 6 test specimens were made from each of the mix-designs of concrete. Three test specimens made from each of the mix-designs were testes without any thermal load and 3 specimens from each of the mix-designs were exposed to elevated temperature according to normative heat curve ISO 834 (EN 1991-1-2, 2004) and then tested. Physico-mechanical characteristics as a compressive strength (EN 12390 – 3, 2009), flexture strength (EN 12390 – 5, 2009) and bond strength of surface layers (ČSN 73 1318, 1987) were measured on prisms with diameter 100 × 100 × 400 mm, the results are presented in Table 3.

Mix-designs were proportioned so that the consistency of fresh concrete was S2 (50 - 90 mm) (EN 12350 – 2, 2009) of the slump test. Concrete with lightweight expanded clay aggregate was based on previously tested concrete mixture. The amount of mixing water was adjusted experimentally (aggregate was submerged in water for 24 hours before mixing) to reach consistency similar to the consistency of the concrete with basalt aggregate.

Test specimens were placed in climatic chamber for aging (28 days), and then dried up in drying furnace at the temperature 110 ± 5°C for 48 hours. Test specimens prepared in this way were used for determination of permeability of surface layers and for loading with high temperature in accordance with normative heat curve ISO 834 (EN 1991-1-2, 2004). Test specimens were heated up in furnace with a gas burner. Test specimens accumulated a lot of heat during heating up and it was necessary to wait 24 hours with measurements.

Table-2. Mix-design of concrete with basalt aggregate (BA) and expanded clay aggregate (LWA) for 1 m^3.

Materials for 1 m^3	Basalt aggregate (BA)	Expanded clay aggregate (LWA)
CEM II/B-S 32.5 R [kg]	300	375
Aggregate 0/4 mm basalt [kg]	1162	500
Aggregate 4/8 mm basalt [kg]	340	-
Aggregate 8/16 mm basalt [kg]	497	-
Expanded clay aggregate 0/4 mm /500 [m^3]	-	0.024
Expanded clay aggregate 4/8 mm /600 [m^3]	-	0.4
Water [kg]	163	79
Plasticizer Chrysofluid Optima 208 (0.8 % m_c) [kg]	2.4	3.0
Water cement ratio v/c [-]	0.54	0.21

Table-3. Results of physico-mechanical characteristics of tested concretes with and without thermal load.

Mixture	Labeling of concrete	Compresive strength [N·mm^{-2}]	Loss of compressive strength in %	Flexure strength [N·mm^{-2}]	Loss of flexure strength in %	Bond strength of surface layers [N·mm^{-2}]	Loss of bond strength of surface layers in %
Basalt aggregate (BA)	BA-N	58.9	21.3	6.5	79.4	2.9	69.0
	BA-T	46.4		1.3		0.9	
Expanded clay aggre-gate (LWA)	LWA-N	30.2	49.1	7.5	91.5	2.8	31.6
	LWA-T	15.4		0.6		1.9	

N – test specimens without thermal load; T – test specimens with thermal load.

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Measurement results and discussion

Determination of water permeability of surface layer of concrete was measured on all twelve test specimens, while two measurements were taken on each of them. The results are given in Table-4, graphically expressed in Figure-3 and Figure-4.

Surface humidity has influence on measurement results; therefore the value of surface moisture content was determined by moisturemeter KAKASO PSXMI before the ISAT. For the purpose of evaluation of surface water absorbing capacity of concrete, the 10 minutes capillary flow ISA is determined [$ml.m^{-2}.s^{-1}$], and the specimens are evaluated by three degrees of absorption - see Table-1.

Table-4. Evaluation of quality of the surface layer of concrete based on measurement of water absorption.

Mix-design	Labeling of concrete	Current moisture content by weight [%]	Permeability after 10 minutes from starting the test [$ml.m^{-2}.s^{-1}$]	Absorption of concrete	Permeability after 30 minutes from starting the test [$ml.m^{-2}.s^{-1}$]	Absorption of concrete	Permeability after 60 minutes from starting the test [$ml.m^{-2}.s^{-1}$]	Absorption of concrete
Basalt aggregate (BA)	BA-N	2.8	0.313	medium	0.232	medium	0.188	medium
	BA-T	2.1	1.600	high	1.029	high	0.626	high
Expande dclay aggregate (LWA)	LWA-N	2.8	0.352	medium	0.182	medium	0.11	medium
	LWA-T	2.1	1.070	high	0.645	high	0.439	high

N – test specimens without thermal load; T – test specimens with thermal load

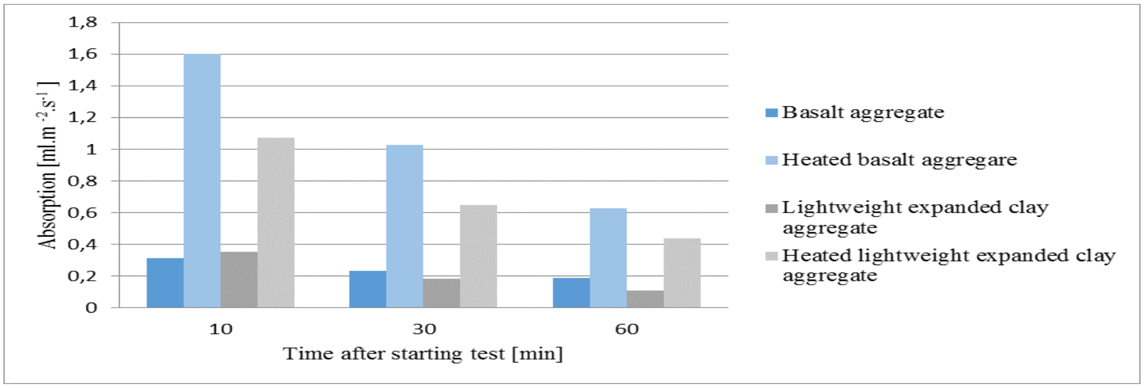

Figure-3. Comparison of water permeability of surface layer of concrete with basalt aggregate and concrete with lightweight expanded clay aggregate without thermal load and exposed to thermal load.

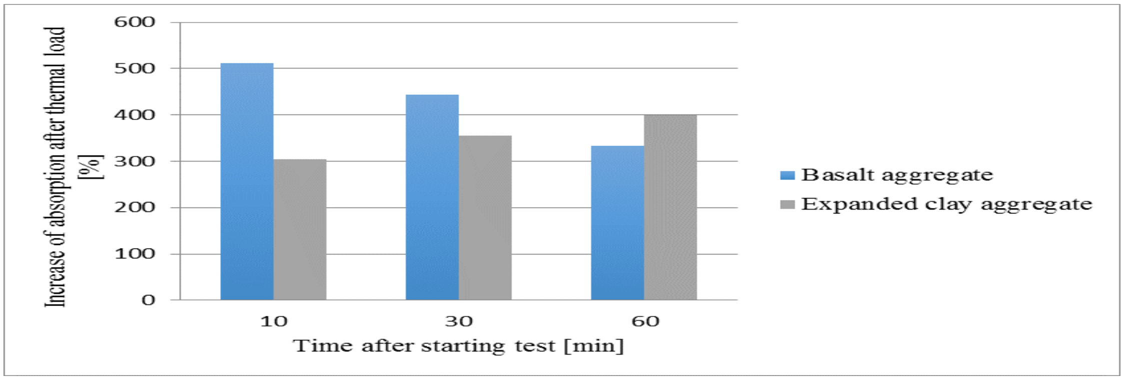

Figure-4. Percentage increase of surface layer permeability of concrete with basalt aggregate and concrete with lightweight expanded clay aggregate after thermal load.

Graphical representation of results implies that test specimens were damaged by the action of high temperature and permeability of the surface layer increased three to five times. Test specimens without thermal load were classed into the medium class; their permeability increased after thermal load and the class changed to high.

As for the concrete with basalt aggregate, the surface layer permeability was on the top limit of the medium class for ISA 60 min, which implies, that the system of pores in the surface layer is quite well interconnected. In case of fire, water vapor could escape from the whole bulk of the concrete structure. Unlike the concrete with basalt aggregate without thermal load (BA-N), permeability of the surface layer of the concrete with lightweight expanded clay aggregate without thermal load (LWA-N) is high at the beginning, and then it decreases. This fact can be caused by less interconnected pores in matrix cement. The lightweight expanded clay aggregate is able to accumulate water in their structure which is later release for completing hydration of the cement in cement paste. Therefore porosity in inner structure is lower and permeability is getting lower in time. Water absorbing capacity of lightweight expanded clay aggregate is higher than that of basalt aggregate and it is possible that lightweight expanded clay aggregate was soaked with water during the first 10 minutes of the test, which caused higher initial value of absorption compared to concrete with basalt aggregate. Network of pores of the concrete with lightweight expanded clay aggregate is not so thoroughly interconnected compared to concrete with basalt aggregate and this is not positive for resistance of concrete exposed to high temperature. Moreover, it has to be taken into consideration that lightweight expanded clay aggregate stays soaked in the structure of concrete and in this way it increases stable moisture content of concrete. During fire, higher amount of water vapour evaporates from concrete and if the system of pores is not sufficient, explosive spilling of the surface layer of concrete may occur. As the samples were dried prior to testing, explosive spilling did not occur at any sample. In case of concrete with lightweight expanded clay aggregate it is more common due to its higher moisture content.

Structure of the concrete with basalt aggregate was damaged more than the structure of concrete with lightweight expanded clay aggregate. Permeability of the surface layer of the specimen BA-T after 10 minutes was 1.6 $ml.m^{-2}.s^{-1}$, which implies formation of cracks not only on the surface but also deep in the specimen. It means that the network of pores and cracks formed after exposition to high temperature are well interconnected; however, such a high permeability may be dangerous not only for the lost of strength but also for durability of concrete. Aggressive substances may easily penetrate into the core of concrete structure and cause faster corrosion of reinforcement steel of reinforced concrete.

Damage of surface layer caused by high temperature in case of concrete with lightweight expanded clay aggregate was also obvious from the comparison of values before and after thermal load. However, the difference was not as extreme as in the case of concrete with basalt aggregate, therefore it can be assumed that the extent of damage is lower. Light-weight compact concrete has lower value of coefficient of thermal conductivity (λ) than standard concrete, therefore the test specimens are heated up slowlier. Temperature in the core of the specimen was not as high as the temperature in the core of the specimen with basalt aggregate, therefore the structure is probably less damaged – the permeability of the surface layer after 60 minutes from the start of the test is lower by 0.187 $ml.m^{-2}.s^{-1}$ than that of the concrete with basalt aggregate.

CONCLUSIONS

Measuring permeability of surface layer with the ISAT method showed higher permeability of test specimens after thermal load; the test specimens were then classed into the group with high absorption. Durability of concrete of such level of permeability decreases because aggressive substances may penetrate into the core of the structure and degradation of concrete is faster. If the structure was made from steel-reinforced concrete, the risk is even higher, because the reinforcement bars loose strength and bond to concrete and the structure may collapse. Usage of concrete with lightweight expanded clay aggregate for constructions with higher fire risk is more suitable because damages are only on surface, inner structure is less degraded. Lightweight expanded clay aggregate has positive influence on compactness of cement paste and it contributes to lower permeability of surface layers.

Detailed study of the network of pores could be carried out by mercury porosimetry test, which could determine number and size of pores in the surface layer as well as in the core of the structure.

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