UNIVERSITY OF PARDUBICE

FACULTY OF TRANSPORT ENGINEERING

EXPERIMENTAL ANALYSIS OF SPECIAL CONCRETE EXPOSED TO EXTREME THERMAL STRESS

DOCTORAL THESIS PRÉCIS

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INTRODUCTION

High thermal stresses (fires) do not cause only huge material losses, but mean a risk of health danger or death of persons or animals. Even though it is not possible to prevent all fires, there is an effort to eliminate their number and, last but not least, extent of their damage (application of active or passive protection).

It can be noted that concrete structures exposed to the effects of fire "can be assessed" in the same way as when designed according to the (ČSN EN 1992-1-1 ed. 2, 2011). Changes of strength and deformation characteristics are included in the calculation in the form of reduction factors, see (ČSN EN 1992-1-2, 2006). Mathematical model of concrete stress-strain curve in compression at higher temperatures is described by a temperature function of plain concrete in relation with the type of used aggregate (siliceous or limestone). However, it is not valid for light aggregate concrete description. In the author's point of view, this methodology (stipulation of reduction factors for residual properties determination), applied at fire design of concrete structures for simple and particularized methods (ČSN EN 1992-1-2, 2006), does not depict the behaviour of other special types of concrete to a sufficient extent.

1 ANALYSIS OF CURRENT STATE IN THE FIELD OF THE DOCTORAL THESIS

1.1 Structural Fire Design

Fire is an undesirable, unrestrained and uncontrollable burning. It is a process accompanied by chemical and physical effects (ČSN ISO 8421-1, 1996).

Actual progress of burning can be divided into three phases (Procházka et al., 2010) – characteristic periods – start of burning, fully developed fire and burning out.

1.2 Fire Resistance

Fire resistance **is often one of the decisive factors** at structural assessment. Fire resistance of a sample **is given by the time (in minutes), during which corresponding criteria are fulfilled** (ČSN EN 1363-1, 2013).

1.3 Consequence of High Temperature Influence on Concrete

Physicochemical properties of concrete change at extreme thermal stress. There is a significant inner tension caused by different thermal expansion of particular constituents of a concrete element or structure.

Following negative aspects happen:

- increase of permeability and porosity, more at (Bangi et al., 2011, Chan et al., 1999), (influence of compactness breach causes formation of cracks and ruptures, or crumbling),
- explosive spalling of concrete (lasts until the concrete falls apart or the fire calms down),
- concrete falling off (happens primarily in the advanced phase of fire),
- reduction of structural strength and the modulus of elasticity (Khoury, 1992).

Decrease of concrete strength depends primarily on **warming rate, maximum achieved temperature, and concrete humidity** and, from the material base, **primarily on the type of used aggregate.**

1.4 Explosive Spalling of Concrete

Temperature increase influences concrete spalling because of rapid water steam formation and thermal expansion of aggregate. The most important driving mechanisms directly relate **to humidity, microstructure** and transport effects of cement material. The most effective measure against spalling is reduction of inner tension (e.g. by use of polypropylene fibres).

Polypropylene fibres melt down at the temperature of 150–160 °C (Guidance on the Use of Macro-Synthetic-Fibre-Reinforced Concrete, 2007), which enables the water steam to escape without creation of inner pressure. This effect prevents or terminates the explosive spalling.

Procházka et al. (2009) points to a **possible transport of water steam in space between fibres and circumjacent concrete surface** (because of their bad cohesion) **even before the beginning of melting of fibres.**

1.5 Concrete Transformation at Higher Temperatures

In the Tab. 1, principal changes of concrete under the influence of high temperature are summarized.

Table 1 Strength and mineralogical changes of concrete by warming

Temperature [°C]	**Changes caused by warming**	
	Mineralogical changes	**Strength changes**
70–80	Dissociation of ettringite causes its decrease in cement matrix.	
105	Loss of physically bound water in concrete causes increasing capillary porosity and formation of smaller microcracks. The type of concrete influences the water evaporation rate.	Reduction of strength < 10 %
120–163	Dissociation $CaSO_4.2H_2O$	

Temperature [°C]	Changes caused by warming	
	Mineralogical changes	**Strength changes**
250–350	The aggregate begins to change colour into pink / red by iron compound oxidation (around 300 °C). Decrease of bound water in cement putty causes degradation that is more significant.	Significant reduction of strength around 300 °C (15–40 %).
450–500	$Ca(OH)_2$ dehydrates. Aggregate coloration into red increases up to the temperature of 600 °C. Siliceous aggregate can change colour into grey or white. Normally isotropic cement putty shows non-homogenously yellow / beige colour in transverse polarized light. Often, it shows even a birefringence at the temperature of 500 °C.	Reduction of strength around 400 °C (> 40 %).
573	There is a transformation from α into β-silica. Volume of silica is growing about ca 5 %, which causes formation of radial cracks and cracking of aggregate grains.	Concrete ceases to be structurally usable at the temperatures over 550 °C (55–70 %).
600–800	Decarbonation of carbonates. Based on contents of carbonates in concrete, contraction happens because of release of carbon dioxide, which results in formation of a significant amount of microcracks in cement putty. There is a substantial manifestation at limestone aggregate.	
800–1 200	Concrete structure sinters at the temperatures over 800 °C. Complete dissociation of limestone constituents of aggregate and cement matrix because of their dissociation. Concrete changes colour into albescent grey and an extensive net of microcracks is being formed. Limestone aggregate changes colour into white.	Reduction of strength at the temperatures over 800 °C (> 90 %).
1 200	Beginning of concrete meltdown (heat-resistant types of concrete as far as around 1 550 °C).	
1 300–1 400	Complete meltdown of concrete.	

Source: Adapted from (Ingham, 2009; Lee et al., 2010)

1.6 Structural Fire Design of Elements

The standard (ČSN EN 1991-1-2, 2004) offers various ways of fire resistance (reliability) verification – time, load capacity, temperature.

The basic condition of fire resistance compliance:

$$\textit{„Required FR“} \leq \textit{„Actual FR“} \qquad (1)$$

1.7 Fire Resistance Testing of Concrete Structures (Experimental Methods)

Experimental methods are the basis of structural fire resistance determination. Unlike theoretical procedures or calculation models, they are, however, **more time-consuming and economically demanding.** Calculations cannot capture e.g. the compactness of areal structure, time development of cracks, layers falling off, etc. The results of calculation models reach less economical solutions. Testing samples are made in real size. If the real size elements do not fit into oven, elements of minimum dimensions according to valid standards have to face the fire at least.

1.7.1 Temperature Curves

Temperature curves are defined by gas temperature in the vicinity of element surface as a function of time (ČSN EN 1991-1-2, 2004). They can be divided into nominal and parametric.

The standard (ČSN EN 1363-2, 2000) defines a standard curve, hydrocarbon curve, outer fire curve, and slow warming curve.

The Standard Curve

The standard (cellulosic) **curve has been derived for fire in underground structures.** It is applied for fire resistance assessment in tunnels, where it is the lowest from the available curves. A fully developed fire is modelled. Start of burning and cooling down is not considered. This curve is described in older literature as ISO 834 (ČSN 73 0851, 1984; Reichel, 1979).

Temperature in Oven

The nominal standard curve is given by equation (ČSN EN 1363-1, 2013):

$$T = 345\, log_{10}(8\, t + 1) + 20 \tag{2}$$

where:
T … average time in oven (or in particular fire section) [°C]
t … time [min]

The Derived Curves

Derived temperature curves are presented in ZTV-ING regulation.

1.8 Fire Design of Concrete Structures

1.8.1 Mechanical, Temperature and Physical Properties of Concrete under Growing Temperature (Summary)

There are recommending standards and regulations for high temperature / fire design of concrete structures: Eurocodes valid in member states **CEN** (ČSN EN 1992-1-2, 2006), **fib** Model Code 2010 (Model Code 2010, 2012), American Concrete Institute – **ACI** (ACI 216R-89, 1994), recommendation **RILEM** – (RILEM TC 129-MHT; RILEM TC 44-PHT; RILEM TC 74-THT), the National Building Code of Finland (**RakMK** B4, 1991), **ASTM** Standards (ASTM E 119; ASTM E 84) and **CEB** Model Code (Bulletin D´Information, 1991).

Some selected regulations for testing of mechanical properties of concrete including experimentally set properties of concrete under high temperatures are presented further in the text.

1.8.2 Mechanical, Temperature and Physical Properties of Concrete under Growing Temperature (ČSN EN 1992-1-2, 2006)

The standard (ČSN EN 1992-1-2, 2006) presents three options of fire resistance design:

- use of tables,
- simplified design methods,
- general design method for modelling of structural elements or a complete structure.

The fire design code for concrete structures (ČSN EN 1992-1-2, 2006) includes degradation of mechanical, temperature and physical properties under growing temperature as a function of temperature – see the Tab. 2. This approach is described by a simple calculation method – reduction of (characteristic) strength.

Table 2 The values of the main parameters of the stress-strain diagram of traditional concrete at high temperature

Concrete	**Siliceous aggregate**			**Limestone aggregate**		
Temperature [°C] Θ	$f_{c,\theta}/f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$	$f_{c,\theta}/f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$
20	1.00	0.0025	0.0200	1.0000	0.0025	0.0200
100	1.00	0.0040	0.0225	1.0000	0.0040	0.0225
200	0.95	0.0055	0.0250	0.9700	0.0055	0.0250
300	0.85	0.0070	0.0275	0.9100	0.0070	0.0275
400	0.75	0.0100	0.0300	0.8500	0.0100	0.0300
500	0.60	0.0150	0.0325	0.7400	0.0150	0.0325
600	0.45	0.0250	0.0350	0.6000	0.0250	0.0350
700	0.30	0.0250	0.0375	0.4300	0.0250	0.0375
800	0.15	0.0250	0.0400	0.2700	0.0250	0.0400
900	0.08	0.0250	0.0425	0.1500	0.0250	0.0425
1 000	0.04	0.0250	0.0450	0.0600	0.0250	0.0450
1 100	0.01	0.0250	0.0475	0.0200	0.0250	0.0475
1 200	0.00	-	-	0.0000	-	-

Source: Adapted from (ČSN EN 1992-1-2, 2006)

where:
Θ … temperature [°C]
$f_{c,\Theta}$ … compressive strength at temperature Θ [MPa]
f_{ck} … characteristic value of compressive strength [MPa]
$\varepsilon_{c1,\Theta}$… thermal strain of corresponding compressive strength $f_{c,\Theta}$ [-]
$\varepsilon_{cu1,\Theta}$ … thermal strain of corresponding compressive strength $f_{c,\Theta}$ (limit value) [-]

1.8.3 Mechanical Properties of Concrete under Growing Temperature (ACI 216R-89, 1994)

Experiments performed by the author converge to the “Unstressed Residual” methodology. Residual strength determined by this methodology reach the lowest values [%], as presented in the Fig. 1–2.

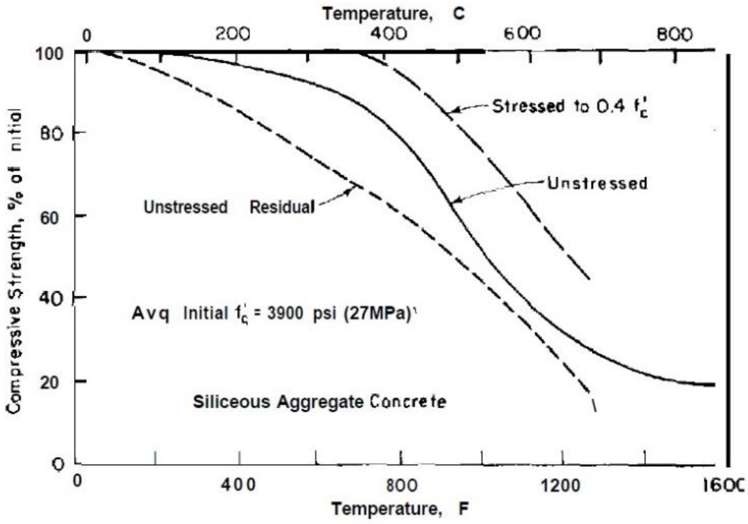

Figure 1 Residual strength (in compression) of siliceous aggregate concrete (ACI 216R-89, 1994)

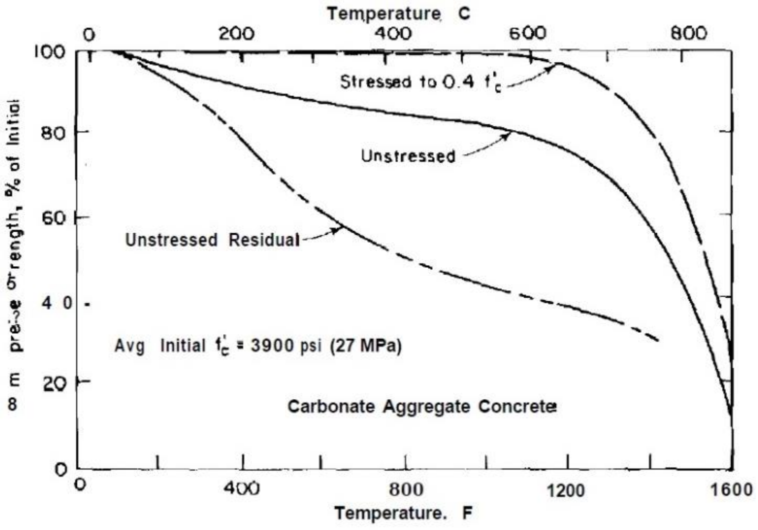

Figure 2 Residual strength (in compression) of limestone aggregate concrete (ACI 216R-89, 1994)

1.9 Description of Concrete Constituents under Higher Temperature

1.9.1 Filler – Aggregate

Concrete with siliceous aggregate shows worse behaviour under high temperature. Better results can be reached **by the use of limestone aggregate**. Concrete with expanded clay aggregate prove the most favourable results.

Siliceous Aggregate

If the temperature exceeds 573 °C, silica (SiO_2) changes from α to β modification with the parallel volume expansion by ca 5 %. Cracks in aggregate grains can appear. Simultaneously, strength of the siliceous aggregate reduces significantly under this temperature.

1.9.2 Binding agent – Cement

If the temperature exceeds 110 °C, physically bound water is expelled and crystal framework of the cement stone is breached, which causes reduction of strength.

If the temperature exceeds 200 °C, cement putty compounds decompose (dehydrates) into compounds without binding abilities.

If the temperature exceeds 500–600 °C, cement stone partly decomposes.

1.9.3 Water

Water transport in pores of concrete is essential as it causes creation of inner tension in the pore vicinity (capillary pressure etc.). Volume change – shrinking or expansion – is the result.

If the temperature exceeds 100 °C, water changes into steam; diffusion is under way. Under higher temperature, **physically bound water** releases from cement hydration products; in the interval of 500–600 °C, it releases from calcium hydroxide.

1.9.4 Limestone

Limestone types of concrete reduce their original strength only by 20 % if the temperature reaches up to 650 °C; see (Collepardi, 2009).

1.10 Special Cement Composite Materials

Considering the fact, that insufficient compaction **is the major cause of deteriorated quality of hardened concrete**, attention focused primarily on self-compacting concrete and its further modification.

1.10.1 Self-Compacting Concrete (SCC)

Definition of SCC – SCC is characterized by higher ratio: cement matrix / aggregate (contrary to ordinary types of concrete); it is able to flow and compact itself by its own weight (significant human factor influence – concrete compaction by external force – is eliminated); better fill in the areas of dense reinforcement and places that are out of reach of vibration is ensured; visible surface is improved; formwork area is well filled out and bled; higher lifetime of forms in the case of prefabrication.

Significant reduction of noise by production, faster process of concrete pouring, increase of concrete (not only surface) quality, use of inorganic fine-grained dust and flour can be determined as **advantages**. On the contrary, **disadvantages** are: higher stress requirements on formwork, possibility to pour concrete up to the slope of ca 3 % (TP 187, 2008), or higher susceptibility to explosive spalling of concrete under high temperatures.

Fresh SCC Testing

Fresh SCC Testing focuses on determination of four key properties: ability to fill out formwork, flow ability, segregation resistance, bleeding resistance.

1.10.2 Lightweight Self-Compacting Concrete (LWSCC)

Advantages of LWSCC are lower density, lower thermal conductivity, better thermal insulation properties, or (based on the type of aggregate) even processing of industrial waste. LWSCC has lower thermal expansion coefficient.

Disadvantages of LWSCC are lower modules of elasticity contrary to ordinary (vibrated) types of concrete (Schutter et al., 2008) and lower ductility. Lightweight aggregate is financially more demanding than ordinary aggregate.

Fresh LWSCC

Fresh LWSCC shows different characteristics (contrary to SCC). Liquidity and "self-compactness" can be reached in a smaller scale (due to insufficient inner kinetic energy). Lightweight aggregate adsorbs part of mixing water and this can lead to an early hardening of LWSCC. Lightweight aggregate "uses" water in pores of the aggregate for additional hydration ("inner self-treatment") and the value of complete shrinking reduces (Hela et al., 2007). If the value of cement paste is higher, lightweight aggregate tends to "float" on the surface of the fresh concrete, because the density of the lightweight aggregate can be lower than the density of the cement paste (tendency to "vice versa" segregation). Determination of air content is not tested according to the standard (ČSN EN 12350-7, 2009), but according to the (ASTM C173, ASTM C 23).

Rugen Aggregate

It excels in processing of high shares of fine inorganic waste materials by keeping the lowest energetic demand (characterized by low production temperature), see Tab. 3.

Table 3 Comparison of technical and technological parameters of lightweight artificial aggregate types available in the Czech Republic

Name	Fraction [mm]	Bulk density [ρ_S]	Fragmentation resistance [MPa]	Share of waste material [%]	Temperature of aggregate production [°C]
Rugen	4/8	500 - 1200	2 - 20	60 - 100	≥ 5
	8/16	400 - 1000	1 - 12	60 - 100	≥ 5
SioPor	0.1/1	120 - 160	0.08	0	300
	0.63/2.5	60 - 100	0.03	0	300
	2.5/4	60 - 80	0.01	0	300
Poraver	2.4/4.8	145 - 230	1.3	100	900
Liapor	0/2	575	4	0	> 1100
	0/4	450	2.1	0	> 1100
	4/8	450	1.7	0	> 1100
	8/16	275	0.6	0	> 1100

Source: Adapted from (Popis produktu RUGEN, 2013)

1.10.3 Fibre Reinforced Concrete (FRC)

"FRC is a type of concrete with dispersed reinforcement in the shapes of fibres out of suitable material – steel, glass, polymer, carbon, etc. Usually, fibres are dispersed in concrete, but can be oriented, too." (Krátký et al., 1999a).

FRC **excel** by higher resilience, impact resistance and ductility, microcracks development resistance, and resistance against sudden high temperature occurrence. Modification of concrete by PP fibres is considered as one of the options of passive fire protection.

Stress transmission into fibres (in the case of orientation in the direction of stress action) is a function of the length of fibres and slenderness ratio α.

Polymer microfibers serve to reduction and mitigation of microcracks formation (caused due to plastic shrinking). Polymer macrofibres (of irregular shape) serve to improvement of cohesion of cement paste and polymer. Fibres are larger (d_f = ca 10 µm) and terminate growth of macrocracks forming as a result of shrinking by drying out.

Addition of 2 kg of PP fibres into 1 m^3 of concrete prevents explosive spalling ("reach of higher diffusiveness" due to increase of porous system after the meltdown of PP fibres).

1.10.4 Steel Fibre Reinforced Concrete (SFRC)

Advantages of SFRC are the possibility to transmit tensile stress (resilience, ductility, impact resistance) in all directions (prevention of cracks propagation). Reinforcement by steel fibres improves bending, tensile and shear strength, stiffness, impact resistance, and frost resistance.

Steel fibres absorb tensile forces in the area of cement putty – under spatial loading – and reduce fragile character of concrete damage. Lower maintenance requirements are another assumption of SFRC. In some cases, SFRC can substitute ordinary concrete reinforcement.

2 AIMS OF THE DOCTORAL THESIS

The dissertation does not aim to perform standard (code) fire resistance tests on large-dimensional testing bodies, but experimentally perform high thermal loading on the basis of author's warming rate gradient on prepared testing bodies out of special types of concrete (modified by author). Goal of this dissertation is the application of two different experimental methodologies of thermal loading, firstly in electric oven and secondly as a simulation of local (point) fire with the use of propane-butane burner. The direction of research will aim to reach the maximum temperature of 400 °C, further the maximum temperature of 1049 °C (approaching the description of standard curve), 680 / 750 °C (curves of outer fire), and additionally, on prepared cement samples, until the temperatures of 70 and 100 °C.

The desire is to capture the contemporary state of knowledge in the area of selected special types of concrete (SCC, FRSCC, SFRC, PFRC, and LWSCC). Further goal is to apply experimental high thermal loading based on testing samples out of special types of concrete prepared by author. Attention is focused on determination of one of the most important characteristics of hardened concrete – strength and deformation properties.

Taking into account the fact that modulus of elasticity of concrete and Poisson's ratio are not set in the standards related to concrete (ČSN EN 206+A1, 2018; ČSN P 73 2404, 2016), author's attempt has been to apply two different approaches to the determination of secant modulus of elasticity in compression, firstly the European standard approach and secondly the digital image correlation – in collaboration with Sobriety s. r. o. company. Simultaneously, the Poisson's ratio of special types of concrete has been experimentally determined.

3 LIST OF USED METHODS

Particular methods used in the experimental part of the dissertation are presented in the Chapter 4.

4 PROBLEMS SOLVING – EXPERIMENTAL PART

4.1 Concrete Production

Motivation of concrete type selection: in view of the fact that the scope of the standard is limited (ČSN EN 1992-1-2, 2006) – (concrete with siliceous or limestone aggregate), production of promising special types of concrete, which are applied (applicable) on real structures (selection of strength classes C 45/55, C 30/37 and LWSC C 25/28), has been chosen. Author has performed its further modification by addition of fibres of various types and weight doses. Selected **key types of concrete** are extensively used in prefabrication (C 45/55 - XF2 (CZ, F1.2) - Cl 0,2 - Dmax16 - SCC (SF2); C 30/37 - XF2 (CZ, F1.2) - Cl 0,2 - D_{max}16 - SCC (SF2); LC 25/28 D1,8 - XC1 (CZ, F.1.1) - Cl 0,2 - Dmax16 - SCC (SF1)). Additional types of concrete add more information about special types of concrete. They have been added in order to determine the modulus of elasticity (in combination with DIC) and Poisson's ratio, in most cases, (C 30/37 - XF4 (F.1.2) - Cl 0,2 - Dmax16 - S3; C 25/30 - XF3 (F.1.2) - Cl 0,2 - Dmax16 - S3; C 25/30 - XC3 - XD1 - XA1 - XF1 (F.1.1) - Cl 0,2 - Dmax16 - S3; alkaline activated material; designed high-strength concrete I, II, III). Author has made self-compacting concrete (SCC), fibre reinforced self-compacting concrete (FRSCC) / steel fibre reinforced self-compacting concrete (SFRSCC), fibre reinforced concrete (FRC) / steel fibre reinforced concrete (SFRC). Author has removed fresh concrete samples from traditional vibrating concrete (TVB) and collected specimens of alkaline activated material (AAM).

Applied fibres were: synthetic microfibers Texiplast – Texzem PPF 370, synthetic large-dimensional fibres Synmix 55, steel wires Dramix 3D 45/50-BL, Dramix 3D 65/35-BG and carbon fabric fibres prepared by author.

4.2 Fresh Concrete Testing

There has been an effort to determine particular characteristics by testing of fresh concrete (consistency / viscosity, density, air content) in the same order and time after mixing / sample removal of fresh concrete.

Maximum effort has been put on performing the tests according to the standards.

4.3 Hardened Concrete Testing

4.3.1 Strength Characteristics

Author has determined density, compressive strength, and flexural strength using reference samples and thermally loaded samples.

4.3.2 Modulus of Elasticity of Concrete in Compression, Poisson's Ratio

Modulus of elasticity is a crucial material parameter describing relation between stress and deformation of concrete. At many structures, it is a determinative characteristic for actual function and bearing capacity (e.g. bridges, pre-stressed structures), because this attribute is applied in the calculation of deformations.

Modulus of elasticity has been set according to the standards (initial and stabilized according to the A Method (ČSN EN 12390-13, 2014) and simultaneously (experimentally) using digital image correlation (in collaboration with Sobriety s. r. o. company).

Selection of methodology (ČSN EN 12390-13, 2014) had been made before the release of the ČBS 05 technical regulations (2016). Upon the release of the regulations, it is possible to specify the concrete type including the required value of the modulus of elasticity.

Poisson’s ratio of special types of concrete has been determined using the 3D DIC application.

4.4 Exposure to Thermal Loading (Summary)

Two different experimental methodologies (created by author) based on designed gradient of warming rate have been used by thermal loading. All thermal loadings have been realized on naturally humid concrete samples even though there was a risk of explosive spalling.

Concrete humidity has always been determined using samples free of thermal loading. They have been neither reference samples, nor thermally loaded samples.

4.4.1 Exposure to Thermal Stress in Electric Oven

Experimental non-standard testing of samples has been done in an electric oven (made for ceramics firing – BVD 800/K). Humidity in additional samples from the same mixture had been measured before commencement of any tests.

Natural humidity of samples had been kept and no mechanical stress had been applied on the samples when they were placed into the oven.

Testing conditions in the electric oven have been set on approach to the description of nominal standard curve (max. temperature of 1049 °C), curves of outer fire (max. temperature of 680 °C), and specific loading under the max. temperature of 400 °C designed by author.

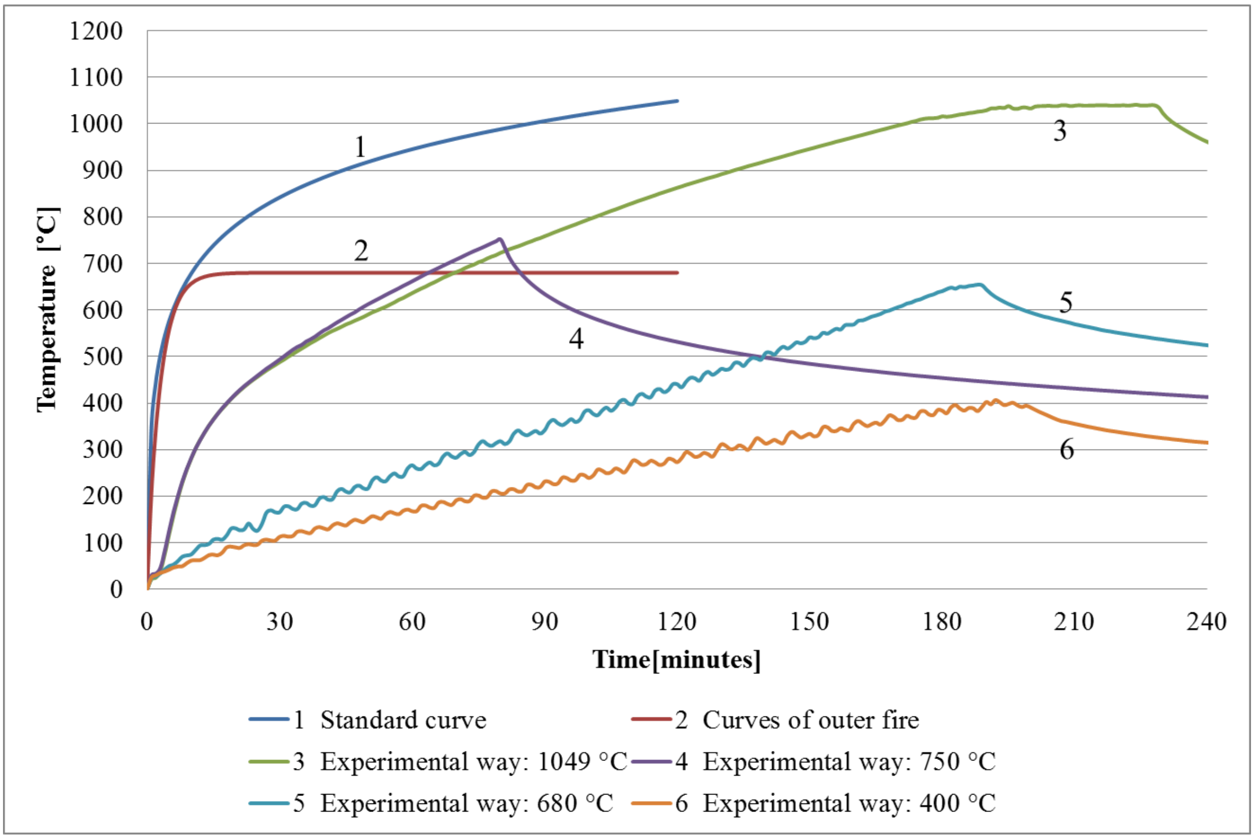

Figure 3 Typical trend of (designed) gradient of loading rate; thermal loading in electric oven

4.4.2 Exposure to Thermal Local (Point) Loading

Local (point) loading has been performed using adjustable propane-butane burner by aiming into the centre of particular loaded prism fragments (note: formerly used by flexural strength test). All heated fragments of samples have been installed between concrete samples that were not mechanically loaded.

Temperature has been detected on the surface exposed to fire on seven exposed spots (0, 0_a, 0_b, 1, 2, 3, 4) – see the Fig. 4). Temperature in the centre of gravity has been measured because of limited measuring range of the contactless thermometer even in points 0_a and 0_b. The far side surface of the samples has been measured on five spots (0, 1, 2, 3, 4 – location identical to the one on the surface exposed to the fire). Thermal share conduction has been represented by temperature progress on the remaining fragment parts (point 5). The values have been noted down every 4 minutes.

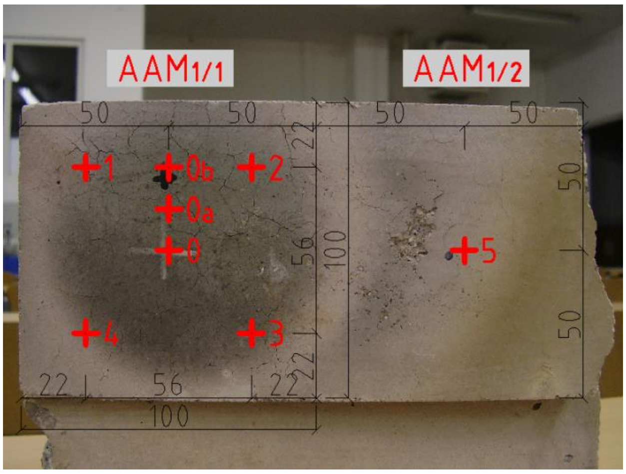

Figure 4 Location of measured points, see Suchánek et al. (2013), sample AAM_annealed_1

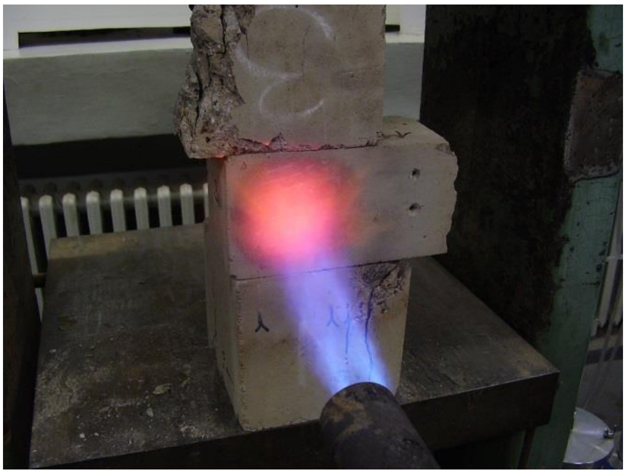

Figure 5 Local fire loading

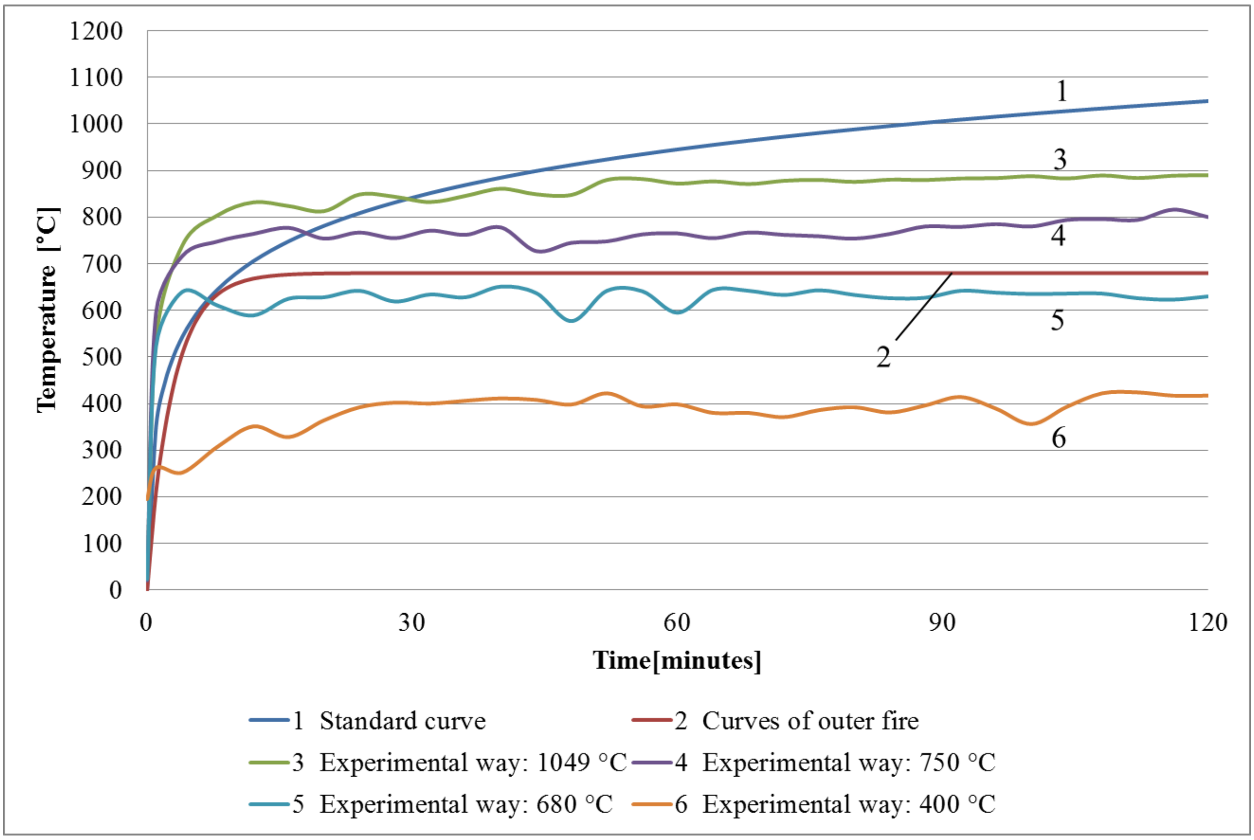

Figure 6 Typical trend of (designed) gradient of warming rate; local (point) loading

5 RESULTS AND DISCUSSION

5.1 Production, Testing of Fresh Concrete – Evaluation

Following Procedure of Dosing of Particular Constituents Proved to be Successful:

1) coarse-grained aggregate (8/16, 4/8) + sand (0/4), 2) addition (limestone), 3) cement, 4) water – ca 2/3 of the dose, 5) / fibres /, 6) super-plasticizing admixture (mixed in ca 1/3 dose of water).

It was proved that the effect of segregation of aggregate to the surface does not arrive by proper selection of artificial porous aggregate.

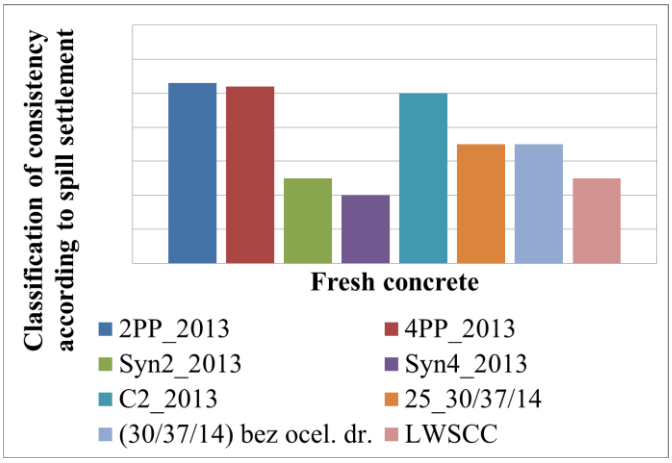

Figure 7 Typical trend of classification of consistency according to spill settlement (SCC, SFRSCC / SFRC)

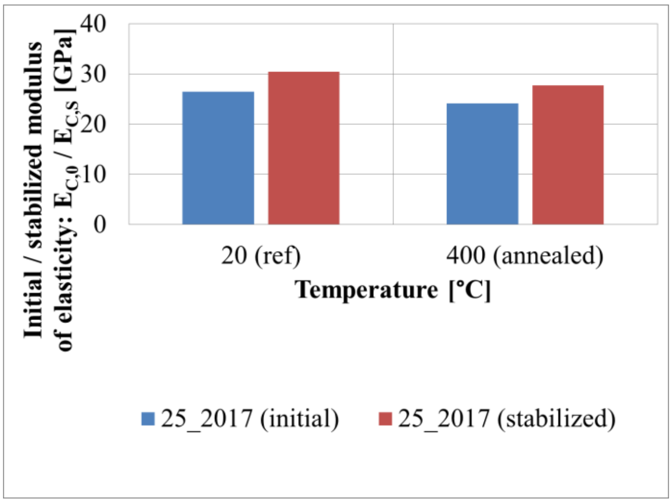

Figure 8 Initial / stabilized secant modulus of elasticity in compression (25_2017), set by standards; loaded on **400 °C** in electrical oven (age$_{\text{ref, annealed}}$: 1 month)

A type of concrete, which has excellent properties in fresh state, increased architectural surface quality, but lower modulus of elasticity, can be made. Considering the microstructure, spalling of surface layers is easier.

The assumption of the viscosity increase of fresh concrete due to added steel fibres has been confirmed; a typical trend is presented in the Fig. 7.

5.2 Modulus of Elasticity of Concrete in Compression, Poisson's Ratio – Evaluation

Table 4 Comparison of secant modules of elasticity in compression (values determined on set of samples, guide values), SCC, SFRSCC, TVB

SCC45/55ref	**25_2016ref**	**25_2017_ref**	**~~FRC~~_ C25/30_2015ref (without fibres)**
According to (ČSN EN 12390-13, 2014), A Method; Stabilized $E_{C,S}$ [GPa], **determined**			
30.3	30.7	30.5	29.5
By means of DIC, Stabilized $E_{C,S,DIC}$ [GPa], vertical dimension 130 mm, **experimentally determined**			
31.2	N/A	31.2	28.6
According to (ČSN EN 1992-1-1 ed. 2, 2011); guide value			
36.0	36.0	36.0	31.0
According to (Model Code 2010, 2012); guide (extrapolated) value			
34.5	34.5	34.5	28.0

Tab. 4 proves reaching of lower values of modules of elasticity of modern types of concrete in comparison to guide values of traditional types of concrete. This is attributed to a higher share of fine constituents and quantity of (super-) plasticizing admixtures.

The assumption of a slight decrease of residual proportional values of modulus of elasticity has been confirmed under the max. temperature of 400 °C, see the Fig. 8.

Poisson's ratio has been determined using 3D DIC. The trend of slightly higher stabilized value in comparison to the initial value of Poisson's ratio has been confirmed. The Poisson's ratio of HSC reaches the average value of 0.19. This lower value is presumably caused by testing of "specific HSC" with the maximum grain size of 16 mm. Application of this coarse fraction in the case of HSC / HPC is very unusual.

5.3 Exposure to Thermal Loading in Electrical Oven - Evaluation

Methodology of experimental determination of residual properties on cooled testing samples approach the methodology of testing according to the "Unstressed Residual"; see the Chap. 1.8.3. It is the most critical approach out of the available ones according to the (ACI 216R-89, 1994).

5.3.1 Loading by the Maximum Temperature of 1049 °C

A negative effect – explosive spalling – has been confirmed due to inner tension and overpressure of steam in naturally humid concrete. Increased fire resistance of SFRC has not been confirmed due to this fact. Selection of steel fibres of different length (shape, diameter) could make different results.

Visible damage by wide cracks (caused by volume changes of concrete structures) has appeared on **LWSCC** and **AAM** samples. Relatively high values of residual compressive and flexural strength have been obtained though the damage was vast and visible (in the case of concrete LWSCC, AAM).

5.3.2 Loading by the Maximum Temperature of 400 °C

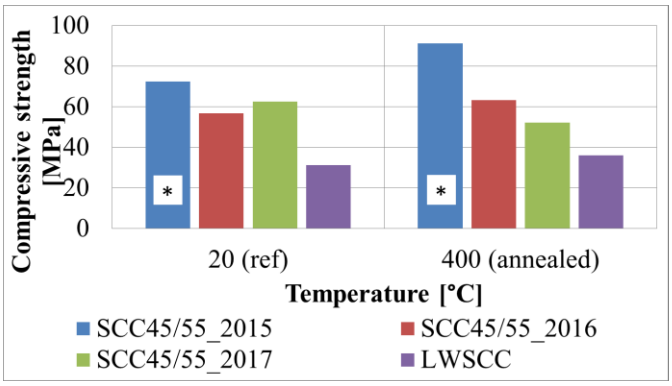

Figure 9 Typical trend of compressive strength of SCC, LWSCC; Thermal Loading in Electrical Oven, loaded on **400 °C**, (age_annealed: SCC: 1 month, LWSCC: 6 months), (* d = 100 mm)

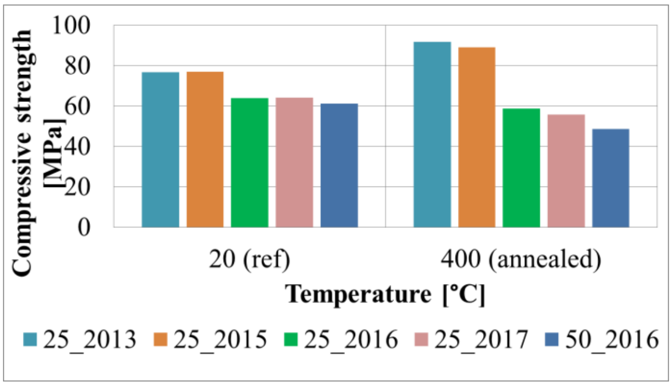

Figure 10 Typical trend of compressive strength of SFRSCC; Thermal Loading in Electrical Oven, loaded on **400 °C** (age_annealed: 25_2013: 3 months, others: 1 month)

5.4 Exposure to Local (Point) Thermal Loading – Evaluation

The effect of synthetic fibres meltdown has been confirmed. Different values of compressive residual strength have been reached in comparison to thermal loading in electric oven. It has been a different way of loading.

Diffusion has appeared. The most significant condensation of water steam has appeared in the case of PFRSCC / PFRC – as soon as in the first minutes of thermal loading.

6 CONCLUSION

Extensive experimental study determines some of the basic characteristics of hardened concrete, strength and deformational properties, using reference and thermally loaded testing samples. Because of the absence of two key sources in the European standards related to concrete – of the modulus of elasticity and the Poisson's ratio – focus has been given on the determination of these important properties.

Exposure to Thermal Loading

Based on two methodologies of thermal loading designed by author, including the concept of warming rate gradient, it can be stated that, under certain conditions and under the maximum temperature of **400 °C**, residual strength characteristics equal or better than reference mechanical properties can be reached. Note: Application of "the most critical methodology" and, at the same time, use of siliceous aggregate concrete has not prevented the increase of residual strength properties.

Exposition to temperature stress – possibilities of further research (~ 400 °C)

Presented experimental methodology of high temperature loading until the maximum temperature of 400 °C is reached could indicate the direction of "modern way of high temperature through-warming" (modern thermal treatment). The determination of the optimum way of temperature loading experimental influence will be a subject of research in the next phase of the experimental work.

Lightweight Self-Compacting Concrete – Further Research Options

Increase of strength of residual mechanical properties of lightweight self-compacting concrete is attributed to chemical processes – in applied type of artificial porous aggregate – caused by high thermal loading. Follow-up experimental studies will aim into the development of concrete with a particular artificial porous aggregate.

Development of "lightweight high performance / high strength fibre reinforced self-compacting concrete", which excels in advantages arisen from the character of particular special types of concrete, including processing of a significant amount of waste material in aggregate, can be labelled as an eccentric idea. This idea emerged based on a verified fact that residual strength properties can be improved by specific high temperature loading. Density simultaneously decreases in the case of lightweight self-compacting concrete (decrease of nearly 500 $kg \cdot m^{-3}$ was achieved in an experiment). This type of concrete will be resistant to high temperature influence and explosive spalling will be prevented. It will have lower thermal conductivity; therefore, reinforcement will be better protected. In fresh state, it will act like a self-compacting fibre reinforced concrete / steel fibre reinforced concrete. Another research options aim to the improvement of artificial aggregate properties even before the beginning of the concrete production.

Summary of Results

Particular evaluations are the subject of the Chapter 5.

Following Summary Can Be Made for Particular Parts:

Exposure to Thermal Loading of the Maximum Temperature of 1049 °C

Explosive spalling directly relates to microstructure and transport mechanisms. In the case of fibre reinforced concrete with added polymer microfibers, explosive spalling has been prevented. Passive protection has been proved. By this modification of concrete, costs have increased in the minimum extent, but the result has increased passive safety including other advantages emerging from the use of fibre reinforced concrete.

It is known that steel fibre reinforced concrete can, under certain conditions, postpone spalling of concrete. Based on performed experimental work, it can be stated that increased fire resistance of steel fibre reinforced concrete has not been confirmed. Explosive spalling of steel fibre resistance concrete (in comparison to the types of concrete without fibres) has happened. It can be assumed that oxidized steel fibres have caused damage of the samples (popping). The oxidation has caused expansion of particular steel fibres. The effect of growing tensile stress between steel fibres and concrete is attributed to thermal flow transmission into the steel fibres due to high thermal conductivity of steel contrary to concrete. Temperature difference between steel fibres and concrete has caused spalling of concrete.

High thermal loading has caused a change of physicochemical properties. The effect of dominant expansion of aggregate has been confirmed; visible damage in the place of border of phases has happened.

Density of concrete has decreased due to expulsion of free and, later, physically bound water. Due to the decrease of physically bound water, degradation that is more significant has happened. Structural changes of studied special types of concrete are shown using SEM and EDXA.

Modulus of Elasticity of Concrete, Poisson’s Ratio

Modulus of elasticity is one of the basic characteristics of hardened concrete. Secant modules of elasticity values of special types of concrete in compression have been determined by standards and by correlation of digital image. Analysis of variance of results has been made by Anova test on the level of significance 0.05. Conclusions could differ in the case of larger statistical data set.

It has been proved, by application of two methods, that “modern types of concrete” have lower values of modules of elasticity. This fact is attributed to the higher share of fine constituents and quantity of (super-) plasticizing admixtures.

It has been proved that modulus of elasticity decreases by high thermal loading more rapidly than strength characteristics.

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