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RESEARCH ARTICLE

Effect of the concrete's component on the heat shock bearing capacity of tunnel linings

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Abstract

During the last decades, the increasing number of incidents in road and railway tunnels have attracted public attention to the danger of tunnel fires. These incidents established that quickly accumulating, huge amount of evolved heat impairs the reinforced concrete structures of tunnel linings. Designing of fire-bearing linings, it is necessary to understand the behaviour of the linings impacted by bumping heat load. In this paper, the results of our heat load examinations of residual strength (compressive strength and split-tensile strength) parameters on different mixtures of concrete were summarised.

Keywords

tunnel · fire · fire load · concrete · residual properties

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Notation

Air	air-entraining admixture
B_θ	Brinke number, heat loaded at θ temperature
d_{MAX}	maximum size of aggregate
$f_{c,\theta}$	residual compressive strength, heat loaded at θ temperature
$f_{ct,\theta}$	residual split-tensile strength, heat loaded at θ temperature
h	length
m%	percentage by mass
m_c%	percentage by mass of the cement
m_{sand}%	percentage by mass of the sand
Ø	diameter
PP-fibre or PP	polypropylene-fibre
V%	percentage by volume

1 Introduction

One of the basics of the existence of our modern industrial community is the provision of reliable, safe and fast traffic infrastructure, as well as safe and efficient public transport in cities. Pertain to the development the forcing of the traffic into tunnel networks is needful.

By forcing traffic into tunnels, i.e. into closed spaces, the safety risks exceed greatly the proper to the "open space" traffic. In case of abnormal operating conditions, the most dangerous situation either to human life or to the tunnel structure is fire.

Despite of growing and rigorous safety directives, the number of accidents and the amount of damage in tunnels around the world show a growing tendency. Serious accidents turn attention to investigate the effect of tunnel fires, as well as increasing residual safety of structures. One important field of research of the last decades is the analysis of tunnel linings materials, on the grounds of the different character and mass of evolving heat, compared to "usual" building fire (e.g. ISO 834). To investigate structural materials, it is necessary to define the character of the fire and the heat loading onto the material. Some European standards determine the air (gas) temperatures of the tunnel fire based on theoretical assumptions, numerical analysis and large-scale tests [4].

At some individual large projects, special temperature-time curves have been defined because of the burning characteristics of vehicles being more specialized. A common property of these curves, as shown in Fig. 1, is the quick rise of temperature (1000 ˚C in 5 minutes).

To efficiently moderate effects on structural materials, it is necessary to recognize the physical and chemical changes of the concrete and the reinforced concrete. Examining the fire resistance of reinforced concrete tunnel linings the following elements should be analysed: behaviour of the concrete, behaviour of the rebars, and characteristic of the bond. The strength of common used rebars starts to decrease at the temperature of 400 ˚C. At 800 ˚C only 10% of the strength is measurable [9]. The protection of the rebars could be fireproof (heatproof) coating or the improved fire-bearing capacity of the concrete. Using concrete cover as a heat proofing material, significant effect could be achieved with a 4050 mm cover layer. Researching the precise behaviour of concrete and analysing the physical and chemical changes is helpful to develop concretes with better fire-resisting qualities.

Increasing the temperature, the components of the concrete physically and chemically change as shown in Tab. 1. The reduction of concrete compressive strength is also noticeable by increasing the temperature (Fig. 2).

The progressing vapour and gas, the drained conditions at the heated surface and the low-permeability of concrete [14] lead to strong pressure gradient close to the surface, in the form of so-called moisture clog, a high-pressure steam barrier that develops near to the surface of the concrete. This pressure zone joining with the volume increasing chemical change of the quartz at 573 ˚C may flake the surface layers of the concrete. This process is called spalling (Fig. 3). The most serious from of spalling in a fire situation is the explosive spalling, which could remove the insulating concrete cover up to 25-100 mm [6]. The decrease of the insulating layer and exposing rebars, the high gas temperature will take effect on the steel (Fig. 4).

The main factors influencing on explosive spalling are [6]:

- permeability: important factor on the spalling, especially on the critical gas pressure level.
- age of concrete: due to the (usually) lower moisture level in older concrete, the age of the concrete may be an influence factor of the spalling.
- strength of concrete: the higher strength level is usually achieved by reducing the water/cement ratio and/or adding special compound to the concrete (e.g. silica-fume) which produce a dense concrete of a very low permeability.
- type of aggregate: the likelihood of explosive spalling is less for concrete containing a low thermal expansion aggregate. The risk of explosive spalling increased in the following order: lightweight, basalt, limestone, siliceous, Thames River gravel.

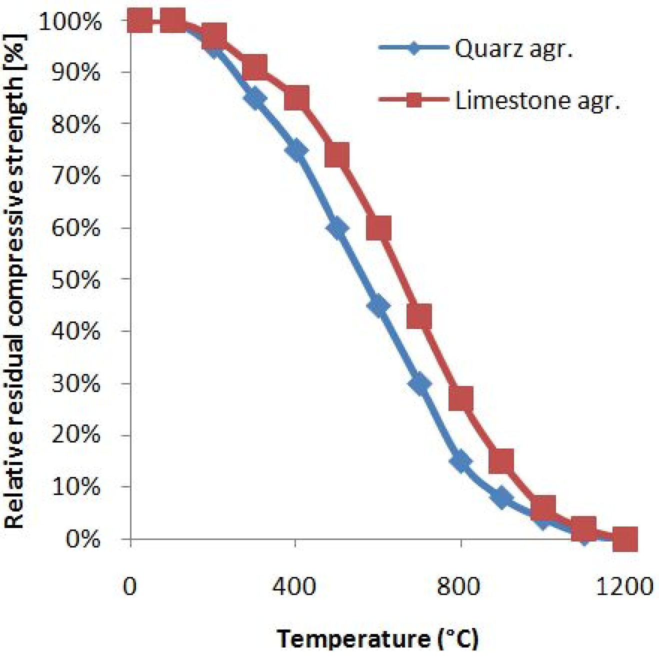

Fig. 2. Relative compressive strength of the concrete (MSZ EN 1992-1-2)

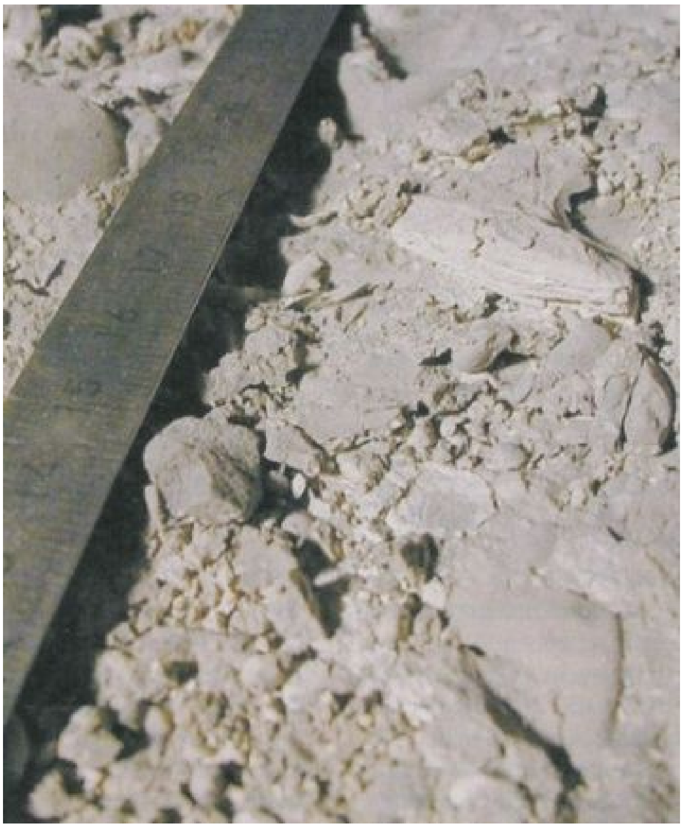

Fig. 3. Spalling (Wetzig, 2000)

- size of aggregate: the increasing of the size of the aggregate is promoting explosive spalling.
- cracking: while micro-crackings facilitate the escape of mois-

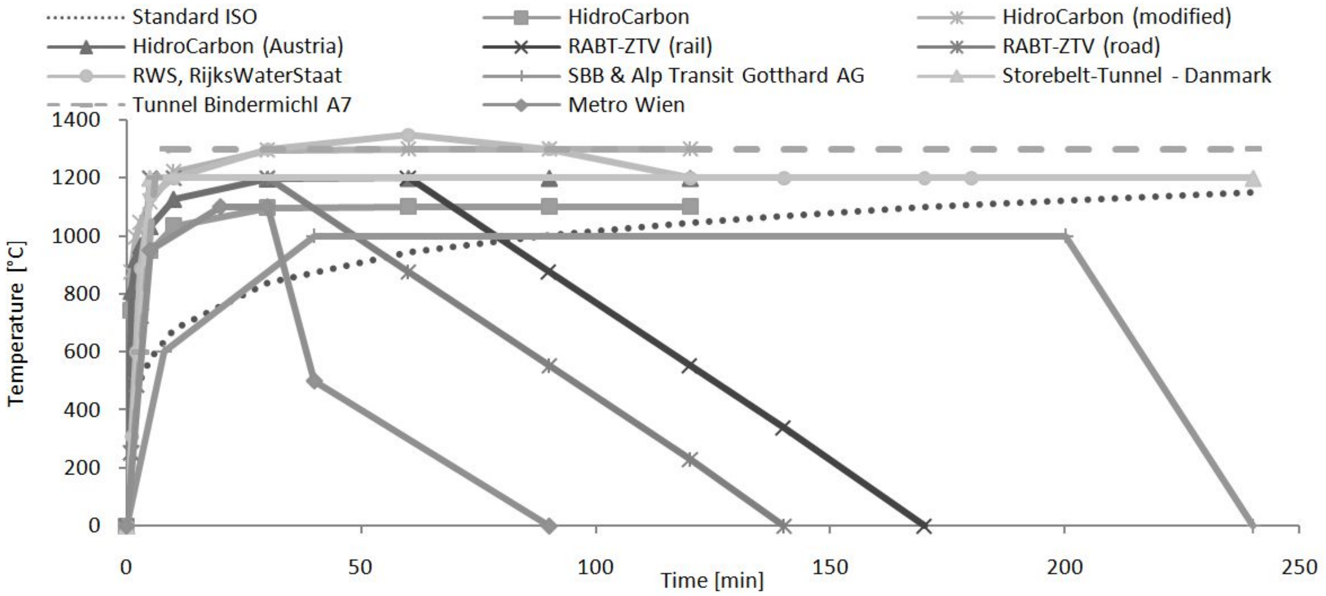

Fig. 1. Standard fire characteristic curves; air (gas) temperatures, [4, 12] and [6].

Tab. 1. Physical and chemical changes in concrete at elevated temperature

Temperature[˚C]	Reaction, converting or property
30-120	discharge of phisicaly bounded water
140180	dehidratation of *ettringit* (C_3 A· 3Cs· H_{32}), and *monosulphate* (C_3 A· Cs· H_{12}) [11]
250-600	discharge of chamicaly bounded water
300-	significant increase of microcrackings and the porosity of concrete [2] and [13]
400-450	dehydratation of $Ca(OH)_2$:$Ca\,(OH)_2 \rightarrow$ CaO+H_2O
573 (575)	change of crystal structure of SiO_2 : $\alpha \rightarrow \beta$ SiO_2 (increase of volume 5,7%) (Beard and Carvel, 2005)
750-850	*decay of* $CaCO_3$: $CaCO_3 \rightarrow CaO + CO_2$ [5] [11]
850-1000	dehydratation of CSH [5]
1300-1700	melting of the concrete's components [11]

ture during heating and thus relieve pore pressure, they also facilitate the process of spalling by providing sites for crack propagation.

- reinforcement: the prescence or absence of reinforcement was found to be more important factor in spalling than the quality of steel.
- concrete cover: the mass of unsupported concrete is significant factor of explosive spalling.
- supplementary reinforcement: the use of light mesh cover does not prevent spalling but could limit the extent of spalling.
- steel fibre: the addition of steel fibre did not eliminate the explosions of concrete.
- polypropylene-fibres: the PP-fibre contents are used in concrete to reduce the probability of explosive spalling in fire [8]. The residual space of the melting fibre could decrease the gas pressure (Figs. 5-6).
- air-entrainment: the higher air content increasing the absorption value of the concrete thus it may remove the risk of spalling.

2 Experimental tests

The effect of the concrete's components was investigated at the laboratory of the Department of Construction Materials and Engineering Geology at Budapest University of Technology and Economics. The aim of our study was to define the change of residual mechanical parameters of concrete to thermal shock.

2.1 Experimental recipes

The effect of the component on residual strength of concrete was investigated in three steps. First, the effect of the water/cement ratio (0,38; 0,45; 0,55) and the maximum size of aggregate (8 mm and 16 mm) were tested with 6 different mixtures. Second, the effect of dosage of PP-fibres and air-entraining admixture on the concrete was tested with 6 different mixtures. Third, the effect of special sand substituent aggregates, barite were tested with 2 different mixtures. In every mixture the cement type (CEM I 42,5 R) and the dosage of cement (400 kg/m^3) were constant. Constant and variable parameters are shown in Tab. 2. Grading curves are summarized in Tab. **??**. If it was necessary, superplasticizer was used adjust the consistency.

To analyse the effect of the variable parameters values of com-

Tab. 2. Constant and variable parameters of the tests

	Mixture		
Test step	**1st**	**2nd**	**3rd**
Sign of Mixture	**E1-E6**	**E7-E12**	**E13-E14**
Constant parameter	cement type (CEM I 42,5 R) dosage of cement (400 kg/m^3)		
	type of aggregates (quartz sand and gravel)		d_{MAX} (16 mm)
		grading curves d_{MAX} (16 mm)	
		water/cement ratio (0,45)	
Variable parameters	– d_{MAX} (8, 16 mm) – water/cement ratio (0,38; 0,45; 0,55)	– dosage of air-entraining admixture (0,15; 0,3; 0,6 m_c%) – dosage of PP-fibre (0,1; 0,2; 0,5 V%)	- dosage of barite (33% and 100% m_{sand}%) grading curves
Storage method	“combination storage” (MSZ 4798-1:2004) in water for 7 days, afterwards at laboratory air conditions		
Tested properties	Compressive strength (cylinder shape specimens Ø=60 mm h=120 mm) Split-tensile strength (cylinder shape specimens Ø=60 mm h=60 mm) tested at cooled down specimens		
Tested temperatures	11 temperature steps (20, 50, 100, 150, 200, 300, 400, 500, 600, 750, 900 °C)		

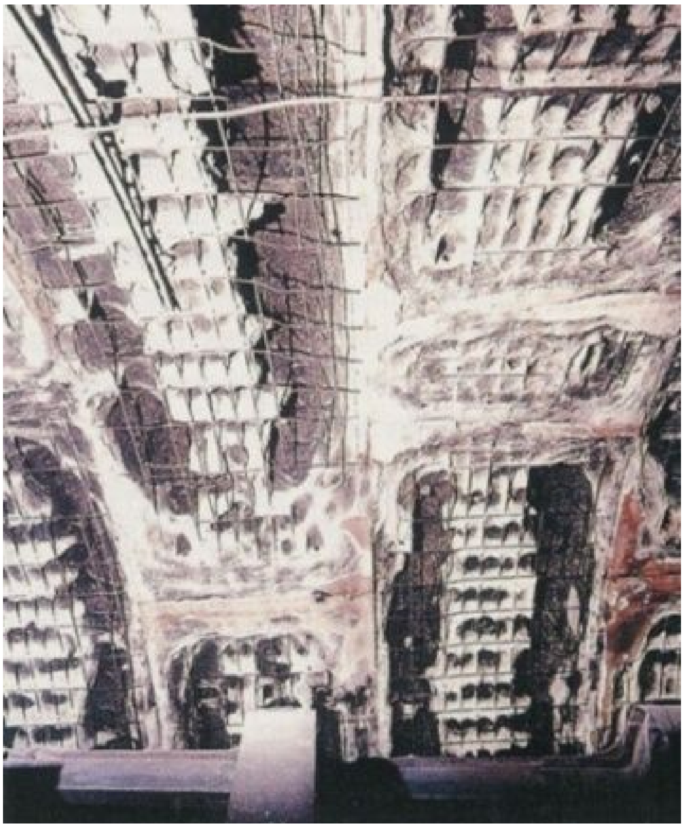

Fig. 4. Spalling with exposed rebar after the Channel Tunnel fire [4]

Fig. 5. Concrete element loaded with direct flame, without fibre (left) and with 2 kg/m^3 fibre (right) (Allen, 2006) [1]

pressive strength, split-tensile strength and the Brinke number (proportion of the compressive and split-tensile strength) were used.

2.2 Test procedure

For testing the residual strength parameters, cylinder shape specimens were made. At each temperature step 3 specimens for compressive strength tests (aspect ratio 2:1, Fig. 7) and 6 specimens for split-tensile strength tests (aspect ratio 1:1, Fig. 8) were made (except the base, 20 °C temperature step which were doubled). The cylinders were cut with diamond blade to make the pressured surfaces plain and parallel (compressive strength’s specimens) and to adjust the aspect ratio (split-tensile strength’s specimens) (Fig. 9). More than 1500 specimens were tested during the research.

Before the heat test the specimens’ mass and size were measured. The specimens were put into a preheated electrical furnace to model the effect of the heat shock. The test duration was 120 minutes. After the specimens cooled down, their mass and

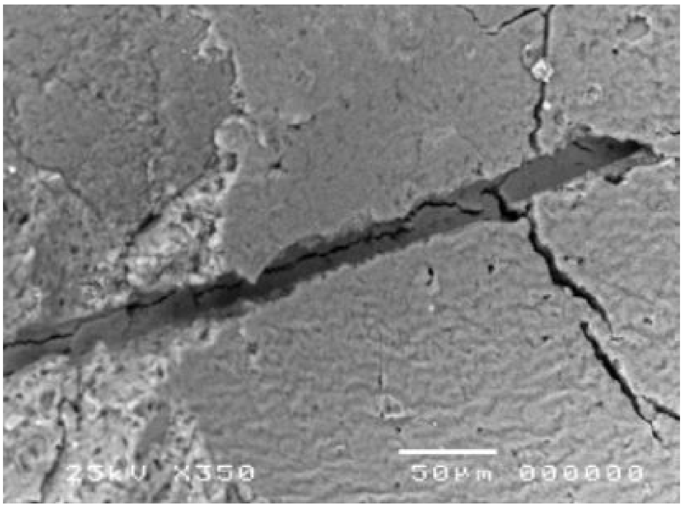

Fig. 6. Residual space of a melted fibre [16]

Tab. 3. Grading curves

Sign of Mixture	Sand (0/4) %	Gravel (4/8) %	Gravel (8/16) %	Barite (0/6) %	Total fineness modulus
E1-E3	50	50	–	–	**5,61**
E4-E12	45	25	30	–	**6,04**
E13	35	20	30	15	**5,91**
E14	–	20	30	50	**5,90**

Fig. 7. Specimen for compressive strength test

size were measured again, and then the specimens were fractured. The strength results were compared to the base laboratory strength value.

Fig. 8. Specimen for split-tensile strength test

Fig. 9. Half of the specimens of a series of one mixture

3 Results

3.1 Principle establishment

During the tests all of the specimens heat treated at 900 °C after 24-48 hours disintegrated or became crushable by hand (Figs. 10 and 11). It is clearly visible on the picture, that the aggregates (except of some decolouration) stayed undamaged; the origin of failure of the specimens is the cement matrix and interface of the aggregate and the cement. These specimens' strength values were visualized on the diagrams with 0 MPa.

3.2 Compressive strength

Residual compressive strength values of the 1^{st} test steps (variable were the water/cement ratio and the grain size) are visualized on the diagram in Fig. 12.

By the analysis of the curves (Fig. 12) it has been determined:

1 The characteristics of residual compressive strength changing consist of three parts. Constant or nearly constant initial phase followed by rapid decrease of relative strength values. Residual strength values loaded with high temperature (over 600 °C) were only 1020 % of the initial strength.

Fig. 10. Disintegration of specimens loaded at 900 ˚C

Fig. 11. Disintegration of specimens loaded at 900 ˚C

2 As water/cement ratio increases, the rapid strength-decreasing phase starts earlier. The difference between the beginning temperatures is approx. 1 temperature steep.

3 Mixtures with the same water/cement ratio have the same characteristic independently of the maximum size of aggregate.

Residual compressive strength values of the 2^{nd} test step (variables were the dosage of PP-fibre and air-entraining admixture) are visualized on the diagram in Fig. 13. Reference values of the mixture of the same water/cement ratio and grading curve, but without any fibre or air-entraining admixture is also shown on the diagram.

By analysing the curves (Fig. 13) it has been determined:

1 The residual compressive strength curves of PP-fibre containing mixtures show almost the same characteristics, independently of the mass of the fibres. Also, the curves of the air-entraining admixture containing mixtures show same characteristic.

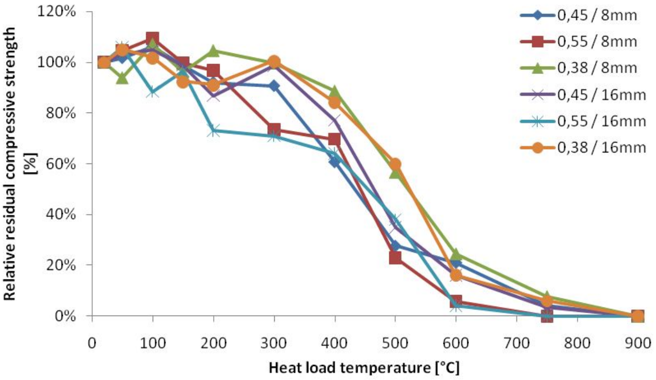

Fig. 12. Effect of water/cement ratio and grain size on relative residual compressive strength of concrete (marking: water/cement ratio / maximum size of aggregate)

2 It has been observed that the characteristic of the PP-fibres containing mixtures have lower values than the reference curves in the range of 200-400 ˚C. The melting fibres effect decreasing strength because of the crack initiating effect. At higher temperature range (higher than 500 ˚C) the difference can be hardly noticed. The relative residual strength values characteristics are almost linear. The approximating function is shown on Eq. (1).

$$\frac{f_{c,\theta}}{f_{c,20^\circ C}} = \left| \begin{array}{l} \begin{cases} 1-\dfrac{\theta}{800} \quad \text{if} \quad \theta < 800^\circ C \\ 0 \quad \text{if} \quad \theta \geq 800^\circ C \end{cases} \\ \theta \in [20^\circ C; 900^\circ C] \end{array} \right. \tag{1}$$

1 Air-entraining admixtures containing mixtures characteristic have constant section in the middle temperature range (100-300 ˚C) at approx. 75-80% relative strength level, lower than the reference curve. Over 500 ˚C temperature level the characteristics are the same with the reference.

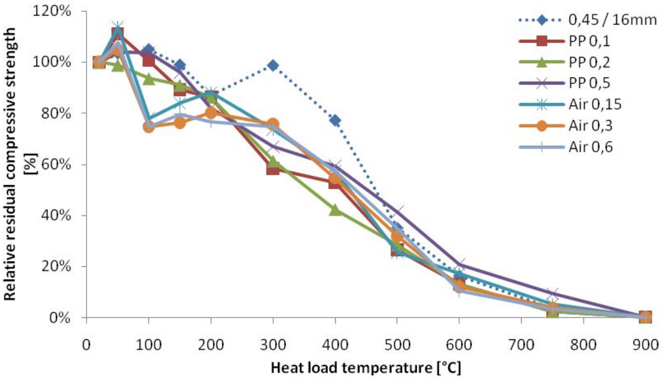

Fig. 13. Effect of dosage of PP-fibre and air-entraining admixture on relative residual compressive strength of concrete (marking: dosage of PP-fibre V% and dosage of air-entraining admixture m_c%)

The air-entraining admixture was barley investigated and not used to improve the heat shock bearing capacity of concrete. Due to our tests the compressive strength characteristics could be comprise to the PP-fibre containing mixture. Although initial strength of these concretes is lower because of the high air content, resistance to the spalling effect is higher compared to ordinary concrete.

Residual compressive strength values of the 3^{rd} test steps (variable was the dosage of barite) are visualized on the diagram in Fig. 14. Reference values of the mixture of the same water/cement ratio and nearly the same grading curve is also visualized on the diagram.

By analysing the curves (Fig. 14) it has been observed:

1 Relative residual characteristics of the barite containing mixtures have nearly linear characteristic.

2 At higher temperatures (500-750 ˚C) dosage of barite improves the heat shock bearing capacity of the concrete. Residual values are higher than the reference curves.

3 Although, in lower temperature zone (below 500 ˚C) the reference values are higher, the difference is minor and the characteristics are auspicious.

3.3 Split-tensile strength

The effect of the concrete's components on split-tensile strength characteristics is highly important because of the resistance to the spalling effect. The results of experimental tests, relative residual split-tensile strength characteristics are shown in Fig. 15. By analysing the curves (Fig. 15) it has been observed:

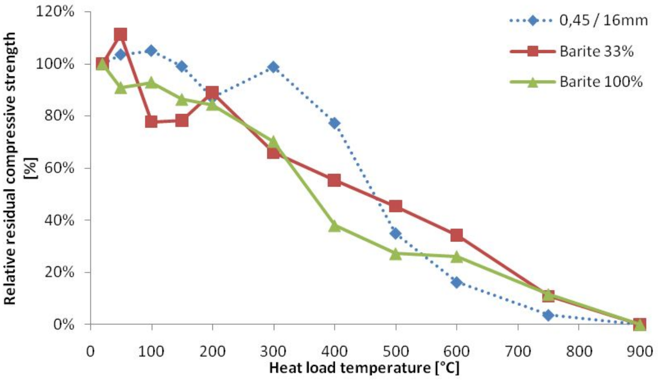

Fig. 14. Relative residual split-tensile strength of concrete (marking: water/cement ratio / maximum size of aggregate; dosage of PP-fibre V% and dosage of air-entraining admixture m$_c$%)

1 All of the series containing only quartz aggregate have nearly the same relative curves.

2 The relative curves have bilinear characteristic. The approximating function is shown on equation (2).

$$\frac{f_{ct,\theta}}{f_{ct,20^\circ C}} = \left| \begin{array}{l} \begin{cases} 1 \quad \text{if} \quad \theta < 200^\circ C \\ 1,5-\dfrac{\theta}{400} \quad \text{if} \quad 200^\circ C \le \theta < 600^\circ C \\ 0 \quad \text{if} \quad \theta \ge 600^\circ C \end{cases} \\ \theta \in [20^\circ C; 900^\circ C] \end{array} \right. \qquad (2)$$

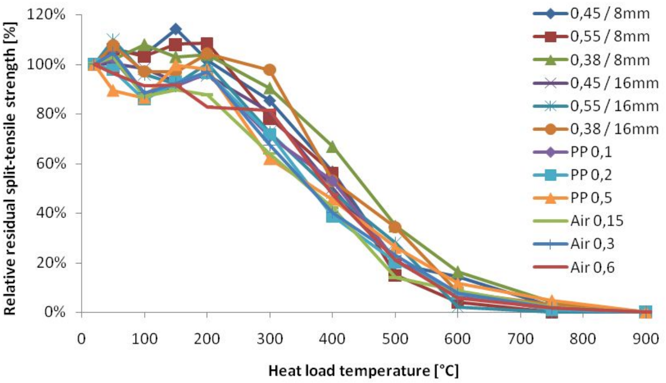

Fig. 15. Relative residual split-tensile strength of concrete (marking: water/cement ratio / maximum size of aggregate; dosage of PP-fibre V% and dosage of air-entraining admixture m_c %)

1 Water/cement ratio, maximum size of aggregate, dosage and mass of PP-fibre, or dosage and mass of air-entraining are undetectable.

The barite is the only component which has effect in our researches. The Fig. 16 shows the results of the heat shock tests.

By analysing the curves (Fig. 16) it has been determined that compressive strength characteristics the barite containing mixtures have very advantageous behaviour at higher temperature (over 500 ˚C).

The barite component used as aggregate has auspicious behaviour (both compressive and split-tensile strength) at higher temperature range (usually over 500 ˚C). Although the relative behaviour at lower temperature (lower than 400 ˚C) is slightly worse than the reference curves, the real initial strength values were better.

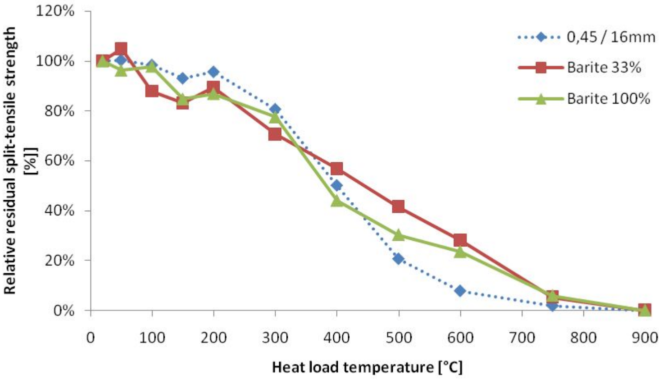

Fig. 16. The effect of the dosage of barite on the relative residual split-tensile strength of concrete (marking: dosage of barite m$_{sand}$%)

3.4 Brinke number

Brinke number's (ratio compressive and split-tensile strength) relative characteristics are shown in Fig. 17. There is opportunity to visualize all of the quartz aggregate contenting mixtures in one diagram, because of the similarity of the curves.

It has been observed that curves (Fig. 17) are nearly similar

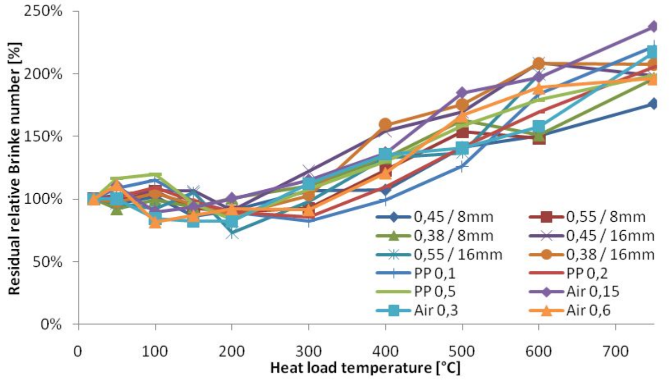

Fig. 17. Relative residual Brinke number's characteristic curves (marking: water/cement ratio / maximum size of aggregate; dosage of PP-fibre V% and dosage of air-entraining admixture m$_c$%)

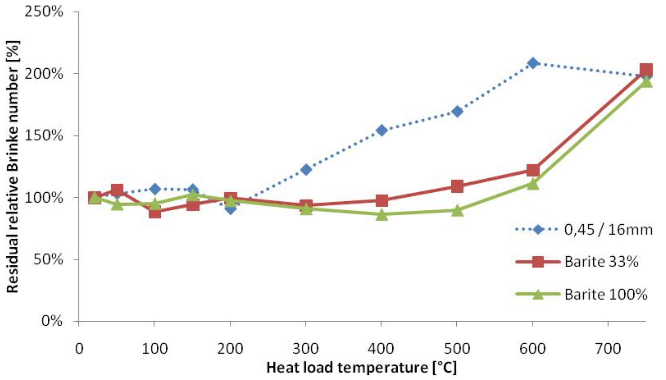

Fig. 18. Effect of dosage of barite on relative residual Brinke number (marking: dosage of barite m$_{sand}$%)

and could be modelled with bilinear characteristics. The approximating function is shown on equation (3).

$$\frac{B_\theta}{B_{20^\circ C}} = \left| \begin{array}{l} \begin{cases} 1 \quad \text{if} \quad \theta < 300^\circ C \\ \dfrac{\theta}{450} + \dfrac{1}{3} \quad \text{if} \quad 300^\circ C \leq \theta < 750^\circ C \end{cases} \\ \theta \in [20^\circ C; 750^\circ C] \end{array} \right. \tag{3}$$

As the split-tensile strength characteristics of barite containing mixtures so have altering characteristic of the Brinke number's curves. The Fig. 18 shows the heat shock test of the barite containing mixtures. It was observed that characteristic could also be modelled with bilinear approximation, but the function is materially different from the Eq. (3). The ratio of the compressive strength value and the split-tensile strength value is nearly equal to the initial value up to 600 ˚C, as contrary to the only quartz containing mixtures, where the Brinke number is equal to the initial value only up to 300 ˚C. The barite containing concrete's relative Brinke numbers are to be modelled with the approximating function shown on Eq. (4).

$$\frac{B_\theta}{B_{20^\circ C}} = \left| \begin{array}{l} \begin{cases} 1 \quad \text{if} \quad \theta < 600^\circ C \\ \dfrac{\theta}{150} - 3 \quad \text{if} \quad 600^\circ C \leq \theta < 750^\circ C \end{cases} \\ \theta \in [20^\circ C; 750^\circ C] \end{array} \right. \tag{4}$$

4 Conclusion

In this paper our experimental results of the heat shock bearing capacity of different concrete mixtures have been summarised. The results of more than 1500 cylinder shape specimens have been evaluated in this research. The concrete' components were tested in 3 steps. The effect of the water/cement ratio (0,38; 0,45; 0,55) and the maximum size of aggregate (8 mm and 16 mm) with 6 different mixtures, the effect of PP-fibre dosaging and air-entraining admixture on the concrete with 6 different mixtures and also the effect of special sand substituent aggregates, barite with 2 different mixtures were tested. The only constant parameters during the research were the cement's type and dosage. The specimens were heated in 11 temperature steps from 20 ˚C up to 900 ˚C. The compressive strength, the split-tensile strength and their ratio the Brinke number was measured and calculated on the cooled down specimens after the heat load. The results were compared with the base laboratory strength value.

It has been observed that the characteristics of the changing of residual compressive strength consist of three parts. Constant or nearly constant initial phase is followed by rapid decrease of relative strength values. Residual strength values loaded with high temperature (over 600 ˚C) were only 10-20 % of the initial strength.

It has been determined that the rapid strength decreasing phase of the relative residual compressive strength characteristics starts earlier, in parallel with the increasing water/cement ratio. The difference between the beginning temperatures of the decreasing is approx. 1 temperature step. It has been also determined that the residual compressive strength characteristic is independent of the maximum size of aggregate. The mixtures with same water/cement ratio but different grading curves have the same characteristic.

Analysing residual characteristics of compressive strength by PP-fibre containing mixtures it has been determined that the characteristics are linear from the base laboratory strength up to the temperature level of disintegration (900 ˚C). Linear approximate function was recommended to model the behaviour. Due to the melting of PP-fibre, difference was observed between the mixtures with and without fibre. In the temperature range of 200-400 ˚C concretes containing PP-fibre have bit lower residual strength than the reference mixture.

The heat shock bearing capacity of the concrete containing air-entraining admixture was never prescribed. It has been determined that the relative residual compressive strength of the mixtures could be comprise to the PP-fibre containing mixtures. Although, the initial strength values are lower of these concrete because of the high air content, but this is the reason of higher resistance to the spalling effect, compared to ordinary concrete.

Dosaging barite aggregate changed the characteristics auspiciously. It has been observed that relative residual compressive strength is higher than the reference curve in the high temperature level range (higher than 500 °C).

It has been observed that relative residual split-tensile strength characteristics of all mixtures containing only quartz aggregate are nearly the same, and can be modelled with a bilinear approximation function. Neither the change of water/cement ratio, nor the different grading curves changed the characteristics, and had also no influence the dosage of either PP-fibre or air-entraining admixture. Bilinear approximation function has been suggested to characterize the behaviour.

Barite aggregate consisting mixtures also had, as well as on compressive strength, advantageous behaviour in higher temperature range.

The effect of the components on the Brinke number (ratio of the compressive and split-tensile strength) is analogue to the split-tensile strength characteristics. All of the 12, only quartz aggregate containing mixtures behaviour were nearly the same. The initial Brinke value (approx. 10) is constant up to 300 °C, afterwards it grows to 200% of the starting value at 750 °C. Also a bilinear approximation function has been suggested to characterize the behaviour.

The barite aggregate altered the residual Brinke number's characteristics behaviour. The value of the initial test could be used up to 600 °C. Afterwards rapid increase was observed to the 200% value. Bilinear approximation function has been suggested.

Summarising numerous results of factorized specimens several determination has been made. The effect of water/cement ratio, grading curves, dosage of PP-fibres, air-entraining admixture and even the dosage of barite aggregate has been enucleate on the residual compressive strength. Inducing rules from the ascertained results it has been determined that the material of the aggregates have an influence on the residual characteristics of split-tensile strength and Brinke number.

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