

fib Symposium
PRAGUE 2011

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**Concrete engineering
for excellence and efficiency**

8–10 June 2011
Clarion Congress
Hotel Prague
Prague
Czech Republic



**Proceedings
Volume 1**

Edited by Vlastimil Šrůma

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METROSTAU



Czech Concrete Society



Czech *fib* National Member Group

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Vlastimil Šrůma

**Managing Director of
Czech Concrete Society**

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ORGANIZER

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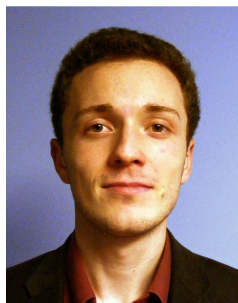
INFLUENCE OF SILICA FUME ON FIRE RESISTANCE



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Abstract

Concrete is a composite material that consists mainly of mineral aggregates bound by a matrix of hardened cement paste. The composition and structure of hardened cement paste has an important influence on the properties of concrete exposed to high temperatures. In case of HPC the application of silica fume is often necessary. Behaviour of concrete with silica fume at high temperatures is different from that of conventional concrete.

An extensive experimental study was carried out to analyze the post heating characteristics of hardened cement pastes subjected to temperatures up to 1000°C. Major parameters of our experimental study were the silica fume and water-cement ratio. Results indicated: the number and size of surface cracks as well as loss of compressive strength depend on the water-cement ratio and on the silica fume content of hardened cement paste.

An extensive experimental study was carried out to analyze the post heating characteristics of concrete with silica fume (0, 3, 9 m_c%) subjected to temperatures up to 1000°C. The probability of spalling was higher for prisms than for cylinders. That could be explained by the different forms of the specimens (i.e. circular or with corners). The increase of the silica fume content decreased the probability of the explosive spalling of the concrete specimens

Keywords: High strength concrete, High temperatures, Silica fume, Spalling, strength reduction

1 Introduction

Studies on the performance of silica fume in concrete began in the 1950s [1, 2]. Silica fume is a by-product resulting from the reaction of high-purity quartz with coal in electric arc furnaces in production of ferro-silicon alloys and silicon metal [3]. It is well known that silica fume improve

the mechanical properties and durability of concrete. The high amount of amorphous silicon dioxide and very fine spherical particles are the main reasons for its pozzolanic activity [2]. The silica fume is the most well known additive material in high-strength concrete.

Several research projects were directed to study the behaviour of concrete made with silica fume after exposure to elevated temperatures [4, 5, 6, 7]. The main aim of these studies was to test the risk of explosive spalling in case of high strength concrete with silica fume.

Hertz [4] suggested to replace 10% of cement by silica fume as upper limit to avoid spalling. The residual compressive strength (170 N/mm^2) with 14-20 % silica fume increased after 350°C and then decreased rapidly at high temperatures.

Phan and Carino [5] reported that concretes containing 10% silica fume showed better performance than normal strengths concrete at 100 and 200°C , but higher relative strength losses were observed in the silica fume concretes after subjected to temperatures of 300 and 450°C .

Saad et al [6] made experiments with 10, 20 and 30% silica fume. The water to cement ratio was 0.4. They concluded, that concrete specimens with 10% silica fume produced lower porosity values at all temperatures of heat treatment than specimens without silica fume. Concrete specimens made with 10% silica fume produced the highest compressive strength values at all temperatures of thermal treatment while more CSH is formed with stronger binding forces and a sufficient thermal stability.

Behnood and Hasan [7] suggested that the dosage of silica fume has no significant effect on the relative compressive strength at 100 and 200°C . In their tests, above 300°C , the amount of silica fume had significant effects on the residual compressive strength.

2 Experimental Studies

Present study is directed to the analysis of simultaneous effects of high temperatures as well as silica fume to the cement. Due to high temperatures, the structure and chemical composition of concrete change the degree of change depends on all constituent of concrete.

Main purpose of our experimental study was to determine the influences of silica fume content on post-heating characteristic of hardened cement pastes.

Test variables were *for hardened cement specimens*: silica fume content (0, 1, 3, 6, 9, 15 $\text{m}_\text{c}\%$), water to cement ratio (0.3; 0.35; 0.4) and maximum temperature (20, 50, 150, 300, 500, 1000°C). Studied characteristics were: surface cracking and reduction of compressive strength.

Test variables were *for concrete specimens*: silica fume content (0, 3, 9 $\text{m}_\text{c}\%$), and maximum temperature (20, 50, 150, 300, 500, 1000°C). Studied characteristics were: surface cracking, spalling, reduction of compressive strength and reduction of flexural strength. The concrete compositions are given in **Tab. 1**. Studied characteristics were: surface cracking, reduction of compressive strength and reduction of flexural strength.

Tab. 1 Concrete mixes (kg/m^3) for the experimental study

	Mix 1	Mix 2	Mix 3
cement (CEM I 42.5N)	400	400	400
silica fume	-	12	36
water	140	140	140
aggregate 0-4 mm	755	748	736
aggregate 4-8 mm	472	468	460
aggregate 8-16 mm	661	655	644
plastificator	6	7.2	8
w/c	0.35	0.35	0.35
w/b binder=cement+k*silica fume where k=2 [8]	0.35	0.33	0.30

After removing the specimens from the formwork they were stored in water for 7 days then kept at laboratory conditions until testing. The specimens were 28 days old by testing. In case of experiments with high temperatures the temperature history and the time of testing are of high importance. Our heating curve was similar to the standard fire curve for buildings up to 800°C. After heating up the specimens were kept for two hours at these maximum temperatures (20°C, 150°C, 300°C, 500°C, 1000°C). Specimens were then cooled down in laboratory conditions. Specimens were tested at room temperature.

3 Test results

3.1 Hardened cement paste

3.1.1 Visual observation

Temperature loading on hardened cement paste specimens caused chemical and physical changes leading to surface cracking. Development of surface cracks as a result of the elevated temperatures is presented in **Fig. 1**. Cracks were formed by heating up to 500°C. The size (width and length) of the cracks were significantly smaller with the increased silica fume content. Size and number of cracks considerably increased by heating up to 1000°C. Possible reasons of crack developments are the chemical reactions in the cement stone, i.e., dehydration of portlandit at about 450°C, decomposition of CSH (calcium-silicate-hydrates) at about 750°C.

After the temperature loading we could observe that the colour of the specimens is changing. This phenomenon is to explain with the decomposition of CSH phases. Amount of surface cracking (lengths and widths) is reduced by increasing the silica content of cement.

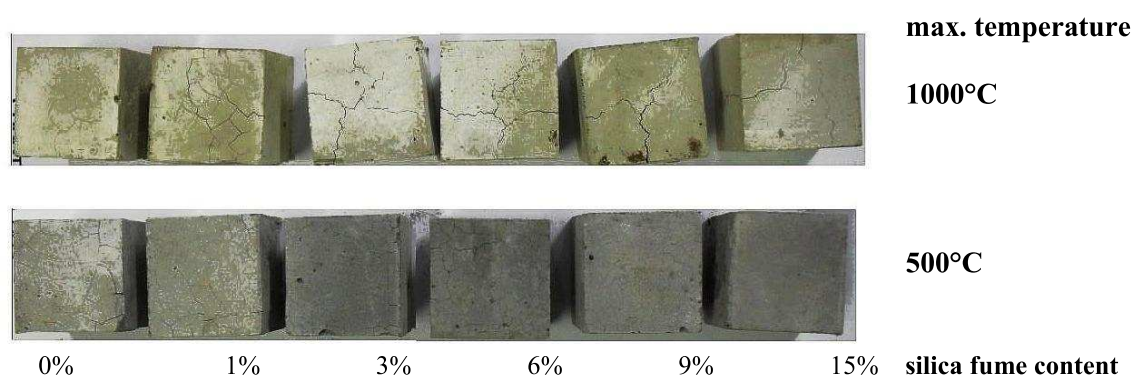


Fig. 1 Effect of cement type on the development of surface cracks as a result of high temperatures (hardened cement paste specimens, w/c=0.40)

3.1.2 Compressive strength

The relative residual compressive strength as a function of silica fume content and maximal temperature is illustrated in **Fig. 2** for 500°C and 1000°C.

- The increase of silica fume content causes the increase of relative residual compressive strength after the temperature loading with 500°C and 1000°C. That could be explained by the increase of silica fume content as well as decrease of the Ca(OH)_2 and CSH contents of concrete. The decomposition of Ca(OH)_2 is about 450°C, and the decomposition of CSH is about 800°C.
- At 500°C and 1000°C the most sensitive hardened cement paste specimens were made with w/c=0.4 independently from the silica fume content. That is to explain by the increase of water by building of CSH phases.
- At 500°C and 1000°C the less sensitive hardened cement paste specimens were made with w/c=0.3, independently from the silica fume content. That is to explain by the decrease of water by building of CSH phases.

After the measurement of the compressive strength at 20°C and at 1000°C the following damage types were registered (**Fig. 3**).

The crack development changed after the measurement of compressive strength by the increase of silica fume content. That could be explained by the increase of the compressive strength.

We left the specimens after the temperature loading and measurement of compressive strength in the laboratory for 3 days. Then we observed, that the specimens with 0% silica fume content failed to pieces, but the specimens with 15% silica fume content did not fail.

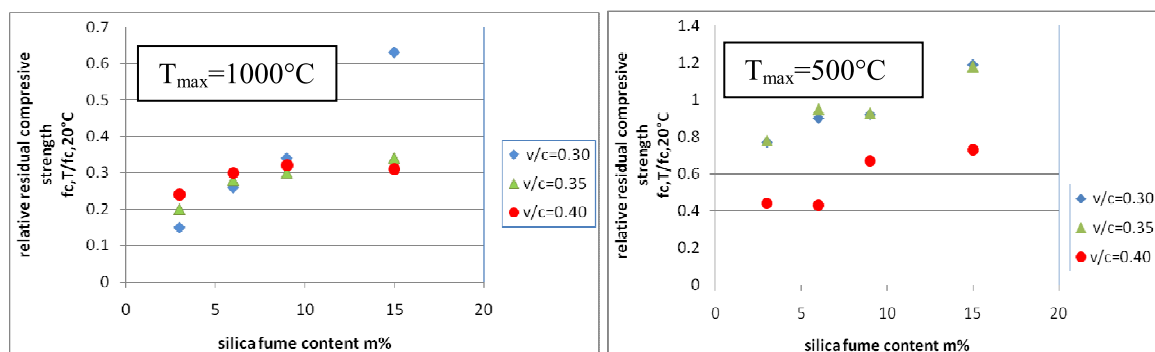


Fig. 2 Relative compressive strength for the different hardened cement pastes as a function of maximum temperature (every point is an average of 3 measurements)

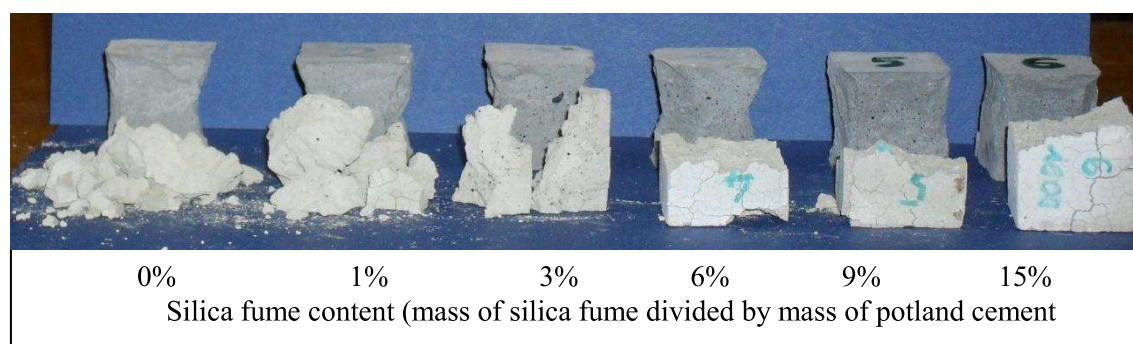


Fig. 3 Specimens after the compressive tests
Front line of specimens: max. temperature was 1000°C
Rear line of specimens: reference specimens (not heated)

3.2 Concrete

For the concrete specimens $w/c=0.35$ ($w/b=0.35$; 0.33; 0.30) was selected. All of the specimens were made by the same cement (400 kg/m^3) and water content (140 l/m^3). The water binder ratio changed during the experiment. For the compressive strength measurement cylinder specimens ($\varnothing=60 \text{ mm}$, $h=120 \text{ mm}$) were used. The flexural strength were measured on prisms of $70 \times 70 \times 250 \text{ mm}$.

3.2.1 Visual observation before compressive tests

Results indicated that the risk of spalling was higher for prisms compared to cylinders (**Fig. 4**). That could be explained by the different layout of isotherm lines produced by the different shapes of the specimens. Mix 1: (0 m% silica fume) two prisms cracked off. Mix 2: (3 m% silica fume) only one prism cracked off. Mix 3: (9 m% silica fume) the prisms did not crack off. These observations indicate favourable influence of increasing silica fume content.

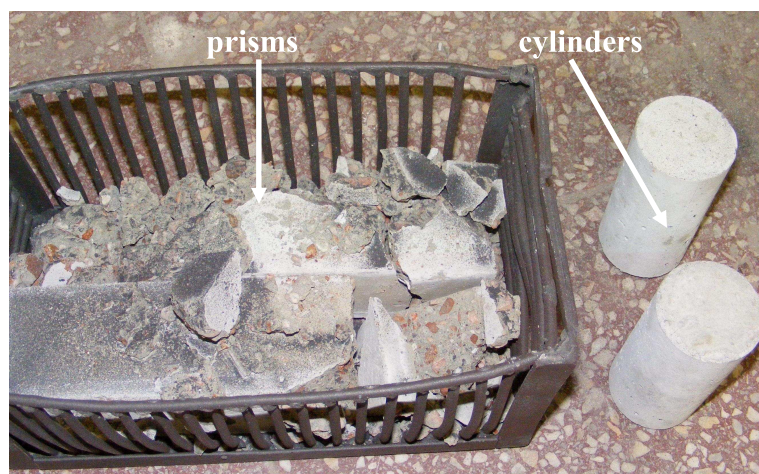


Fig. 4 Specimens after the temperature loading with 1000°C

3.2.2 Compressive strength

Average compressive strength of reference concrete (Mix 1) was 57 N/mm². Average compressive strength of concrete Mix 2 was 67 N/mm². Average compressive strength of concrete Mix 3 was 72 N/mm². Fig. 5 indicates the measured relative residual compressive strength values of different concrete mixes as a function of maximal temperature up to 1000°C.

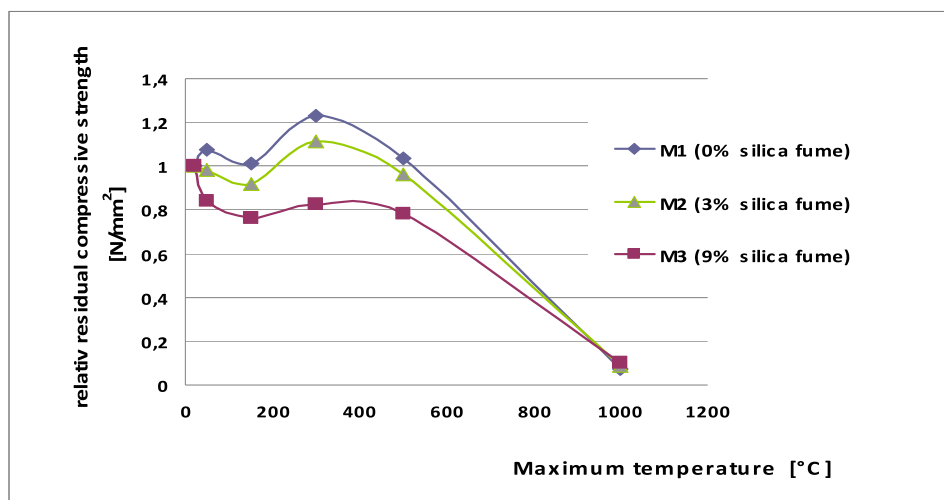


Fig. 5 Relative residual compressive strength for the different concrete mixes as a function of maximal temperature (every point is an average of 3 measurements)

- A strength valley seems to appear (observed also by other researchers [9, 10]) for relatively low values of maximal temperatures, i.e. a small strength decrease then small increase between 20°C to 300°C for reference concrete. This valley might be explained by the relatively high pore water content of tested concrete specimens at an age of 28 days.
- The strength valley ends up at 300°C with a relative compressive strength 1.23 in case of Mix 1, 1.14 in case of Mix 2 and 0.83 in case of Mix 3.
- This valley is followed by strength decrease of compressive strength for higher values of maximal temperatures.
- The relative residual compressive strength value at 1000°C was 0.07 for Mix 1, 0.09 for Mix 2 and 0.1 for Mix 3, respectively.

3.2.3 Flexural strength

In Fig. 6 test results are presented up to 500°C maximum temperature, because the specimens completely failed up to 1000°C.

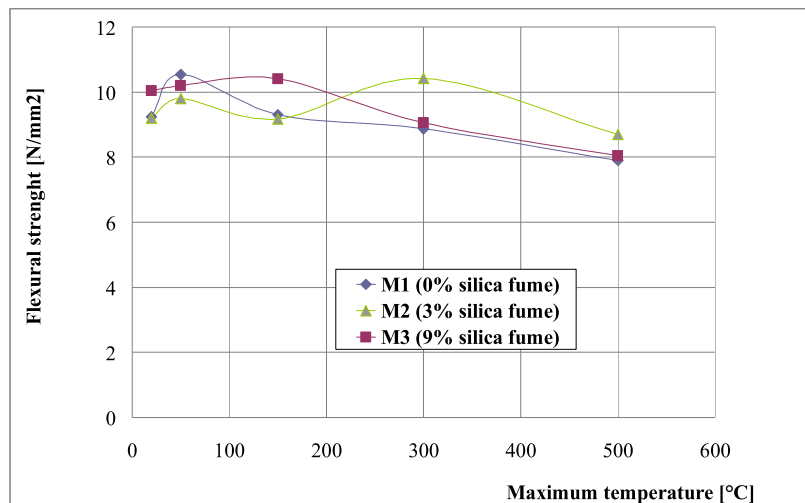


Fig. 6 Residual flexural strength for the different concrete mixes as a function of maximal temperature (every point is an average of 3 measurements)

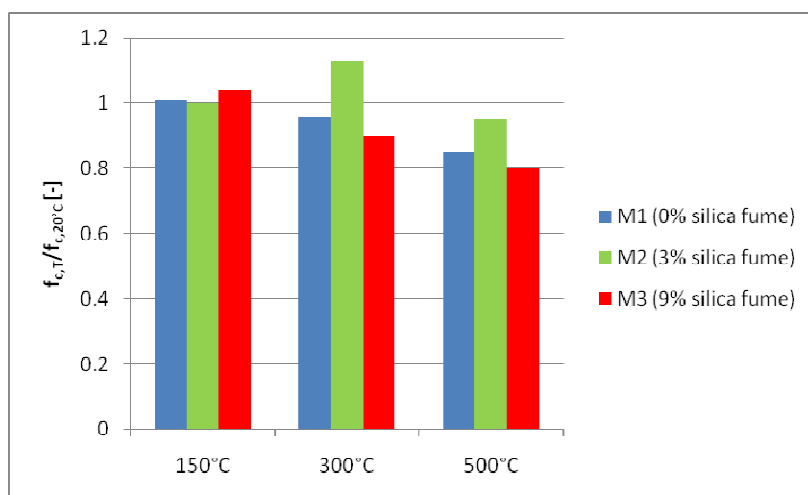


Fig. 7 Relative flexural strength for the different concrete mixes as a function of maximal temperature (every point is an average of 3 measurements)

Relative flexural strength values are presented in Fig. 7 according to maximal temperature values (150°C, 300°C, 500°C) for the various mixes (M1, M2, M3). Observed flexural strength values raider similar for 0 m% and 9 m% silica fume content, however somewhat better for 3 m% silica fume content.

3.2.4 Visual observation after flexural tests

Fig. 8 pesents cracked surfaces of prisms after flexural failure. Clear difference in colour can be observed. Section of specimens after 1000°C temperature loading shows whitish gey colour compared tos the normal colour of concrete at 20 °C temperature.

In case of the testes at laboratory temperature (20°C) same of large aggregates cracked trough owing to the relatively high strength of cement paste (Fig. 8. a). On the other hand, flexural testes after 1000°C temperature loading resulted debonding of aggregates in the failed section (Fig. 8. b).

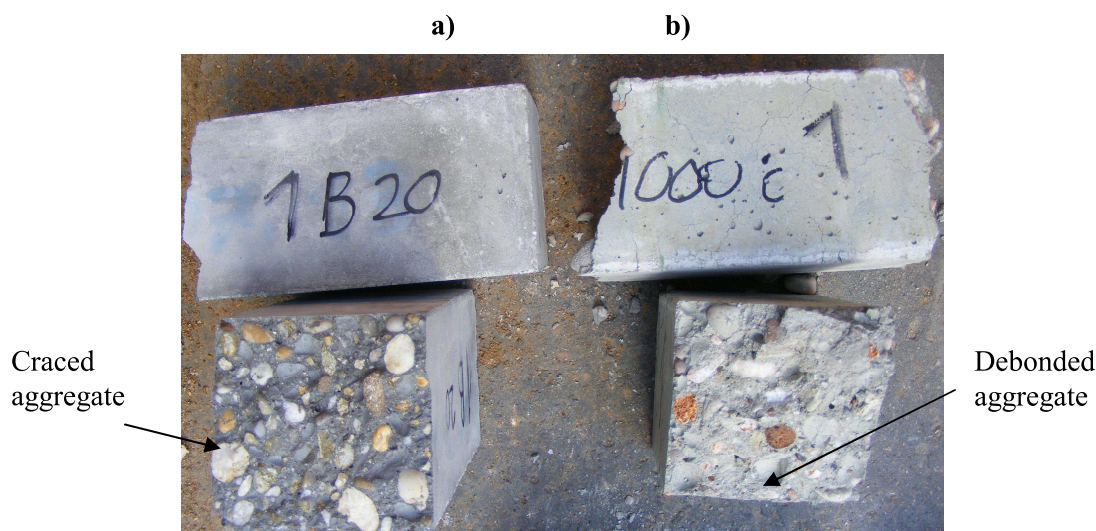


Fig. 8 Cracked surface of flexural specimens after failure
a) 20°C b) after temperature loading of 1000°C

4 Conclusions

Main purpose of our experimental study was to determine the influences of silica fume content on post-heating characteristics of hardened cement pastes. Experiments were carried out both on (a) hardened cement paste specimens and on (b) concrete specimens.

- (a) Test variables were *for hardened cement specimens*: silica fume content (0, 1, 3, 6, 9, 15 mc%), water to cement ratio (0.3; 0.35; 0.4) and maximum temperature (20, 50, 150, 300, 500, 1000°C). Studied characteristics were: surface cracking and residual compressive strength.
- (b) Test variables were *in case of concrete specimens*: silica fume content (0, 3, 9 mc%), and maximum temperature (20, 50, 150, 300, 500, 1000°C). Studied characteristics were: surface cracking, spalling, residual compressive strength and residual flexural strength.

Results for hardened cement paste specimens: Development of surface cracks as a result of the elevated temperatures are very important. Cracks were formed above 300°C. The size (width and length) of the cracks were significantly smaller with increased silica fume content. Possible reason of crack development are the chemical reactions in the cement stone: dehydration of portlandit at about 450°C, decomposition of CSH (calcium-silicate-hydrates) at about 750°C.

At 500°C and 1000°C the most sensitive hardened cement paste specimens were made with $w/c=0.4$ independently from the silica fume content. At 500°C and 1000°C the less sensitive hardened cement paste specimens were made with $w/c=0.3$, independently from the silica fume content.

Results for the concrete specimens $w/c=0.35$ was selected. The specimens were made by constant cement and water content. Cylinder specimens ($\varnothing=60$ mm, $h=120$ mm) were used for the measurement of compressive strength. The flexural strengths were measured on prisms (70x70x250 mm). Silica fume content did not result in improved residual strength after high temperatures. For same compositions even reduction of residual strength was observed.

The risk of spalling was higher for prisms than for cylinders. That could be explained with the different shape of the specimens. The increase of the silica fume content decreased the risk of the explosion of the concrete specimens.

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- 1 New Model Code – expected impacts and practice of use
- 2 Concrete and construction technology – transfer of experience
- 3 Modelling and design of outstanding and innovative structures
- 4 Structures integrated into environment in a balanced way
- 5 Combination of structural concrete with other materials