MECHANICAL PROPERTIES OF SELF-COMPACTING CONCRETE WITH DIFFERENT MINERAL ADITIVES AFTER HIGH TEMPERATURE EXPOSURE

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Abstract

This paper presents an experimental research on the performance of high-strength self-compacting concrete (SCC) with different mineral additives after exposure to high temperature of up to 600°C. For this purpose, four SCC mixtures were studied: one reference and three mixtures where the Portland cement was replaced with mineral additive (fly ash, metakaolin and limestone) in certain proportions. After natural cooling in the furnace, compressive strength and static modulus of elasticity were determined and compared to results obtained from other studies and those provided in EN 1992-1-2 and EN 1994-1-2 for normal-vibrated concrete. Additionally, in order to characterize the damage of the specimens caused by high temperatures, AE parameters during compression test of heated and unheated specimens were also obtained.

Keywords: self-compacting concrete, high temperature, metakaolin, fly ash, limestone

INTRODUCTION

Self-compacting concrete (SCC) is a special type of high performance concretes that fill the formwork with its own weight without need for vibration. There is trend for its increased use in the structural applications, because of the many benefits of SSC compared to conventional concrete. Although SCC consists of the same components as normal and high - strength types of concrete, higher amounts of powder materials are necessary to obtain satisfactory stability of the mixture. For that purpose usually pozzolanic or filler materials such as fly ash, granulated ground blast furnace slag, metakaolin, limestone powder etc. are used. Thus, compared to traditional normal vibrated concrete, increased paste volume and specific placing condition can modify SCC properties on ambient and high temperature.

Although concrete is considered as an excellent thermal-resistant material among various construction materials, high temperature cause physical and chemical changes that result in deterioration of concrete mechanical and thermal properties (Bazant and Kaplan, 1996). Up to now, results of the influence of high temperature on the properties of SCC are rather limited, but show behaviour similar to that of normal-vibrated concrete with increased risk of spalling (Persson, 2004; Bamonte & Gambarova, 2012).

In order to help better characterisation of the performance of SCC mixtures after exposure to high temperature, this preliminary study is focused on testing of mixtures with similar compressive strength where part of Portland cement is replaced with different mineral additive.

1 EXPERIMENTAL PROGRAM

Experimental program includes determination of following residual concrete properties of SCC obtained by uniaxial loading

- compressive strength,
- static modulus of elasticity,

- AE parameters during compression tests,

before exposure to high temperatures and immediately after cooling down to the ambient temperature. In addition, weight loss and ultrasonic pulse velocity tests were also obtained before and after high temperature exposure.

1.1 Concrete mixtures composition

Details of studied concrete mixtures are given in Tab. 1. All mixtures were designed in accordance to CBI method developed in Sweden (Billberg 2002). CEM I 42.5 R and dolomite powder were used for all mixtures. In addition, the mineral additives, namely fly ash (FA), metakaolin (MK) and limestone (LF) were used as a partial replacement of cement by weight as indicated in Tab. 1. The fine and coarse aggregate used was dolomite aggregate with a nominal maximum size of 16 mm. Constant powder quantity (670 kg/m^3) and constant water-powder ratio ($w/p=0,27$) were selected for all mixtures, in which the powder content, p, is defined as the sum of the cement, mineral additive and dolomite filler content. All concrete mixtures were designed to give slump flow of 700±50 mm which was achieved by using the superplasticizer based on polycarboxylic ether polymers and viscosity modifying agent at amounts as indicated in Table 1. Other fresh properties required for SCC mixtures were also examined in order to guarantee a good flowability, workability and segregation resistance of studied mixtures according to HRN EN 206-9. The actual compressive strength and static modulus of elasticity at ambient temperature, indicated in Table 1, is the average of three tests on identical cylinders (Ø/L = 75/225 mm where the variability of each mix was limited to ± 2 MPa or 2 GPa respectively.

Tab. 1 Concrete mixture proportioning for 1 m^3

Mix ID	M1 - ref	M2 (MK5)	M3 (FA30)	M4 (LF10)
Cement, *kg*	450	427,5	315	405
Metakaolin (5% c.w), *kg*	-	22,5	-	-
Fly ash, (30% c.w), *kg*	-	-	135	-
Limestone, (10 % c.w.), *kg*	-	-	-	45
Dolomite filler, *kg*	220	220	220	220
Water, *l*	180	180	180	180
w/c	0,40	0,42	0,57	0,44
Fine aggregate, *kg*	862	862	862	862
Coarse aggregate, *kg*	696	696	696	696
SP, *l*	5,6	4,5	3,6	4
VMA, *l*	0,7	0,7	0,7	1,0
Hardened concrete properties				
Compressive strength, *MPa*	83,5	85	82	69,5
Static modulus of elasticity, *GPa*	48	47	44	46

Prepared specimens for high temperature exposure were also cylinders with dimensions of Ø = 75 mm and L = 225 mm (i.e. with slenderness equal to 3). All specimens were demoulded one day after casting and were kept at a temperature of 20±3°C and relative humidity of 95% in a curing room for another 27 days. Then the specimens were moved to the ordinary environmental conditions (T=15-25°C; R.H. = 50-70%) until testing. Testing programme was initiated at an age of more than 180 days.

1.2 Testing

Temperature exposure and procedure of testing followed recommendations of the RILEM Technical Committee TC-129. The specimens were subjected to three different temperature cycles up to 200°C, 400°C and 600°C in an electrical furnace (T_{max} = 1000°C). The temperature 600°C was chosen as maximum because above this temperature decarbonation occurs and mechanical properties of concrete usually rapidly decrease. The first part of the temperature cycle consisted of heating rate $\Delta T/\Delta t$ of 2°C/min (inside the furnace) up to target temperature in order to avoid dangerous self-stresses. After that, the temperature was kept constant until steady-state thermal conditions throughout the specimens were ensured, while the last part of the cycle consisted of a slow cooling down to ambient temperature in closed furnace in order to avoid thermal shock. Specimens were tested immediately after cooling down to ambient temperature. For each temperature cycle, eight cylindrical specimens were used where one specimen was equipped with NiCr thermocouples monitoring temperature evolution, surface and centre temperature, according to mentioned RILEM recommendations. No spalling of the specimens was observed which can be attributed to slow heating rate as also as low moisture content of the specimens. Compressive strength and modulus of elasticity were tested using hydraulic Toni Technik testing machine with 3000 kN capacity and speed of applied load of 0,5 MPa/s. Elastic modulus is measured between 0,5 MPa and 1/3 of ultimate compressive strength. Ultrasonic pulse velocity measurement were determinated using commercial device of Proceq company (Tico), while weight losses were determined by weighing specimens with precision balance. Acoustic emission system consisted of resonant R6 sensor from Physical Acoustics Corporation (PAC), 8 channel µ-disp unit and a PAC 1220 preamplifier. Studied initial and residual concrete properties were expressed as the mean value of three measurements per each temperature.

2 RESULTS AND DISCUSSION

2.1 Compressive strength

Fig. 1a) and b) show the results of relative residual compressive strength vs. temperature of the studied concrete along with models proposed by EN 1992-1-2, EC2, for high-strength normal-vibrated concretes, EN 1994-1-2, EC 4, for carbonate normal-vibrated concrete aggregate concretes and results obtained by two other study based on testing SCC concretes with limestone filler (Persson 2004; Bamonte and Gambarova 2012).

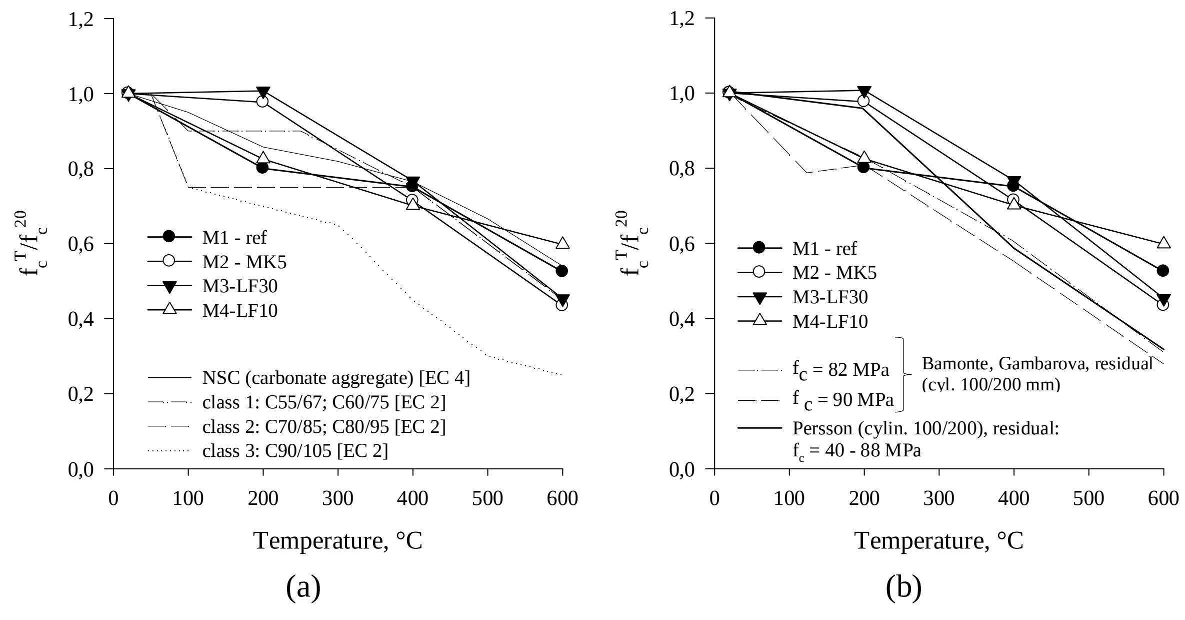
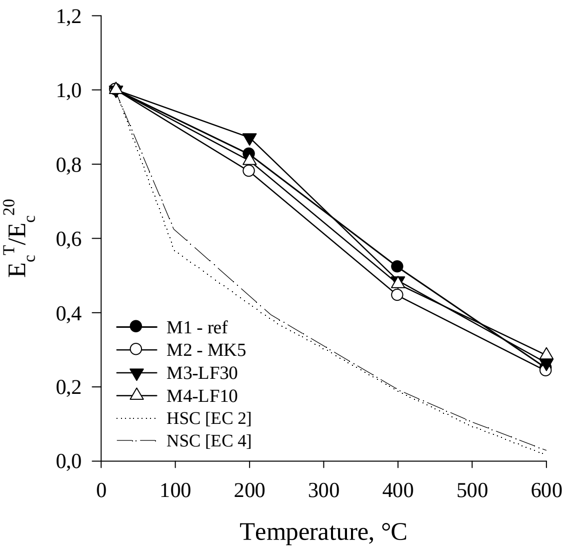


Fig. 1 Plots of the residual compressive strength vs. temperature: a) this study and models in EC2 and EC4 and b) this study and results in Persson, 2004 and Bamonte 2012

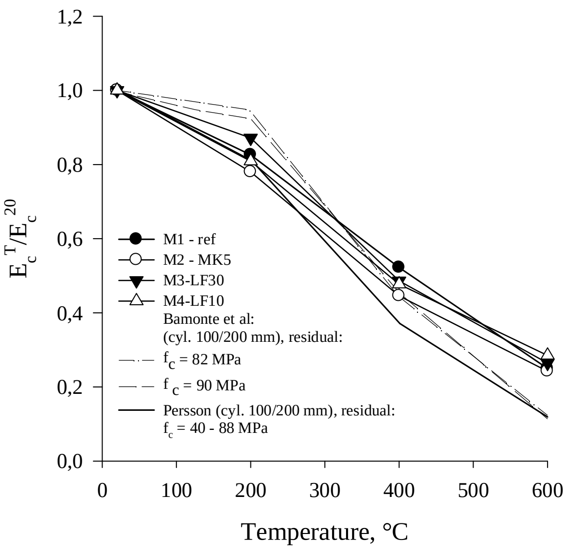
From the figures, it is visible that there are two important stages in residual strength-temperature relationship: 1) 0-200°C with negligible strength loss up to 2% for mixtures with metakaolin, M2, and fly ash, M3, on one side, and reference mixture, M1, and mixture with limestone, M4, on the other side with strength loss of 20 and 18% respectively and 2) 200 – 600°C with permanent strength loss. In the later, mixtures M2 and M3 show sharp loss up to temperature of 400°C, at point which all mixtures have similar relative residual compressive strength (from 70% for M1 to 77 % for M3). Positive influence of fly ash in the whole temperature range and metakaolin up to 200°C on the residual strength is in line with results obtained for normal-vibrated concrete with the same mineral additives in (Poon et al, 2003; Xu et al, 2001). Relating proposed models in EC2 and EC4, results obtained within mixtures M1 and M4 are in good agreement with that proposed with EC 4 for carbonate aggregate in the whole temperature range, while results of M1 and M4 follow it at higher temperature, 400-600°C. Results of all mixtures are in good agreement with the models proposed in EC2 for class 1 and 2 in the temperature range 400 – 600°C. Relating comparison to other studies presented at Fig. 1b) the agreement is satisfactory in the temperature range 0 – 200°C, while at higher temperatures, results of other studies are lower which can be attributed to aggregate type (crushed gneiss and gravel in Persson` s study and river gravel in Bamonte´s study).

2.2 Modulus of elasticity

Fig. 2a) and b) show the results of relative residual modulus of elasticity vs. temperature. Results obtained in this study show that all mixtures have very similar trend of loss no matter which mineral additive were used in the mixture.



(a)



(b)

Fig. 2 Plot of the relative secant modulus of elasticity vs. temperature: a) this study and models in EC2 and EC 4 and b) this study and results in Persson, 2004 and Bamonte 2012

Large discrepancy exists between the experimental results and the values obtained from the initial point of stress-strain curves in EC-s (Fig. 2a), because the stress-strain curves from EC implicitly account for additional strains occurring during first heating of concrete, i.e.transient thermal creep, which is beyond the scope of this study. There is good agreement between results obtained in this study and results obtained in other studies presented in Fig. 2b.

2.3 Ultrasonic pulse velocity and mass loss

The weight loses of the SCC mixtures with increasing temperatures are given in Fig. 3 which show that evolution of the weight losses versus temperature is very close for all studied concrete mixtures.

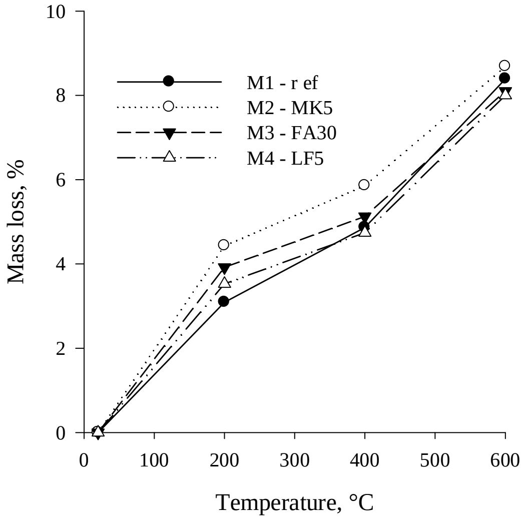


Fig. 3 Plot of mass loss vs. temperature

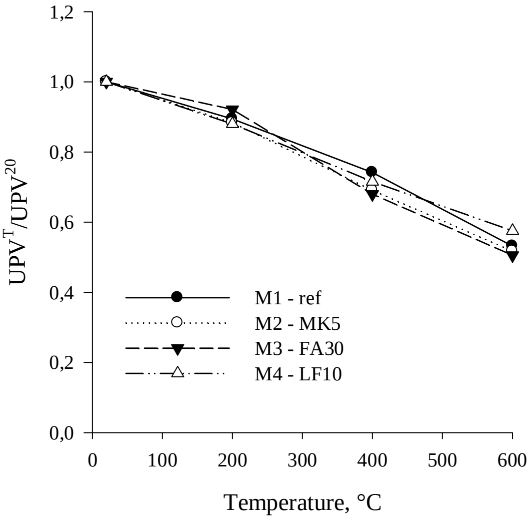


Fig. 4 Plot of UPV vs. temperature

At around 120°C only a small amount of water escaped from the specimens, but at the 200°C the mass loss is up to 4,5 % (for mixture M3). Fig. 4 presents the results of the relative residual pulse velocities as a measure of the extent of deterioration of the concrete microstructure. As for modulus of elasticity, it can be concluded that the studied types of concrete have very similar decrease in UPV no matter which mineral additive is used in the particular mixture.

2.4 AE measurement

On Figs. 5a) – d) the relative signal strength of AE is plotted against relative stress applied during compression tests of the specimens heated to different high temperatures. AE parameter signal strength represents area under rectified waveform or more generally it represents energy released during crack propagation. Results presented are average values obtained on three specimens with AE sensor positioned on side of cylindrical specimens during compression test.

From presented figures, it can be seen that, apart for temperature 400°C, all studied mixtures have almost the same relationship relative signal strength-relative stress. After exposure to temperature of 400°C, this relation is different for different mixtures where the highest values of relative signal strength were obtained for mixture with fly ash, M3, which, in the same time, have the highest value of the residual strength (77%), Fig.1. For other studied mixtures, also can be stated that relationship relative signal strength-relative stress follow the values of the residual strength after exposure to 400°C. These preliminary observations need further detailed research in the next step of the study, but certainly represent good tool for identifying exposure temperature in dependence of the proposed relationship.

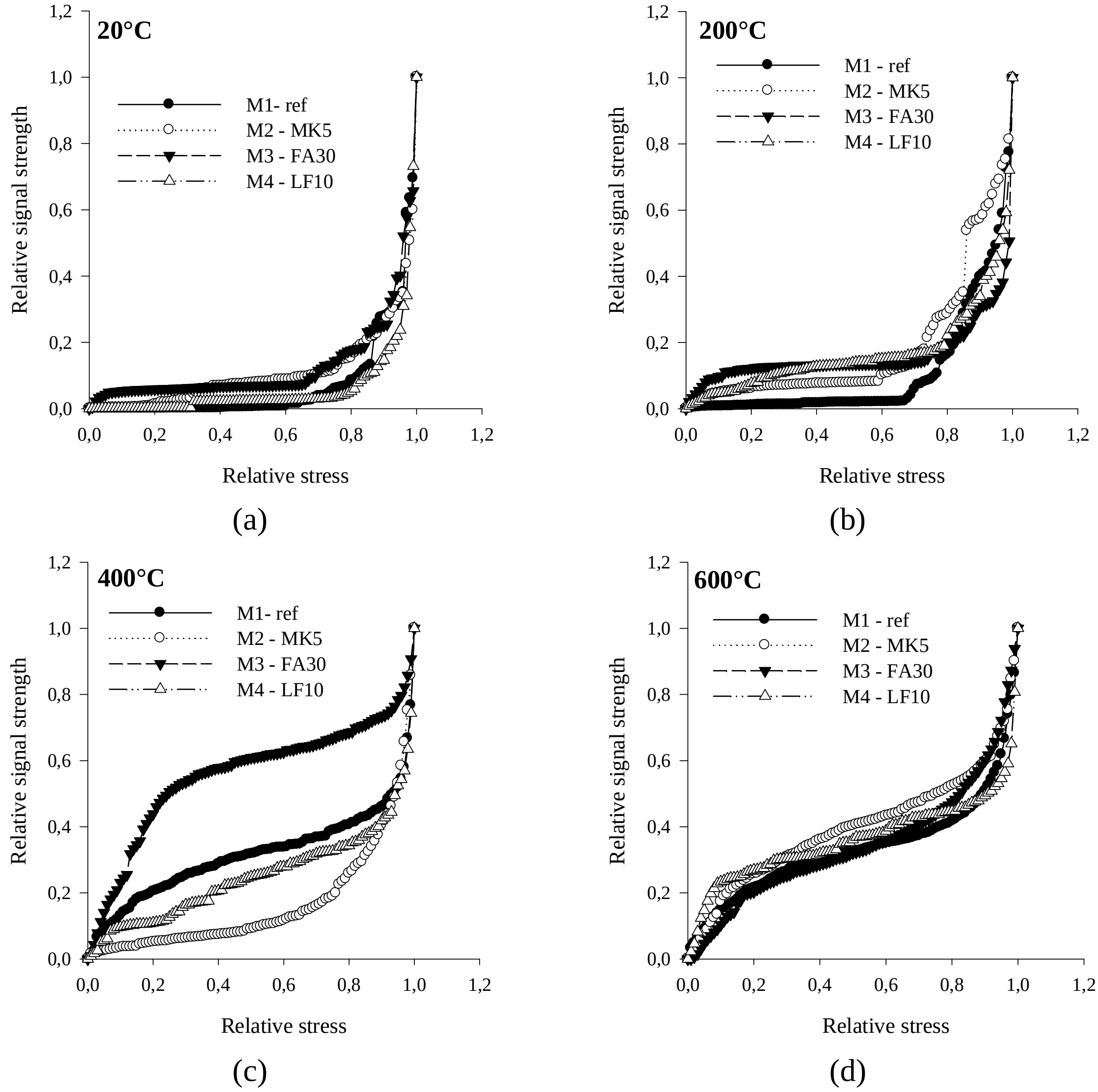


Fig. 5 Plot of relative signal strength vs. relative stress obtained during compression tests of the specimens: a) at ambient temperature, b) after heated to 200°C; c) after heated to 400°C; d) after heated to 600°C

3 CONCLUSIONS

The following conclusions may be stated on the basis of the results obtained in this study:

- Mineral additives have great influence on the residual compressive strength between ambient temperature and 400°C; at temperatures above 400°C, the decrease of the residual compressive strength is similar for all studied mixtures and is in good agreement with the model proposed of EC 4 for normal-vibrated calcareous aggregate concretes.
- Higher temperatures have more influence on the residual modulus of elasticity compared to the compressive strength; related to different mineral additives, results show that they have not significant effect on modulus, because all studied mixture show almost the same trend of decrease in dependence of the applied temperature.
- As for residual modulus of elasticity, there is very similar trend in decrease of residual UPV for all studied mixtures which indicates that mineral additive has no particular effect on the residual UPV.
- In order to withdraw general conclusions about the influence of the different mineral additives in concrete mixtures on mechanical properties of self-compacting concrete after exposure to high temperatures (compressive strength and modulus of elasticity, in

particular) there is need for further research with mixtures containing different percentage of each mineral additive. This research is currently underway.

- Preliminary results of AE parameters (signal strength in particular) obtained during compression test of specimens after heating to high temperatures show good tool for identifying exposure temperature of the concrete needed for assessment of concrete structures after fire.

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