PHD WORKSHOP 2018 — COMPRESSIVE STRENGTH OF AIR-ENTRAINED CONCRETE AT HIGH TEMPERATURES

*Jakub Holan, **

Katedra betonových a zděných konstrukcí, Fakulta stavební,
České vysoké učení technické v Praze, Thákurova 7/2077, 166 29 Praha 6, Česká republika.
jakub.holan@fsv.cvut.cz

ABSTRACT

The fire response of concrete has been investigated for the past decades; however only few studies were focused on the mechanical properties of air-entrained concrete at high temperatures. This paper is focused on the effect of air-entrainment on the compressive strength of concrete at high temperatures. Heat treatments and compression tests were performed on reference and air-entrained specimens. The obtained results show that the air entrainment has an adverse effect on the compressive strength of the concrete when subjected to high temperatures for a prolonged time period.

KEYWORDS

Concrete • High temperature • Air-entrainment • Compressive strength • Experimental investigation

1. INTRODUCTION

When concrete is subjected to high temperature, severe irrecoverable changes happen in its internal structure. It is, therefore, looked for means of improving concrete so that it is less affected when subjected to high temperatures. One of the responses of concrete to high temperatures is spalling, which most probably happens due to evaporation of water which causes the pore vapour pressure growth and the spalling of concrete (Dwaikat and Kodur, 2009).

Air-entrainment provides the porosity, which should help with decreasing the pore vapour pressure, and thus decrease the risk of concrete spalling. Studies investigating the effect of air-entrainment (Khaliq, Waheed and Khushnood, 2018; Drzymała et al, 2018; Drzymała et al, 2017; Ahmad and Abdurrahman, 2009) were conducted only on specimens at an ambient temperature after a high-temperature exposure and a cool down phase. These experimental investigations provide insight into the effects of air-entrainment on the residual strength of concrete. However, it has not been fully understood whether the results correspond with the properties of air-entrained concrete during the high temperature exposure, which might be different due to the pore vapour pressure. An adverse effect of the air-entrainment of concrete is a reduction in its strength caused by the increased porosity (Thomas, 1979).

The state of the art review shows that most experimental investigations focused on the fire response of air-entrained concrete were carried out on specimens at an ambient temperature after the high-temperature exposure. The results presented in these studies do not accurately describe the material properties of concrete at high temperatures. The main objective of this experimental investigation is to determine the effect of air-entrainment on the compressive strength of normal-strength concrete at high temperatures.

2. METHODS

2.1. Specimens

To investigate the effect of air-entrainment on the compressive strength of concrete at high temperatures, experiments were carried out on 15 reference specimens and 15 air-entrained specimens. The experiments were carried out at an ambient temperature of 20°C and at elevated temperatures of 200°C, 400°C, 600°C, and 800°C.

Cylindrical specimens with the diameter of 100 mm and height of 200 mm were used in this experiment. The concrete mixture used for the specimens was composed of commonly used ingredients. The Mikroporan 2 air-entraining agent was used for the process of air-entrainment.

2.2. Heat treatment

The heat treatment of the specimens was executed using the Mannings HTC 70 kW control machine, ceramic pads, and K-type thermocouples, see Figure 1.

Each specimen was covered with two ceramic pads and wrapped by high-temperature resistant glass wool insulation before the heat treatment. A thermocouple was placed between the ceramic pads and a specimen to monitor the surface temperature. The Mannings HTC 70 kW control machine both provided electric current for the pads and displayed the temperature measured by the thermocouple. During the heat treatment, the temperature was always gradually increased until the target temperature was reached, and then the target temperature was held for 3 hours to ensure uniform temperature distribution throughout the specimen as recommended by RILEM (1995).

---

* Supervisor: Ing. Radek Štefan, Ph.D.

Four types of heating programs were executed, each for one of these target temperatures: 200°C, 400°C, 600°C, and 800°C. During the heat treatment, the temperature measured by thermocouple was regularly checked by the observing researcher. An infrared thermometer was used to monitor the surface temperature of insulated specimens and to check for possible heat leeks. Three reference specimens and three air-entrained specimens were subjected to each target temperature. Overall 24 specimens were subjected to high temperatures – 12 reference specimens and 12 air-entrained specimens.

2.3. Compression test

The compression test of each specimen was conducted right after its heat treatment was finished in order to determine its compression strength at the target temperature.

The Inova 200F computer-controlled compression machine was used to execute the compressions test. The test was driven by a constant rate of deformation 0.02 mm/s until the failure of the specimen. The vertical deformation of the specimen was measured by the control computer, and the relative strain was later calculated from the deformation.

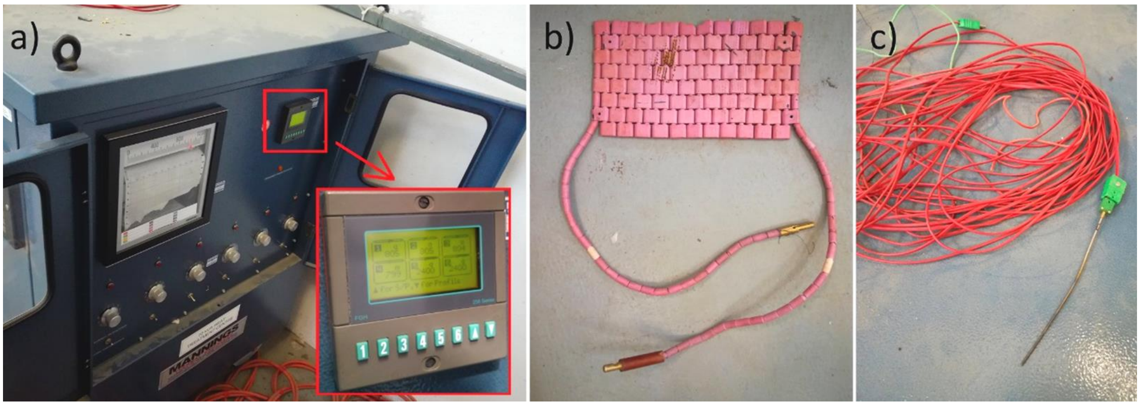

Figure 1 – *Setup used for the heat treatment*

3. RESULTS & DISCUSSION

Compression stress-strain diagrams were created by plotting the data obtained by compression tests, see Figure 2 and Figure 3. These diagrams correspond with the typical behaviour of concrete in compression; with increasing strain, the stress increases linearly until the concrete starts yielding and compressive strength is reached (Novak and Kohoutkova, 2018). The figures show that with increasing temperature the modulus of elasticity and compressive strength decrease significantly while the ductility increases.

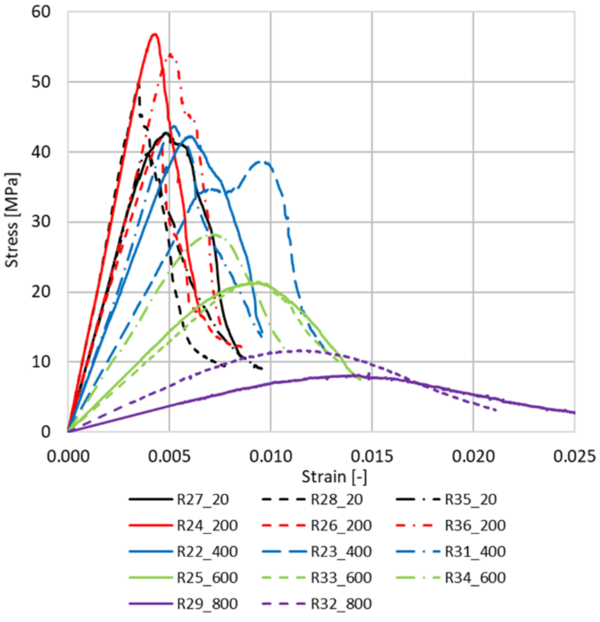

Figure 2 – *Stress-strain diagrams of reference concrete*

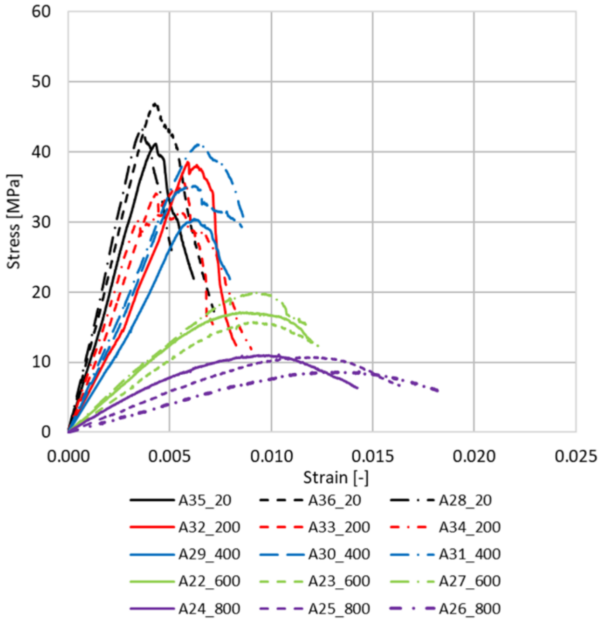

Figure 3 – *Stress-strain diagrams of air-entrained concrete*

The effect of temperature on the compressive strength is similar for reference and air entrained concrete at temperatures above 400°C. However, the effect differs for the temperatures up to 400°C; in this temperature range, the strength of reference concrete first increases before it starts decreasing, whereas the strength of air-entrained concrete decreases right from the beginning, see Figure 4.

This difference between the reference and air-entrained concrete is caused by further hydration of cement grains and water evaporation, which both happen up to the temperature of 300°C (Saad et al, 1996) but affect each concrete to different extents. The hydration of cement grains results in an increase of compressive strength, whereas the water loss adversely affects the compressive strength of concrete. The former process is more dominant in low permeability concrete, whereas the latter process is more dominant in more porous concrete (Ma et al, 2015). Therefore, the sharp decline of the strength of air-entrained concrete makes sense as the air-entrained concrete is more permeable and porous than the reference concrete. No further hydration nor any water loss happen above the temperature of 400°C, and thus, neither affects the strength of concrete.

In the temperature range of 400°C to 800°C, more degradation processes happen in the structure of concrete, all of which affect the reference and air-entrained concrete in the same manner – i.e., all processes decrease the strength of the concrete.

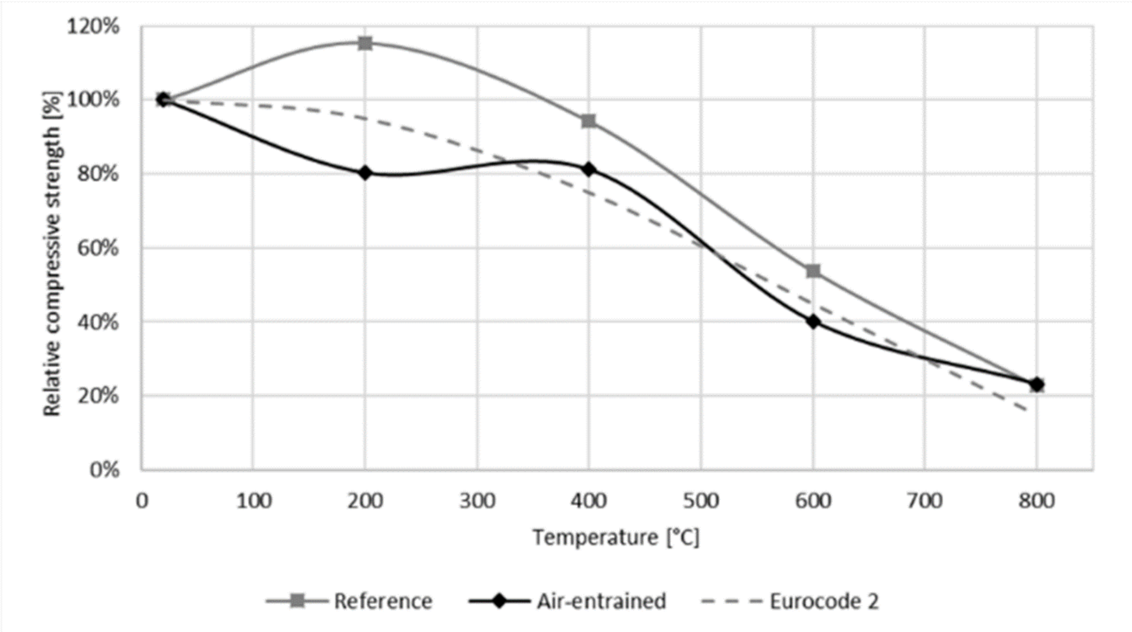

Figure 4 – *Relative mean strength of reference concrete and air-entrained concrete at various temperatures compared to Eurocode 2 recommended values*

The presented values of the strength of the reference concrete differ from the values recommended by (*Eurocode 2,* 2004) for siliceous aggregates. The recommended values are smaller and, therefore, more conservative than the presented values, see Table 1.

Table 1 – *Relative mean strength of reference concrete and air-entrained concrete at various temperatures compared to Eurocode 2 recommended values*

	Temperature				
	20°C	200°C	400°C	600°C	800°C
Eurocode 2	100%	95%	75%	45%	15%
Reference	100%	115%	94%	54%	23%
Air-entrained	100%	80%	81%	40%	23%

4. CONCLUSIONS

An experimental investigation focused on the compression strength of reference and air-entrained concrete at high temperatures has been presented in this paper. Within the scope of work, heat treatments and compressive tests were conducted. From the obtained results, the following observations are highlighted:

- Concrete spalling did not occur in any of the specimens. The air-entrained as well as non-air-entrained concrete had high enough porosity and permeability to conduct and release almost all vapour during the prolonged time of heating. No significant effect of the remaining vapour on the strength of concrete has been observed.
- With increasing temperature, the compressive strength of the non-air-entrained concrete increased before it started decreasing. The compression strength of the non-air-entrained concrete at the temperatures of 200°C, 400°C, 600°C, and 800°C was found to be 115%, 95%, 54%, and 23%, respectively, of its initial strength at an ambient temperature.
- With increasing temperature, the compressive strength of the air-entrained concrete decreased. The compression strength of the air-entrained concrete at the temperatures of 200°C, 400°C, 600°C, and 800°C was found to be 80%, 81%, 40%, and 23%, respectively, of its initial strength at an ambient temperature. The highest loss of compression strength was in the temperature ranges of 20°C to 200°C and 400°C to 600°C.
- At a very high temperature (800°C), the difference between the compressive strength of air-entrained and non-air-entrained concrete was negligible.

From the highlighted observations, the following conclusions are made:

- Air-entrainment has an adverse effect on the compressive strength of normal-strength concrete when the concrete is exposed to high temperature for a prolonged time.
- With increasing temperature, the compressive strength of air-entrained concrete decreases more rapidly than the compressive strength of non-air-entrained concrete.
- Air-entrainment has no effect on the compressive strength of concrete at a very high temperature (800°C).

Based on the findings, it is concluded that air-entrainment has an adverse effect on the compressive strength of concrete when the concrete is subjected to high temperatures for an extended period of time. As no vapour is present in the pores after the prolonged exposure to high temperatures, the increased porosity of air-entrained concrete, which would otherwise have a beneficial effect of decreasing the pore vapour pressure, only has an adverse effect on the compressive strength of the concrete.

ACKNOWLEDGEMENTS

This paper was supported by the Grant Agency of the Czech Technical University in Prague, project no. SGS19/034/OHK1/1T/11. The support is gratefully acknowledged.

References

Ahmad, A.H.H. and Abdurrahman, R.B. (2009). Effect of Elevated Temperature on Some Properties of Air-Entrained Steel Fibers Reinforced Concrete. *Al-Rafidain Engineering*, 17(4), pp. 28-41.

Drzymała, T., Jackiewicz-Rek, W., Gałaj, J. and Šukys, R. (2018). Assessment of mechanical properties of high strength concrete (HSC) after exposure to high temperature. *Journal of Civil Engineering and Management*, 24, pp. 138-144.

Drzymała, T., Jackiewicz-Rek, W., Tomaszewski, M., Kuś, A., Gałaj, J. and Šukys, R. (2017). Effects of High Temperature on the Properties of High Performance Concrete (HPC). *Procedia Engineering*, 172, pp. 256-263.

Dwaikat, M.B. and Kodur, V.K.R. (2009). Hydrothermal model for predicting fire-induced spalling in concrete structural systems. *Fire Safety Journal*, 44, pp. 425-434.

Khaliq, W., Waheed. F. and Khushnood, R.A. (2018). High-Temperature Residual Strength and Microstructure in Air-Entrained High-Strength Concrete. *Materials Journal,* 115, pp. 425-435.

Ma, Q., Guo, R., Zhao, Z., Lin, Z. and He, K. (2015). Mechanical properties of concrete at high temperature – A review. *Construction and Building Materials*, 93, pp. 371-383.

Novak, J. and Kohoutkova, A. (2018). Mechanical properties of concrete composites subject to elevated temperature. *Fire Safety Journal*, 95, pp. 66-76.

Saad, M., Abo-El-Enein, S.A., Hanna, G.B. and Kotkata, M.F. (1996). Effect of temperature on physical and mechanical properties of concrete containing silica fume. *Cement and Concrete Research*, 26(5), pp. 669-75.

Thomas, T.L. (1979). The effects of air content, water-cement ratio, and aggregate type on the flexural fatigue strength of plain concrete. *Retrospective Theses and Dissertations*.

Eurocode 2: Design of concrete structures - Part 1-1: General rules - Structural fire design (2004). *CEN*.

RILEM TC 129-MHT (1995). Rilem draft recommendation 129-MHT test methods for mechanical properties of concrete at high temperatures – Compressive strength for service and accident conditions. *Materials and Structures*. 28, pp. 410-414.