Air-entrainment as an alternative to polypropylene fibers and its effect on the compressive strength of concrete at high temperatures

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Abstract. Although much research has been done in the area of the fire response of concrete in the past decades, only few studies are focused on the mechanical properties of air-entrained concrete at high temperatures. This paper presents preliminary results of an experimental investigation focused on the effect of air-entrainment on the compressive strength of concrete at various high temperatures. Within the scope of this work, heat treatments and compression tests have been performed on reference and air-entrained concrete specimens. The results obtained from the experiments have been analysed and show that the air entrainment seems to have an adverse effect on the compressive strength of the concrete at high temperatures when exposed for a prolonged period of time.

1. Introduction

Although concrete does outperform other commonly used building materials in terms of high temperature response, severe irrecoverable changes still happen in its internal structure when it is subjected to high temperature. We, therefore, look 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 [1]. One of the possible and common ways of decreasing the pore vapour pressure at high temperatures is incorporating polypropylene fibres into the concrete mix [2]; however, polypropylene fibres greatly reduce the slump flow, requiring more effort in placement and compaction [2, 3]. It would, therefore, be beneficial to find a suitable alternative to polypropylene fibres.

An alternative to polypropylene fibres in terms of reducing the spalling of concrete could be the air-entrainment of concrete which intrinsically provides the much-needed porosity. Existing studies investigating the effect of air entrainment [4–7] were conducted only on specimens at an ambient temperature after a high-temperature exposure and a cool down phase, and thus, provide insight only into the residual strength of air-entrained concrete. These results cannot be related to the mechanical properties of air-entrained concrete at high temperatures as it has not been fully understood whether the results correspond with the properties of air-entrained concrete during the high temperature exposure. Only a single study focused on the mechanical properties of air-entrained concrete at high temperatures [3] was found. Moreover, only high-strength concrete (HSC) was investigated within this study; and thus, the results and conclusions...
may differ from those applicable to normal-strength concrete. It is also worth to mention that
the air-entrainment of concrete has an adverse effect of reducing the strength of concrete at
ambient temperature due to the increase in porosity [8].

The state-of-the-art review of the fire response of air-entrained concrete shows that most
relevant experimental investigations have been focused on either the residual properties of air-
entrained concrete or on the high-temperature properties of HSC. The results presented in these
studies may not accurately describe the material properties of normal-strength 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.

In this paper, a preliminary results of an experimental investigation focused on air-entrained
normal-strength concrete at high temperatures are presented. The work presented in this paper
is part of an ongoing extensive research on the Czech Technical University in Prague, Faculty
of Civil Engineering – see our previous work [2,9–15].

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 in order to obtain as uniform temperature distribution throughout the specimen
as possible. The concrete mixture used for the specimens was composed of commonly used
components, see table 1.

| Mixture component | Reference specimens | Air-entrained specimens |
|-------------------|---------------------|------------------------|
| Cement CEM I 42,5 R | 370                 | 370                    |
| Water             | 135                 | 135                    |
| w/c ratio         | 0.36                | 0.36                   |
| Silica sand 0/2   | 863                 | 863                    |
| Fine silica aggregate 4/8 | 195                 | 195                    |
| Coarse silica aggregate 8/16 | 755                 | 755                    |
| Plasticizer       | 2.6                 | 2.6                    |
| Air-entraining agent | 0                  | 0.4                    |

2.2. Heat treatment

Before the compresion test could be executed, it was first necessary to subject the specimens to
the high temperature and achieve a uniform heating of the specimens. The heat treatment of
the specimens was performed using a control machine, ceramic pads, and K type thermocouples,
see figure 1.

Before the heat treatment, each specimen was covered with two ceramic pads, which provided
the heat, and wrapped by high-temperature resistant glass wool insulation, which worked as
thermo-box ensuring heat accumulation. Subsequently, a thermocouple was placed between
the ceramic pads and a specimen in order to monitor the specimen surface temperature. The thermocouple and the ceramic pads were connected to the control machine.

During the heat treatment, the control machine both provided and regulated the electric current for the pads and displayed the temperature measured by the thermocouple. The temperature was always steadily gradually increased until the target temperature was reached. Then, the target temperature was held for 3 hours to ensure uniform temperature distribution throughout the specimen as recommended by [16] and stated in [2]. During the heat treatment, the temperature measured by thermocouple was regularly checked by the observing researcher, and an infrared thermometer was used to monitor the surface temperature of insulated specimens and to check for possible heat leaks.

![Figure 1. Setup used for the heat treatment: (a) control machine, (b) ceramic pads, (c) K-type thermocouples.](image)

Four types of heating programs were executed, each for one of the target temperatures of 200 °C, 400 °C, 600 °C, and 800 °C. The rate of temperature increase was 600 °C per hour for all target temperatures except the target temperature of 800 °C where a rate of 1000 °C per hour was used. 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
Right after the heat treatment was finished, a compression test of each specimen was conducted in order to determine the compressive strength of the concrete specimen at the target temperature. The test was executed in accordance with Czech standard ČSN EN 12390-3 [17]. A computer-controlled compression machine was used to execute the compression test, and 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 a control computer, and the relative strain was later calculated from the deformation.

3. Results and discussion
The data obtained by compression tests show that 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 2. The two processes causing this phenomenon, i.e. the different behaviour of reference and air-entrained concrete,
are further hydration of cement grains and water evaporation. Those processes both happen in both types of concrete up to the temperature of 300 °C [18] but affect each concrete to different extents. The hydration of cement grains, which results in an increase of compressive strength, is more dominant in low permeability concrete. The water loss, which adversely affects the compressive strength of concrete, is more dominant and faster in more porous concrete [19]. As the air-entrained concrete is more permeable and porous, the water loss is more dominant than the hydration of cement grains, and thus, the sharp decline of the strength is justified. In the case of reference concrete, which is less permeable and porous, the hydration of cement grains is more dominant and the water loss is delayed into higher temperatures, and thus, the initial increase of the strength followed by a sharp decrease is justified. 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, such as micro-cracks in the cement matrix and calcium carbonate decarbonation, happen in the structure of concrete. These processes affect the reference and air-entrained concrete in the same manner – i.e., all decrease the strength of the concrete.

![Figure 2. Relative mean strength of reference concrete and air-entrained concrete at various temperatures compared to Eurocode 2 recommended values.](image)

The presented values of the strength of the reference concrete differ from the values recommended by [20] for siliceous aggregate concrete. The recommended values are lower and, therefore, more conservative than the presented values, see table 2.
Table 2. Relative mean strength of reference concrete and air-entrained concrete at various temperatures compared to Eurocode 2 recommended values.

|                  | 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

In this paper, a preliminary results of an experimental investigation focused on the compressive strength of reference and air-entrained concrete at high temperatures has been presented. Heat treatments of specimens and compressive tests on those specimens were conducted. From the obtained results, the following observations are highlighted.

- Due to the low enough rate of temperature increase and sufficient porosity and permeability of both reference and air-entrained concrete, concrete spalling did not occur in any of the specimens. Moreover, the porosity and permeability were high enough to conduct and release almost all vapour during the prolonged time of the heating. No significant effect of the remaining vapour on the strength of concrete has been observed.

- With increasing temperature, compressive strength of the non-air-entrained concrete first increases before it starts decreasing. The compression strength at the temperatures of 200 °C, 400 °C, 600 °C, and 800 °C was found to be 115%, 95%, 54%, and 23%, respectively, of the initial strength at an ambient temperature.

- Compressive strength of the air-entrained concrete generally decreases with increasing temperature. The compression strength at the temperatures of 200 °C, 400 °C, 600 °C, and 800 °C was found to be 80%, 81%, 40%, and 23%, respectively, of the initial strength at ambient temperature.

- At a very high temperature (800 °C), the difference between the compressive strength of air-entrained and the compressive strength of non-air-entrained concrete is negligible.

From the highlighted observations, the following conclusions are made.

- 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).

- Generally, 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 period of time, which was required for the uniform heating of specimens.

Based on the preliminary finding, it is currently 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. A more detailed study aimed at the air-entrainment and its effect on the compressive strength of normal-strength concrete at high temperatures will be done in our future work.
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