Determination of mechanical properties of normal strength limestone concrete after exposure to elevated temperatures

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ABSTRACT

Fire resistance is one of the essential requirements that has to be considered in the design process of any structure. Methods for ensuring fire resistance of new structures are therefore, relatively well developed. Thus, loss of bearing capacity of a concrete structure during fire is relatively well known and documented, while determination of remaining bearing capacity of concrete structure after fire is less known. This can mainly be attributed to the lack of adequate knowledge of mechanical properties of concrete after fire, duration of fire exposure, heating rate, and maximum temperatures reached in the structure during fire. These factors have to be taken into account when making a decision on the rationality of the structure’s restoration. Estimation of bearing capacity of concrete structures after fire depends on precise but difficult determination of temperature dependent changes in material. Bearing capacity of structures after fire is in general, often assessed with simplified procedures and experimental investigation. These mainly covers visual inspection of the damaged structure and the execution of some standard, mostly destructive tests. Such tests are precise, but often difficult to implement, expensive, time-consuming, limited to certain pre-selected locations and can somehow weaken the individual structural element. Therefore, in order to determine bearing capacity of concrete structure after fire, various non-destructive methods are being developed. Among these, different ultrasonic (US) tests are frequently used and well described in the literature. These results indicate good connection between US pulse velocity and concrete compressive strength after exposure to elevated temperatures.

This article presents the first part of the ongoing research. Main goal of the research is to develop a numerical method based on artificial neural network approach to estimate concrete properties after fire using non-destructive tests. In this paper, results of destructive and non-destructive tests are presented and analyzed to determine changes in basic mechanical properties of standard concrete mixture after exposure to elevated temperatures, namely 200 °C, 400 °C, 600 °C, or 800 °C. With the aim of separating ‘material’ and ‘structural’ effects, temperature gradients within the concrete specimens, were minimized, as possible. Prior experimental testing, the damage to the concrete was roughly detected by observing the specimen’s surface. Compressive strength, tensile strength, surface hardness, dynamic elastic modulus, and shear modulus are determined. It is noticed that crack formation at 400 °C has an influence on reduction of the US pulse velocity, tensile strength, dynamic elastic, and shear modulus. Analysis of variance is used for assessing the experimental results sensitivity on temperature elevation. It is noticed that US method detects statistically significant impact of elevated temperatures on US pulse velocity. On the other hand, rebound hammer technique indicates statistically significant impact of elevated temperatures on concrete surface hardness between 400 °C and 600 °C.

KEYWORDS: concrete, elevated temperatures, compressive strength, non-destructive tests.
INTRODUCTION

Concrete is a widespread construction material due to its strength, durability, and affordability. It is a composite material consisting of aggregate, cement, and water where the choice of aggregate has a significant impact, since it represents around 70% of the total volume of concrete [1]. During fire exposure different chemical, physical, and mechanical changes of the material occur. Various experiments were made and presented in the literature, where limestone [2-6], granite [2, 5-6], silicate [2-3], quartz [6], and marine gravel [2] were used as an aggregate to investigate the concrete’s mechanical properties after exposure to elevated temperatures. In general, silicate concrete has lower mechanical properties after exposure to elevated temperatures compared to limestone concrete [2], due to limestone’s higher degradation temperature.

Mechanical properties of concrete after fire exposure are commonly determined using destructive techniques like compressive test, bending test, and test of elastic modulus determination [3, 7-8]. On the other hand, results of non-destructive tests are used as relation to destructive ones [9-10]. Different US tests based on measuring US pulse transition are frequently described in literature. This has been proved to be one of the most appropriate non-destructive tests for estimating mechanical properties of concrete at ambient temperature [11-12] and determining internal damage of concrete [13-14], due to its clear physical foundation. US method is very sensitive to the changes of microstructure inside the concrete and related mechanical properties [15-16]. With results of before mentioned non-destructive tests an advanced and effective method for estimating concrete compressive strength, at ambient temperatures, was developed using artificial neural networks [17]. As literature reveals, advanced non-destructive methods for assessing the mechanical properties of fresh and hardened concrete are commonly used at ambient temperature, but not often after fire testing. In case of non-destructive experimental research of silicate concrete after fire exposure, the correlation between US pulse velocity and concrete compressive strength was proposed [10]. During the experiment [10] it was found that the specimen size had no influence on the measured US pulse velocity and that concrete with silicate aggregate was damaged to that level that unrealistic results were obtained around temperature 600 °C. In the last year a relationship between measured concrete compressive strength after fire and results of nonlinear US methods were presented [9].

The article presents experimental materials, test methods, and results obtained from the concrete specimens. Experimental tests were carried out at ambient temperature and after exposure to elevated temperatures up to 800 °C. During heating and cooling down, temperature gradients within the concrete specimens were minimized to obtain isothermal conditions. Before experimental testing, the specimens were observed for crack propagation and spalling. The compressive and tensile strengths were determined with standard destructive tests and different non-destructive tests. Description of experimental work is followed by presentation of elevated temperatures influence on the concrete mechanical properties, after exposure to elevated temperatures.

MATERIALS AND METHODS

Specimens were made of normal strength concrete with high initial strength Portland cement (CEM I 52.5 R), limestone aggregate, water, and plasticizer, presented in Table 1. The maximum nominal aggregate size was 16 mm.

| Material          | Type    | Amount [kg] |
|-------------------|---------|-------------|
| Cement            | Cem I 52.5 R | 15.65       |
| Water             | Tap     | 7.36        |
| Hyper plasticizer |         | 0.09        |
| Limestone aggregate | 0-4 mm | 40.50       |
| Limestone aggregate | 4-8 mm | 12.15       |
| Limestone aggregate | 8-16 mm | 28.35       |

Mixing was performed in a pan mixer. Specimens were either 40 x 40 x 160 mm or 100 x 100 x 400 mm concrete prisms, shown in Fig. 1 (left). The small prisms were used in standard bending tests, while the big prisms were divided into four cubes of 100 x 100 x 100 mm before used for experimental testing. One of such cubic specimens had two embedded temperature resistant thermocouples for monitoring the temperature development.
5 millimeters below the surface and in the center of the cube. After a period of 28 days of moist curing (20 ± 2 °C, RH ≥ 95 %) the specimens were cured under laboratory conditions (20 ± 2 °C, RH 60 ± 5 %) for 5 days. For every tested temperature, there were 3 concrete cubes and 3 prisms available, i.e. 15 cubes and 15 prisms all together.

Before heating, specimens were tested with US and resonant frequency method. Time of the US pulse traveling through the specimen was measured with US method and US velocity was calculated according to EN 12504 standard [18]. The US tests were carried out with Proceq Pundit PL-200 instrument. The wave induction caused by mechanical impulse was measured with resonant frequency method. Based on these measurements, the dynamic elastic and shear modulus were determined as proposed in ASTM standard [19]. After preliminary testing, specimens were heated in an electric furnace (Fig. 1 (right)). Average heating rate in the center of the cube was between 0.78 °C/min and 1.61 °C/min for heating up to the maximum temperature of 200 °C and 800 °C, respectively. During the heating, temperatures within concrete cubes were continuously recorded with two thermocouples, one below the surface and one in the center of the cube. The isothermal conditions at 200 °C, inside the cube, was reached after 4.3 hours, and it took 8.3 hours to reach isothermal conditions at 800 °C.

After the maximum temperature inside the concrete cube was reached, it was maintained for a short period before the specimens were slowly cooled down to the ambient temperature. In Fig. 2 temperature development inside concrete cube is depicted. Presented experimental work was derived from standardized tests and thus temperature gradients within the concrete specimens were intentionally minimized, with the aim of separating ‘material’ and ‘structural’ effects, as far as possible. It is worth noting that during heating internal thermal gradients have an influence on structure’s bearing capacity to some extent [20, 21], but this influence will be investigated in future research.

After cooling and crack observation various non-destructive methods such as US, resonant frequency method, rebound hammer, and destructive ones such as compressive and bending tests were carried out to determine the mechanical properties of concrete. Schmidt rebound hammer was used for determination of surface hardness of concrete according to EN 12504 standard [22]. Compressive and tensile strength were measured by standard compressive and bending tests, according to EN 12390 standards [23-24]. Finally, analysis of variance [25] was used for assessing experimental results’ sensitivity on temperature elevation.
EXPERIMENTAL RESULTS

Non-destructive tests

By observing the concrete surface after being subjected to elevated temperatures the damage of the concrete can be roughly detected. Assessment of fire-damaged concrete usually starts with visual observation of cracking, spalling and color change of concrete surface. Fig. 3 illustrates the concrete surfaces after exposure to elevated temperatures. There is no visible effect on the surface of the specimens heated up to 200 °C. The concrete starts to crack at temperatures above 400 °C but the effect is not significant at that temperature level. The cracks become pronounced at 600 °C and 800 °C, where the spalling of the specimens due to excessive cracking is not observed. In comparison to limestone concrete surface observation in [4], the cracks here appear at lower temperatures.

Fig. 3. Concrete prisms after exposure to elevated temperatures, from left to right: 20 °C, 200 °C, 400 °C, 600 °C, and 800 °C.

Results from non-destructive tests are shown in Fig. 3, where minimum, average and maximum values from three measurements are presented. US pulse velocity and surface hardness, shown in Fig. 3 (a, b), were determined on concrete cubes. Dynamic elastic and shear modulus, shown in Fig. 3 (c, d), were determined on concrete prisms.

Fig. 4. US pulse velocity in concrete cubes (a), surface hardness of concrete (b), dynamic elastic modulus (c), and shear modulus (d) after cooling down.
Experimental results show that average US pulse velocity is decreasing with increasing temperature up to 600 °C. Increase at 800 °C may result from measurement error or other errors, therefore more tests at this temperature are required to prove or omit the observed increase of US pulse velocity. Average surface hardness at ambient temperature is lower than at 200 °C. Above 200 °C the average hardness is decreasing with increasing temperature. Great dispersion of results for surface hardness of concrete is observed at 200 °C and 800 °C, due to this, more tests at these temperatures are required to prove or omit the observed increase. Average dynamic elastic and shear modulus are decreasing with increasing temperature, where larger reductions of both values are observed up to 400 °C. At 400 °C, also larger reductions in US pulse velocity, is observed and concrete starts to crack.

Analysis of variance (Anova) [25] is used for observing sensitivity of used experimental tests at elevated temperatures. It is noticed that the US test detects statistically significant impact of elevated temperatures on US pulse velocity at all tested temperatures. On the other hand, rebound hammer detects statistically significant impact of elevated temperatures on concrete surface hardness between 400 °C and 600 °C. With resonant frequency test statistically significant impact of elevated temperatures on dynamic elastic and shear modulus is observed up to 600 °C and 800 °C, respectively.

**Destructive tests**

Results from destructive tests are shown in Fig. 4, where minimum, average and maximum values from three measurements are presented. Compressive and tensile strengths of concrete after cooling down are determined on concrete cubes and prisms, respectively.

![Fig. 5. Compressive (a) and tensile strength (b) of concrete after cooling down.](image)

Experimental results show that average compressive strength and tensile strength of concrete after cooling down are decreasing with increasing temperature. It is observed that mechanical properties at selected temperatures are close together except at 200 °C where tensile strength results are more scattered than the other ones. Average compressive strength is 77.4 %, 52.5 %, 39.5 % and 14.1 % of the ambient temperature one at 200 °C, 400 °C, 600 °C and 800 °C, respectively. It is noticed that compressive strength is decreasing linearly, when tensile strength experience larger drop in strength at 400 °C, when also concrete starts to crack.

Statistically significant impact of elevated temperatures on the compressive strength is noticed at all tested temperatures, while for bending test this range is between 200 °C and 800 °C.

**CONCLUSIONS**

Presented experimental research was conducted on limestone concrete after exposure to elevated temperatures. Before testing concrete cubes and prisms were exposed to maximum temperature of 200 °C, 400 °C, 600 °C, or 800 °C and naturally cooled down. During heating and cooling, temperature gradients within the concrete specimens were minimized as possible, to obtain isothermal conditions. With destructive and non-destructive tests concrete compressive strength, tensile strength, surface hardness, dynamic elastic, and shear modulus were determined. The greatest impact of elevated temperature on decreasing mechanical properties was observed at dynamic elastic modulus. US pulse velocity and concrete compressive strength were observed to have similar decrease in case of exposure to 400 °C, around 42 % in comparison with properties at ambient temperature. In case of other temperatures, the influence of elevated temperature was not directly comparable. At 400 °C it was noticed that concrete started to crack at the same temperature the US pulse velocity, tensile strength, dynamic
elastic, and shear modulus experienced larger drop in value. The cracking seems not to affect the concrete compressive strength and surface hardness to the same extent as the rest of the mechanical properties. When considering method’s ability to detect the elevated temperature’s impact on the mechanical properties US method, resonant frequency for determining shear modulus, and standard compressive test are able to detect statistically significant impact at all tested temperatures. Thus, obtained experimental results from non-destructive and destructive tests will be used in future research. Next step is to develop a numerical model for estimating different concrete’s mechanical properties after fire with non-destructive measurements where artificial neural network approach will be used.

ACKNOWLEDGMENT

The work of U. Dolinar was financially supported by the Slovenian Research Agency with decision No. 802-7/2016-215. The work of G. Trtnik and T. Hojzjan was also supported by the Slovenian Research Agency through the research core funding No. P2-0260. The support is gratefully acknowledged.

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