Non-Destructive Assessment of Residual Strength of Thermally Damaged Concrete Made with Different Aggregate Types

Katarzyna Mróz 1, Izabela Hager 1

1 Cracow University of Technology, Institute of Building Materials and Structures, Warszawska Str. 24, 31-155 Cracow, POLAND

Abstract. The paper presents the results obtained for four concretes made with four different aggregate types: basalt, granite, dolomite and riverbed gravel. In this study, the cement paste and mortar compositions and their volumes remained the same for all the four concretes that allow clear comparisons and conclusions of aggregate type effect. Moreover, the aggregate particle size distribution is chosen to be quasi identical for all concretes so that this factor does not affect the concrete behaviour. The residual material properties (after heating and cooling down) are determined with the use of destructive and non-destructive testing methods for each concrete type being not thermally damaged and after thermal exposure at temperature of 200 °C, 400 °C, 600 °C, 800 °C and 1000 °C. Residual mechanical properties are compared with diagnostic parameters obtained with NDT methods. The aim of this study is to provide and compare the regression curves between selected non-destructive diagnostic parameters and the residual values of mechanical properties. The NDT methods used in this experiment are: surface hardness and Ultrasonic Pulse Velocity.

1. Introduction

As aggregate represents a major volume of concrete mixture, it is expected that its nature significantly affects concrete behaviour. In case of thermally damaged concrete the aggregate type effect is enhanced due to the numerous changes taking place in aggregates at elevated temperature, e.g. quartz phase β – α change, decomposition of carbonate stones (limestone and dolomite). Therefore, the changes in mechanical properties (compressive strength, splitting tensile strength or elastic modulus) caused by elevated temperature are dependent on aggregate nature [1, 2].

The quality of thermally damaged concrete may be assessed with the use of destructive and non-destructive method. Non-destructive parameters are highly dependent on concrete composition; thus, the calibration procedures are required. The objectives of the presented work are to perform a comparison of the non-destructive and destructive residual parameters obtained for concrete made of four compositions differentiated by an aggregate type. The aim of this study is to provide and compare the regression curves between selected non-destructive diagnostic parameters and the residual values of mechanical properties. For determination of non-destructive parameters, the Ultrasonic Pulse Velocity (UPV) and Rebound Hammer tests are performed and the relations between rebound index and sound
velocity in tested material are determined. The present study is part of a larger project on the influence of temperature on cement concrete and its fire damage diagnosis [1, 3, 4].

UPV method is commonly used to evaluate the concrete quality on the basis of measurement of velocity of sound wave propagated through tested material. As the previous tests have shown, the sound speed is sensitive to any changes of compressive strength of tested material [5]. Particularly, in case of thermally damaged concrete, the method is susceptible to concrete deteriorations due to, ex. CSH gel dehydration or portlandite decomposition and cracks development that influence significantly the quality of material.

Rebound Hammer tests allow to assess the concrete strength by surface hardness of tested material. The rebound of an elastic mass is proportional to the hardness of concrete surface. In case of concrete exposed to elevated temperature, the decrease of hardness of concrete surface is expected as the density, moisture content, and mechanical properties are reduced at higher temperature.

2. Materials and test methods

2.1. Mix composition

The presented research was carried out on high strength concrete (HSC) specimens made with four various compositions, differentiated by aggregate nature: basalt, granite, dolomite and riverbed gravel. In this study, the cement paste and mortar compositions and their volumes remained the same for all the four concretes that allows clear comparisons and conclusions on aggregate type effect. Moreover, the aggregate particle size distribution is chosen to be quasi identical for all concretes so that this factor does not affect the concrete behaviour. A detailed description of properties of four aggregates used in this research was previously given in [1]. The mix composition of four concretes is presented in table 1.

| Component | Unit | Concrete designation |
|-----------|------|-----------------------|
| Cement CEM I 42.5 R | kg/m³ | B basalt agg. concrete | 482 |
| Water | dm³/m³ | D dolomite agg. concrete | 145 |
| w/c ratio | - | G granite agg. concrete | 0.30 |
| Aggregates: | | O riverbed agg. concrete | |
| Riverbed quartz sand 0-2 mm | kg/m³ | 662 | 664 | 663 | 663 |
| Riverbed 2-8 mm | - | - | - | 610 |
| Riverbed 8-16 mm | - | - | - | 558 |
| Basalt 2 - 8 mm | kg/m³ | 709 | - | - | - |
| Basalt 8-16 mm | 648 | - | - | - |
| Dolomite 2 - 8 mm | - | 645 | - | - |
| Dolomite 8-16 mm | - | 590 | - | - |
| Granite 2-8 mm | - | - | 635 | - |
| Granite 8-16 mm | - | - | 580 | - |
| Admixtures: | | | |
| Plasticizer | % mc | 0.90 | 0.90 | 0.90 | 0.90 |
| Superplasticizer | 2.20 | 2.20 | 2.20 | 2.10 |
| Cement paste content | dm³/m³ | 300 | - | - | - |
| Mortar content | dm³/m³ | 550 | - | - | - |
| Coarse aggregate content | dm³/m³ | 450 | - | - | - |
| Consistency (slump) | mm | 120 | 130 | 130 | 160 |
| Air content in concrete mix | % vol. | 1.9 | 1.4 | 2.0 | 1.7 |
2.2. Specimen manufacturing and curing

The specimen series consist in the laboratory testing cubes (150 mm x 150 mm x 150 mm) for compressive strength test and cylinders (Ø100 mm, h = 200 mm) for determination of splitting tensile strength and elastic modulus. Directly after casting, specimens are stored in plastic moulds for 24 hours for preliminary curing. Subsequently, concrete is protected from water evaporation by covering it with plastic lids for next 7 days. After pre-curing, all the specimens are stored in air-drying conditions: temperature of 20 ± 5°C and relative humidity of 50 ± 5%. The initial and residual properties are determined after 90 days.

2.3. Heating and testing procedure

2.3.1. Heating. After 90 days of curing, cubic and cylindrical specimens manufactured for determination of residual properties are subjected to heating with the linear rate of 0.5 °C/min in electrical laboratory furnace. The temperature in furnace increases from 20 °C to set temperature T (T = 200, 400, 600, 800, 1000 °C). In order to minimize the thermal gradient in the specimen interior the value of 0.5 °C/min of heating rate is used as it is recommended by RILEM Technical Committee [6]. The set temperature is maintained for 3 hours. Then the specimens are freely cooled down in furnace. Mechanical tests are performed for two specimens of each material per temperature and for three unheated specimens.

2.3.2. Destructive testing. Residual compressive strength ($f_{ct}$) for each tested concrete are determined by following the standard EN 13791 [7]. The residual changes in modulus of elasticity ($E_T$) are determined from σ-ε curves. Elastic modulus values are calculated as the relationship between stress and strain in the range from 10 to 40% of the breaking stress. Finally, residual tensile strength ($f_{Tt}$) is performed with the use of splitting Brazilian test method.

2.3.3. Non-destructive testing. In the presented tests, the PUNDIT plus – Portable Ultrasonic Non-destructive Digital Indicating Tester is used. The cylindrical transducers of nominal frequency of 54 kHz are located at opposite surfaced of cubic specimens and the sound wave velocity ($V_T$) is measured. For Rebound Hammer method, the Schmidt Hammer is used. The rebound number ($L_T$) is measured at 5 points with spacing of 20 mm at each surface of cubic specimen. The mean $L_T$ value is reported.

3. Test results and discussion

3.1. Initial properties

The initial properties of manufactured concretes are determined after 90 days of curing in air-drying conditions. Physical properties (bulk density $\rho_o$) and mechanical properties (compressive strength $f_c$, splitting tensile strength $f_t$ and modulus of elasticity $E$) are tested using standard concrete specimens. Non-destructive parameters are measured by the aforementioned method. Sound velocity $V$ measured for four concretes takes values between 4.9 – 6.2 km/s what indicates a very good initial quality of concrete. Obtained values for initial properties are presented in table 2.

| Property                  | Unit  | B basalt agg. concrete | D dolomite agg. concrete | G granite agg. concrete | O riverbed agg. concrete |
|---------------------------|-------|------------------------|--------------------------|------------------------|-------------------------|
| Bulk density $\rho_o$     | kg/m$^3$ | 2558.8                | 2416.5                   | 2376.7                 | 2300.7                  |
| Compressive strength $f_c$ | MPa   | 84.9                   | 79.8                     | 73.3                   | 77.0                    |
| Splitting tensile strength $f_t$ | MPa | 6.2                    | 5.4                      | 4.9                    | 6.0                     |
| Modulus of elasticity $E$ | GPa   | 44.4                   | 42.6                     | 30.6                   | 29.7                    |
| Sound velocity $V$        | km/s  | 5.01                   | 5.05                     | 4.6                    | 4.6                     |
| Rebound index $L_T$       | -     | 40.5                   | 41.6                     | 42.9                   | 46.5                    |
3.2. Residual properties

The residual relative changes of destructive and non-destructive parameters for each of four tested concretes are presented in figure 1 as the function of temperature. The curves illustrate the mean values from three unheated specimens (table 2) and from two thermally damaged by target temperature $T$, described in paragraph 2.3.1.

The obtained relationships show for each tested concrete that the quantitative changes of ultrasonic pulse velocity ($V_T$) follow the changes of residual mechanical properties ($f_{cT}$, $f_{tT}$ and $E_T$). However, the values measured for Rebound index seems not to be as consistent with mechanical properties as $V_T$. Those observations are similar, irrespectively of the aggregate nature.

For dolomite aggregate the mechanical properties $f_{cT}$, $f_{tT}$ and $E_T$ are determined up to 600 ºC. The higher temperature causes carbonate aggregate decomposition into CaO and CO$_2$. Additionally, the CaO forms during decarbonation hydrated when specimen is cooled down, with a consequent of 44 % of expansion causing crack network development. Thus, mechanical properties cannot be not determined. Due to this fact determination of regression curves for this material was not possible.

![Figure 1. Relative residual parameters from destructive and non-destructive tests for concretes: a) Basalt concrete, b) Dolomite concrete, c) Granite concrete and d) Riverbed concrete.](image)

3.3. Regression curves

Having acquired initial and residual properties from destructive and non-destructive tests for each tested temperature, the correlation between non-destructive and destructive parameters is established on the basis of their absolute values. For rebound index, the relations with: compressive strength ($f_{cT}$-$L_T$), elastic modulus ($E_T$-$L_T$) and splitting tensile strength ($f_{tT}$-$L_T$) are determined, figure 2. Also on the basis of ultrasonic pulse velocity, the correlations with: compressive strength ($f_{cT}$-$V_T$), elastic modulus ($E_T$-$V_T$) and splitting tensile strength ($f_{tT}$-$V_T$) are established, figure 3.
Figure 2. Regression curves for relation: $f_c(T,L)$, $E(T,L)$ and $f_t(T,L)$ obtained for concretes: Basalt concrete, Dolomite concrete, Granite concrete and Riverbed concrete at elevated temperature.
3.3.1. Results for rebound index \( L \). For relation \( f_{cT}(LT) \), the linear relation \( f_{cT} = a\cdot LT - b \) may be written for each tested concrete, where \( a \) and \( b \) are constants. It can be observed that the relation obtained for granite concrete is characterized by the smallest scatter, while results for dolomite concrete do not provide reliable conclusions. It may be caused by instability of dolomite aggregate at heating (dehydration) and during cooling down (rehydration process).

Both the slope \( (a) \) and the y-intercept \( (b) \) of linear function \( f_{cT}(L) \) are dependent on the initial concrete strength affected by aggregate type. On the basis of regression curves given in figure 2a,d,g,j for each tested concrete separately, the constant \( a \) may be assumed as 0.04 of initial concrete strength \( (a = 0.04 f_{c20°C}) \) \( \) (1). It is consistent with [3] where the analysis of water content effect on NDT parameters was presented. Therefore, the slope of regression curve seems to be more dependent on concrete quality than its composition and \( a \) value equal 0.04 \( f_{c20°C} \) may be considered as being in force for all tested HSC concretes. The \( b \) constant in presented analysis is proposed to be equal: 60, 40, 54, 68 for basalt, dolomite, granite and riverbed aggregate concrete, respectively. It seems not to be in relation with concrete strength or other physical or mechanical properties.

\[
\begin{align*}
    f_{cT}(LT) &= 0.04 \cdot f_{c20°C} \cdot LT - b \\
    f_{cT}(L) &= 2.8 \cdot LT - 50 \\
    f_{cT}(L) &= 2.8 \cdot LT - k_i; 40 < k_B < k_G < k_D < k_O < 60
\end{align*}
\]

Moreover, while analysing the gathered data \( f_{cT}(L) \) obtained for all tested concretes, the general linear regression curve is proposed \( (2) \) (red solid line in figure 2m). It can be noticed that with the use of proposed formula, the values of compressive strength \( f_{cT} \) are underestimated for basalt concrete \( (B) \) and overestimated for riverbed aggregate concrete \( (O) \). Therefore, it may be concluded that general regression curve may be a linear function \( (3) \), where \( k \) is a factor dependent on aggregate type used for concrete production.

In case of non-destructive assessment of concrete elastic modulus by rebound index \( E_T(L) \), the power functions are proposed for each tested concrete. It has been noticed that for dolomite concrete \( (D) \), there is a small change of rebound index and the elastic modulus of concrete cannot be determined by this NDT parameter. However, for concretes made with basalt, granite and riverbed aggregate, the relations are strong \( (R^2 > 0.93) \) and for each concrete are proposed as the function \( (4) \), where \( d \) is located in narrow interval \( (4.5 – 4.9) \) and \( c \) constant is higher for basalt concrete than for granite and riverbed aggregate. It can be related to the stiffness of the material as basalt aggregate is characterised by greater thermal stability than remaining aggregates (dolomite, granite and riverbed).

\[
\begin{align*}
    E_T(L) &= c_i \cdot (LT)^d; c_G < c_O < c_B \ \text{and} \ 4.5 < d < 4.9 \\
    E_T &= 0.0011 \cdot (LT)^{4.48}
\end{align*}
\]

When all data of \( E_T(L) \) are compared, the \( (5) \) general formula can be written. The curve presented this relation is plotted in figure 2n in red solid line. Similarly, to data for \( f_{cT}(L) \) it can be observed that elastic modulus is underestimated for basalt concrete \( (B) \) and overestimated for riverbed aggregate concrete \( (O) \) when the general formula \( E_T(L) \) is used. Moreover, it shall be noticed that the scatter of gathered results for all concretes is very high and the general analysis does not provide sufficient results. Therefore, it may be advised that regression curves for determination of elastic modulus on the basis of rebound index shall be developed separately for concretes made with different aggregate type.

\[
\begin{align*}
    f_{cT}(L) &= g_o \cdot e^{0.09 \cdot L}; 0.05 < g_O < g_B < g_G < 0.11
\end{align*}
\]
Finally, the relations between rebound index and splitting tensile strength for four thermally damaged concretes are compared. The conclusions coming from this analysis are similar to those given for relation $E(L)$. Similarly, the regression curves are rather strong ($0.95 > R^2 > 0.93$) for individual type of concrete and the proposed formulas take the nature of exponential curves (6). Again, the results obtained for dolomite concrete are not evident in this analysis.

While considering the overall data obtained for all the tested concretes, the general formula (7) is given. It is worth to note that the discrepancy between calculated results by this formula is much greater for concrete of good quality than for thermally damaged concrete. Therefore, it is advised to provide regression curves for concretes made with different aggregate nature separately, if possible.

$$f_{rT}(L_T) = 0.11e^{0.009L_T}$$  \hspace{1cm} (7)

3.3.2. Results for ultrasonic pulse velocity $V$. While describing the $f_c-V$ relations the logarithmic formulas are commonly given for a different type of concrete. Particularly for thermally damaged HSC concrete it was previously proposed that the general regression curve takes the form of (8) [5]. It can be concluded that by shifting the proposed in [5] curve (8), it is possible to adjust it to the presented in this experiment results. It can be done by replacing the value of 25.15 to 9.2 as it is plotted in figure 3m in red solid line. Then the accuracy of the regression curve for the experimental data are the best ($R^2 = 0.86$). The individual regression curve for each tested in this paper concrete indicate that relation $f_c(V)$ takes form of $f_c = X\ln(V) + Y$, when $X$ value is greater for concretes of higher strength as it was shown in previous studies [3].

$$f_{cT} = 45\ln(V_T) + 25.15$$  \hspace{1cm} (8)

$$f_{cT} = 45\ln(V_T) + d$$  \hspace{1cm} (9)

However, as it can be seen while considering the concrete made with different type of aggregate separately, the accuracy of the other regression curves proposed for the obtained data are only slightly stronger than the general equation, Therefore, it can be concluded that relation $f_c(V)$ does not depend strongly on the aggregate nature being used to concrete production and general equation (9) may be successfully used, where $d$ is a value that characterize a shift of curve on the basis of experimental data.

As it is commonly known, the velocity of sound wave propagated through the material is strongly affected by its stiffness, and hence the relations between $V$ value and elastic modulus are expected to be evident. This assumption is confirmed by the presented research analysis. For all the tested concretes the power function of relation $E(V)$ is very strong, $R^2 > 0.97$, irrespectively of concrete compositions and properties. Among other relationships presented in this paper, the $E(V)$ one seems to provide the most reliable method for non-destructive assessment of elastic modulus in thermally damaged concrete. The proposed regression curve is a power function (10) that seems to give reliable results for residual modulus of elasticity for all tested concretes, irrespectively of their composition.

$$E_{T}(V_T) = 988(V_T)^{3.33}$$  \hspace{1cm} (10)

$$f_{rT}(V_T) = 0.25f_{20^\circ C} \cdot V_T - y$$  \hspace{1cm} (11)

$$f_{rT}(V_T) = 1.5V_T - 1.2$$  \hspace{1cm} (12)
Figure 3. Regression curves for relation: $f_{ct}(V_T)$, $E(V_T)$ and $f_d(V_T)$ obtained for concretes: Basalt concrete, Dolomite concrete, Granite concrete and Riverbed concrete at elevated temperature.

Finally, the ultrasonic pulse velocity method allows also to assess the splitting tensile strength by developing a linear regression curve. Within four tested concretes with different aggregate type, the
linear relation \( f_t = x \cdot V - y \) may be written for each tested concrete, where \( x \) and \( y \) are constants, and \( x = 0.25f_{20°C} \) and \( y \) is greater value for concrete characterized by higher strength (11). It seems that proposed in figure 3o general regression curve of formula (12) is strong enough to assess the reliable values of splitting tensile strength in thermally damaged concretes.

4. Conclusions

In view of the experimental results of destructive and non-destructive testing methods application to high temperature damaged concrete that are presented in this paper, the following conclusions can be drawn:

- The high temperature exposure directly influences the mechanical and physical properties of concrete and has an evident impact on measured values of non-destructive parameters;
- The quantitative relations between ultrasonic pulse velocity (\( V_T \)) and residual mechanical properties (\( f_{ct}, f_{ctT} \) and \( E_T \)) seem to present a good correlation while values measured for Rebound index are not so strongly consistent with mechanical properties evolution related to temperature exposure;
- The formula for estimation of compressive strength of HSC concretes on the basis of rebound index \( f_{ct}(LT) \) is presented. General regression curve may be a linear function in which the slope is proportional to initial compressive strength of tested concrete and y-intersect constant is a factor dependent on aggregate type used for concrete manufacturing;
- In case of non-destructive assessment of concrete elastic modulus by rebound index \( E_T(LT) \), the power functions are proposed for each tested concrete. The constants in the proposed formulas are related to the stiffness of the material as basalt aggregate is characterised by greater thermal stability than remaining aggregates;
- In case of \( f_{ctT}(LT) \) relation, the significant differences in regression curves are presented between concretes made with different aggregate type. It shall be noticed that while comparing results obtained for all tested concretes, greater scatter in \( f_{ctT}-LT \) correlation is observed for higher value of rebound index \( LT \) measure for concrete subjected to lower temperature. Therefore, it is advised to provide an individual regression curve to assess the degree of thermal damage in concretes made with different type of aggregate;
- On the basis of results collected for ultrasonic pulse velocity \( V_T \) and mechanical properties related to the gathered data, it can be concluded that sound velocity provides a reliable information about concrete quality, irrespectively of its composition and degree of thermal damage. The logarithmic formulas for relation between \( V_T \) and residual compressive strength \( f_{ct} \) are proposed while for residual splitting tensile strength \( f_{st} \) the linear function provide a best correlation;
- As stiffness of the material affects greatly the capability of any wave propagation through its section, the relations between \( V_T \) value and residual elastic modulus \( E_T \) are evident and the error in assessment of elastic modulus on the basis of sound velocity is minimized.
- Rebound hammer method, as taking information of the surface hardness does not provide the reliable information and seems to be affected by material changes taking place in aggregate and cement paste. Therefore, the most reliable correlation between non-destructive parameters measured by means of this method and mechanical properties of concrete are observed for concrete made with more thermally stable aggregates, like basalt. It shall be emphasized that for concrete made with dolomite aggregate the Rebound hammer method deliver results that do correspond with concrete condition. It may be due to processes of dehydration and rehydration taking place in dolomite aggregate during heating and cooling phases.
- As the velocity of sound wave propagates through the entire cross-section of thermally damaged concrete UPV method may be used to reflect its condition in great extent. Due to the same reason, the Ultrasonic Pulse Velocity method may be successfully used for all the concrete compositions and the regression curves for thermally damaged concrete may be established and unified.
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