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Investigation for Estimating of Concrete Strength by the Maturity Method and the Rebound Hammer Test

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Abstract. Estimating the in-situ strength of the concrete is an important factor in planning the execution of reinforced concrete structures. The evaluation of the concrete characteristics development can be based on different methods-maturity methods, temperature-matched curing, rebound hammer testing, ultrasonic pulse velocity and other. The recent article presents the results of an experimental study to determine the compressive strength of the concrete in test specimens by a maturity method based on ASTM C1074-19e1 and a rebound hammer test according to BDS EN 13791/NA and BDS EN 12504-2. The maturity calculation are based on temperature measurements taken at a depth of 10 mm below the surface of the test specimens. Calculations were also performed to assess the compressive strength according to FIB Model Code 2010. The obtained results are compare with the actual concrete strength established by testing cubic test specimens, cured on site. Furthermore, there was found a very high correlation between the values of the compressive strength, calculated by maturity method based on ASTM C1074-19e1 and the rebound hammer test according to BDS EN 13670/NA and BDS EN 12504-2.

INTRODUCTION

Estimating the in-situ strength of the concrete is an important factor when planning the execution of reinforced concrete structures. The concrete strength is of great importance when starting a number of technological operations, such as removal of formwork and reshoring, post-tensioning of tendons in structures, termination of cold weather protection, opening of the roadways to traffic etc. [1]. The problems related to the early striking of the reinforced concrete structures, shoring and reshoring and effectiveness from the use of different formwork systems are very significant, as the different aspects are the subject of a number of studies [2-5].

The standard EN 13670 states that the detailed estimates of the concrete properties development may be based on one of the following methods: maturity calculation from temperature measurements taken at a maximum depth of 10 mm below the surface; maturity calculation based on the daily average air temperature; temperature-matched curing; rebound hammer testing; other methods of established suitability [6]. But the standard EN 13670 does not regulate which method or standard shall be used for maturity calculation from temperature measurements.

At the present moment, a number of standardized methods, which are based on different maturity functions are used in the world practice – ASTM C1074, NEN 5970, NCh 3565, TS 13508, FIB Model Code, etc. [1, 7-10]. Analysis of strength estimation from maturity functions is presented in [11] and the tendency is to use various measuring devices and maturity meters, including those equipped with wireless sensors based on IoT [12-14]. Examples of the practical application of the method are discussed in [15] and [16].

Also, in construction practice a number of standardized indirect methods are used to determine the characteristics of the concrete – pulse velocity method, rebound hammer test, etc. [17, 18], and a combination of them [19]. For determining the in-situ strength of the concrete, especially in Bulgaria, the greatest application has BDS EN 13791 and in particular its National Annex – BDS EN 13791/NA:2011 in combination with series EN 12504-2 [20].

The main focus of this study is to determine and compare the compressive strength of the concrete through maturity calculations based on temperature measurements taken at a depth of 10 mm below the surface and rebound hammer testing carried out on the same place.

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METHODS

In the study, the strength of the concrete at different ages was determined according to ASTM C1074-19e1 [1], FIB Model Code [10] and the rebound hammer test according to BDS EN 13791/NA:2011 [21]. In addition, the obtained results are compared with the compressive strength of cubic test specimens (150 mm) cured on site and tested according to BDS EN 12390-3. The results obtained in the tests on the compressive strength of cubic test specimens aged 1, 3, 7, 14 and 28 days are presented in [22].

Estimation of In-Situ Strength by the Maturity Method according to ASTM C 1074

For the purposes of this article and to establish the strength-maturity relationship of the concrete, initial studies were performed trough laboratory tests according to ASTM C 1074, which are presented in [22]. Based on these preliminary studies, the temperature-time factor and the relationship between compressive strength and temperature-time factor were calculated. The relationship is expressed as a linear function of the logarithm (Equation 1) and was used for evaluating the strength of the hardened concrete cured under different temperature conditions:

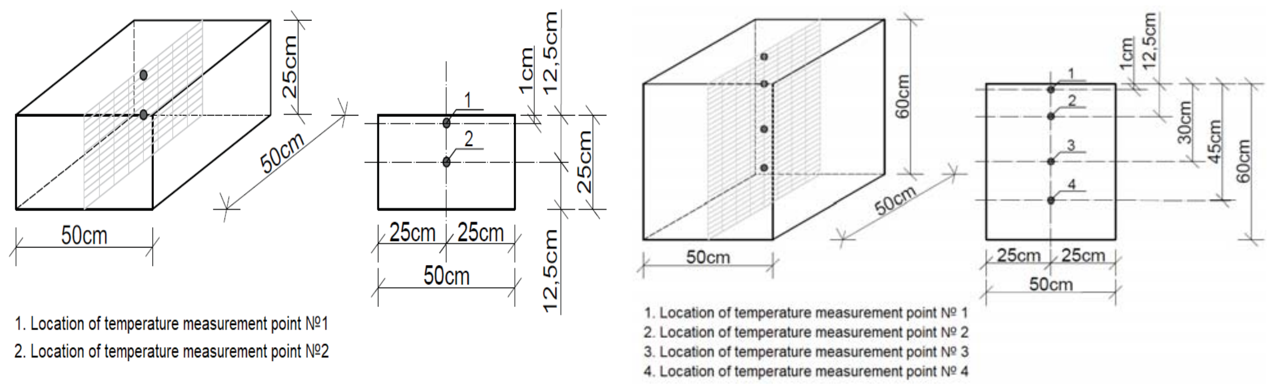
$$y = 8,948\ln(x) - 43,689, \quad (1)$$

where y is the compressive strength of the concrete, MPa; x is the temperature-time factor.

Two experimental test specimens (Fig. 1) were made – a fragment of reinforced concrete slab with dimensions 50/50/25 cm (test specimen 1) and a fragment of a reinforced concrete column with dimensions 50/50/60 cm (test specimen 2), which are stored at real weather conditions within the period from 04 June to 01 July. The concrete used is strength class C 20/25, manufactured by a licensed commercial concrete plant in Sofia. The test specimens were used to determine the strength of the concrete by its age according to ASTM C 1074 and the rebound hammer test as per BDS EN 12504-2 respectively.

FIGURE 1. Test specimens after placing of the concrete.

The temperature measurement sensors were set at various depth in the reinforced concrete specimens, prior to concreting – Fig. 2. In test specimen 1, temperature measurement sensors were located at 1.0 cm and 12.5 cm below the concrete surface (Fig. 2 a), and in test specimen 2 the depths of installation were 1.0 cm, 12.5 cm, 30 cm and 45 cm (Fig. 2 b). The requirement for locating the sensors at a depth of 1.0 cm from the surface is in conformity with the requirements of BDS EN 13670 [6]. The temperature measuring devices (sensors) have accuracy of ±1 °C, temperature range from -50°C to +50°C and sampling interval - 20 s. The measurements of the temperature were performed according to ASTM C 1074.



a) b)

FIGURE 2. Locations of temperature measurement points (a) in test specimen 1; (b) in test specimen 2.

The temperature of the concrete was measured within 28 days. Using the data from the sensors, a calculation of the temperature-time factor was performed by the Nurse-Saul function. Using the strength-maturity relationship developed in [22], given in equation (1), the value of compressive strength corresponding to the measured maturity index was reported.

Estimation of Concrete Strength by the method described in FIB Model Code 2010

According to FIB Model Code 2010 [10], the related compressive strength of concrete at various ages $f_{cm}(t)$ may be estimated from Equations 2, 3 and 4.

$$f_{cm}(t) = \beta_{cc}(t) f_{cm} \tag{2}$$

with

$$\beta_{cc}(t) = \exp\left\{ s \left[1 - \left(\frac{28}{t} \right)^{0,5} \right] \right\}, \tag{3}$$

where $f_{cm}(t)$ is the mean compressive strength in MPa at an age t in days; f_{cm} is the mean compressive strength in MPa at an age of 28 days; $\beta_{cc}(t)$is a function to describe the strength development with time; t is the concrete age in days adjusted acc. to Equation (4) (taking into account temperature during curing); s is the coefficient which depends on the strength class of cement as given in Table 5.1-9 of [10].

$$t_T = \sum_{i=1}^{n} \Delta t_i \exp\left[13,65 - \frac{4000}{273 + T(\Delta t_i)} \right], \tag{4}$$

where t_T is the temperature adjusted concrete age which replaces t in the corresponding equations in days; Δt_i is the number of days where a temperature T prevails; $T(\Delta t_i)$ is the temperature in °C during the time period Δt_i.

In order to determine the concrete compressive strength, its temperature was introduced with the values taken from the previous experimental study. Based on the methodology given in FIB Model Code 2010, the compressive strength of all points in test specimen 1 and test specimen 2 was calculated.

Estimation of In-Place Strength by rebound hammer test according to EN 12504-2 and BDS EN 13791/NA:2011

Within the study, the compressive strength was determined according to BDS EN 13791/NA:2011 using the results obtained by rebound test – BDS EN 12504-2 [20]. It is well known that the method is based on the dependence between the compressive strength of the concrete and its surface hardness measured by rebound number when testing with spring-loaded steel hammer. During the test, the position of the instrument was chosen so that the steel body strikes firmly and perpendicular to the test surface (Fig. 3). The pressure on the steel body was gradually increased until the hammer strikes it. After impact, the magnitude of the rebound was measured. At least ten records were made to perform a realistic evaluation of the rebound number from the tested surface. For each series of tests, the direction and orientation of the instrument were noted by adjusting the reading at an angle. The correlation between the rebound number and the concrete strength was determined based on the results obtained from parallel indirect tests by a Schmidt hammer and standard destructive testing of 150 mm cubes (BDS EN 12390-3). The in-situ strength of the concrete for a test surface was determined by taking into account the experimentally determined correlation [20].

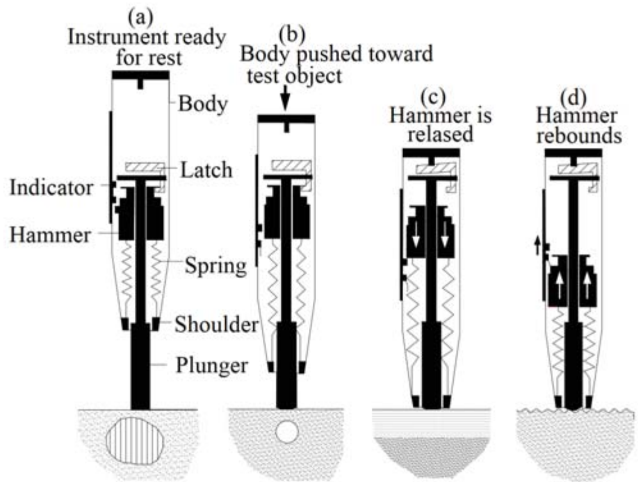


FIGURE 3. Principle of the rebound hammer test [12].

RESULTS AND DISCUSSIONS

Measurement of Concrete Temperature in Test Specimens

In the study, the temperature was reported daily for 28 days. The results obtained from the measurements in the first seven days are presented in Fig. 4 for test specimen 1 and in Fig. 5 for test specimen 2, respectively.

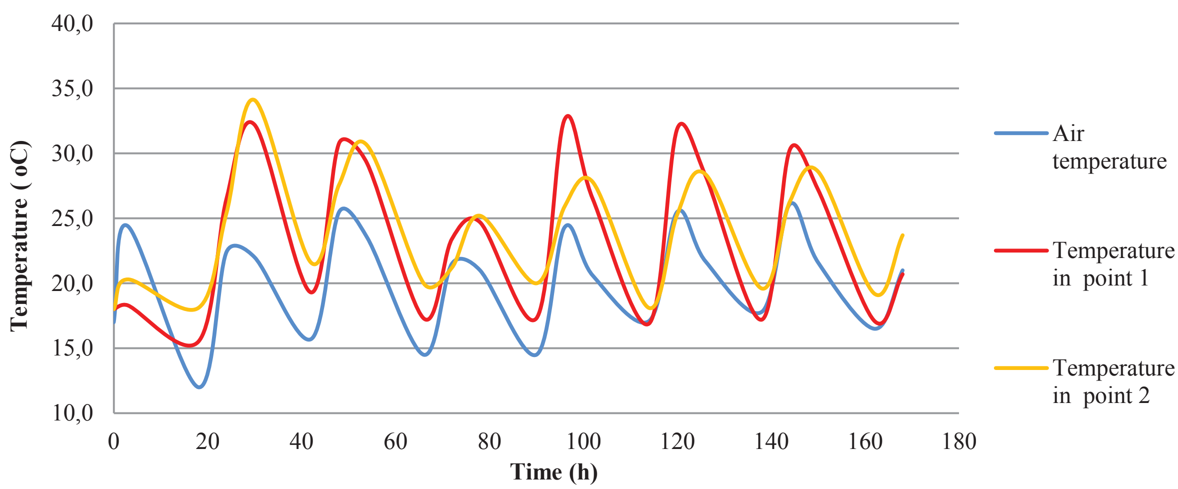


FIGURE 4. Temperature evolution of concrete in test specimen 1 for 7 days.

The results presented in Fig. 4 and Fig. 5 show a greater heat release of the concrete during the first 24 hours of hardening. Although, in general, the temperature of the concrete follows the course of the air temperature, in point 2 of test specimen 2, a higher temperature was observed in the first 48 hours resulting from cement hydration. Approx. 48 hours later, the temperature in both point 1 and point 2 starts to follow the air temperature. It is obvious that after the 48th hour, the temperature of the concrete in point 1 (located immediately below the surface of the element) was higher than the temperature in point 2, when measured in the hours with the highest solar radiation. This indicates the additional effect from the direct sunlight and solar radiation. The lowest temperature of the concrete on the surface (in point 1) is identical to the ambient temperature during the night.

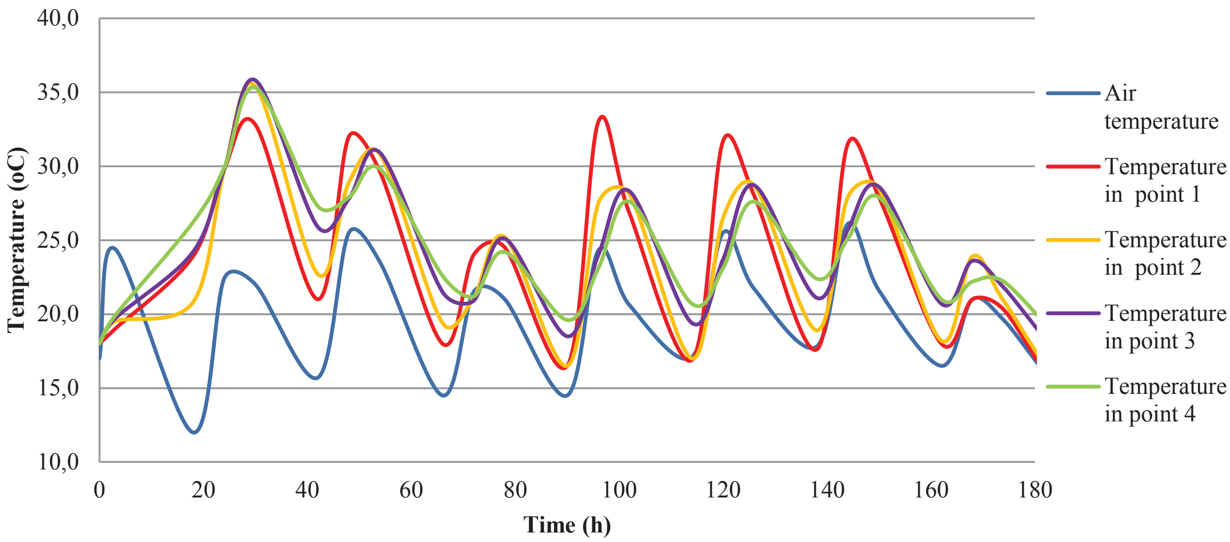


FIGURE 5. Temperature evolution of concrete in test specimen 2 for 7 days.

The test specimen 2 also shows a greater heat release during the first 24 hours – see Fig. 5. The highest temperature was recorded in point 3 of test specimen 2, and approx. after 48 hours of hardening, the temperature of the concrete starts to follow the air temperature. The temperature course observed in test specimen 2 were similar as in test specimen 1. The main difference between two specimens is the higher temperature measured during the first 48 hours in specimen 2 compared to those measured in test specimen 1 in the same time. This phenomenon can be easy explained by larger dimensions of the element and the smaller surface modulus (the surrounding surface relative to the volume of the element), respectively. The influence of the ambient temperature and solar radiation on the temperature of the concrete surface was observed in both specimens. It can be concluded that the concrete temperature in reinforced concrete elements with dimensions similar to test specimen 1 and test specimen 2 (slabs, columns, walls, etc.), is significantly influenced by the atmospheric conditions – the ambient temperature and the solar radiation, especially in areas near the surface area of the concrete member.

Concrete Strength at early age estimated by the Maturity Method and Rebound Number

The strength of the concrete was determined using the method described above. The calculated values of the compressive strength of concrete in point 1, located at a depth of 10 mm below the surface, of test specimen 1 and test specimen 2 were compared using different methods included in the study – ASTM C 1074, BDS EN 13791/NA:2011 and FIB Model Code 2010. The concrete strength, calculated according to ASTM C 1074 and FIB Model Code 2010, was determined taking into account the temperatures measured in the individual points. The determination of compressive strength according to BDS EN 13791/NA (in combination with BDS EN 12504-2) was performed also on daily basis in point 1 of test specimens 1 and 2. The comparison of the concrete strength is shown in Fig. 6 for test specimen 1 and in Fig. 7 for test specimen 7, respectively. The figures also show the determined compressive strength of the cubic test specimens cured on site and tested according to BDS EN 12390-3.

Several significant trends, visible in Fig. 6, could be highlighted based on the values of the concrete strengths determined according to the different methods and standards. In a concrete up to 14 days of age, the differences between the compressive strength of cubic specimens cured on site and the calculated compressive strength in point 1 of test specimen 1, determined by the Maturity method based on ASTM C 1074, were from 1% to 20%. The maximum difference (20 %) was obtained on age 1 day, but in age 3 days and in age 7 days, this difference was 1%. On age 14 days and age 28 days, the difference of the compressive strength was 10% and 12%, respectively.

The comparison of the values obtained for the compressive strength of the cubic specimens and for the strength assessed in situ according to BDS EN 13791/NA shows that the largest difference (27%) was obtained also at an age of the concrete of 1 day. With increasing the age, these differences decrease, and for the age of the concrete from 3 to 14 days, the differences between the strength obtained from the rebound hammer test and the destructive method were within the range of 2-4%.

Therefore, it can be concluded that such a difference is normal for application of non-destructive (indirect) testing methods, especially in the early age.

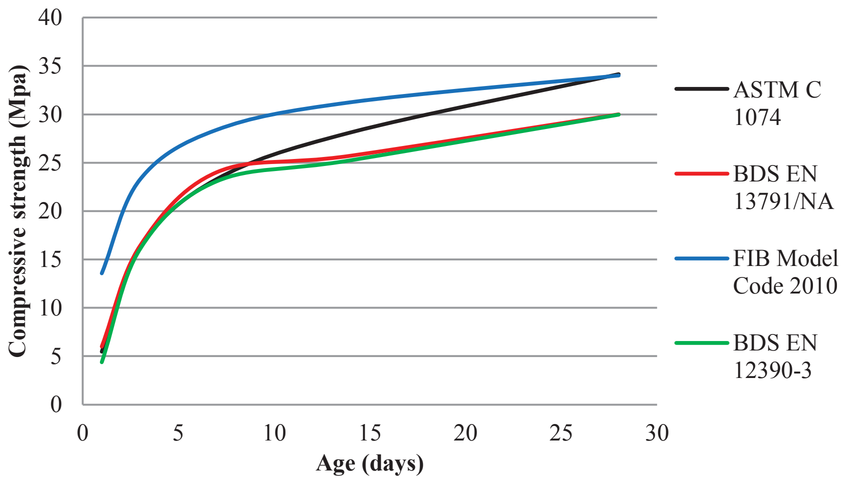


FIGURE 6. Comparison between the compressive strengths of concrete obtained in point 1 of test specimen 1 according to ASTM C 1074, BDS EN 13791/NA, FIB MODEL Code 2010 and BDS EN 12390-3.

On the other hand, the comparison of the compressive strength of the concrete in point 1 of test specimen 1, determined by FIB Model Code 2010, and of the cubic specimens cured on site, shows that the resulted values differ by up to approx. 68% and these differences decrease in time. These relatively large differences (68%) were found at the age of 1 day. At the age of 3 days, the difference was 31% and at the age of 7 and 14 days – 19%. Differences in the strength values of 12%, determined by both methods, were established at the age of 24 days.

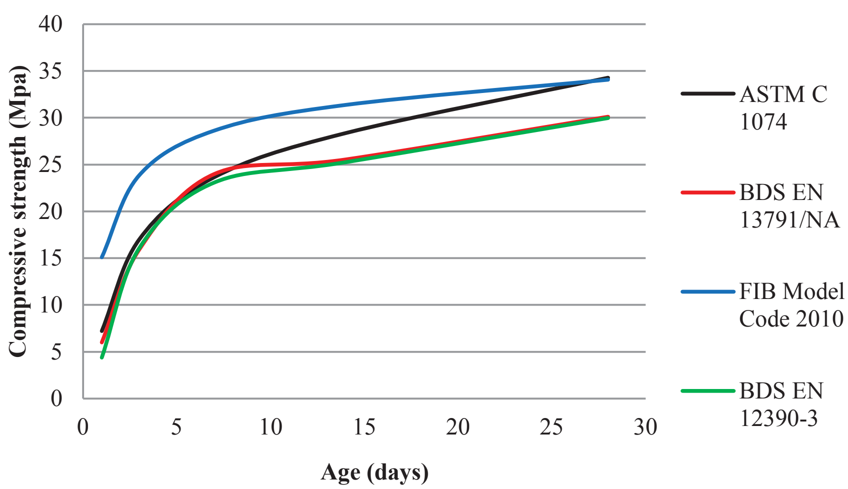


FIGURE 7. Comparison between the compressive strengths of concrete obtained in point 1 of test specimen 2 according to ASTM C 1074, BDS EN 13791/NA, FIB MODEL Code 2010 and BDS EN 12390-3.

Some trends similar to those of test specimen 1 can also be traced from the analysis on the results, relating to test specimen 2 presented in Fig. 7. In a concrete stored up to the age of 14 days, the differences in the strength of the cubic specimens and the compressive strength in point 1 of test specimen 2, determined by ASTM C 1074, were within 11%÷39%. The largest difference (39%) was determined at a concrete age of 1 day. In a concrete aged of 3 to 14 days, the strength difference determined by both methods was in the range from 2% to 11%. At the age of 28 days, this difference was 13%, i.e. practically the same as in the test specimen 1.

For the compressive strengths determined according to BDS EN 12390-3 and BDS EN 13791/NA, the biggest differences were obtained also at an age of the concrete of 1 day - 27%. With increasing the age, these differences decreased to 4% and 1%, for the age of 7 days and 14 days, respectively.

Taking into account the above mentioned, it can be assumed that such a difference is normal for the application of non-destructive testing methods.

Also, the compressive strength of the cube specimens and the strength in point 1 of test specimen 2, determined by FIB Model Code 2010, show that the resulted values differ among themselves up to approx. 71% and these differences decrease with increasing the age. These considerable differences were also pronounced at the early age of the concrete. Differences in the strength values of 12%, determined by both methods, were established over the concrete hardening period of 28 days – the same as in test specimen 1.

The strength relationship, determined taking into account the test results obtained in point 1 of test specimens 1 and 2, according to ASTM C 1074 and according to BDS EN 13791/NA respectively, has also been analysed. Correlation analysis was used for this purpose. When comparing the values obtained in the experimental study, the correlation equations for point 1 of test specimen 1 (Fig. 8) were derived and the corresponding coefficients of determination R^2 were determined. The high values of R^2 indicate that there is a correlation between the strengths obtained as per the two standards. The correlation relationship can be assessed as very high. Similar high values of R^2 ($R^2 = 0.94$) were derived for point 2 of test specimen 2.

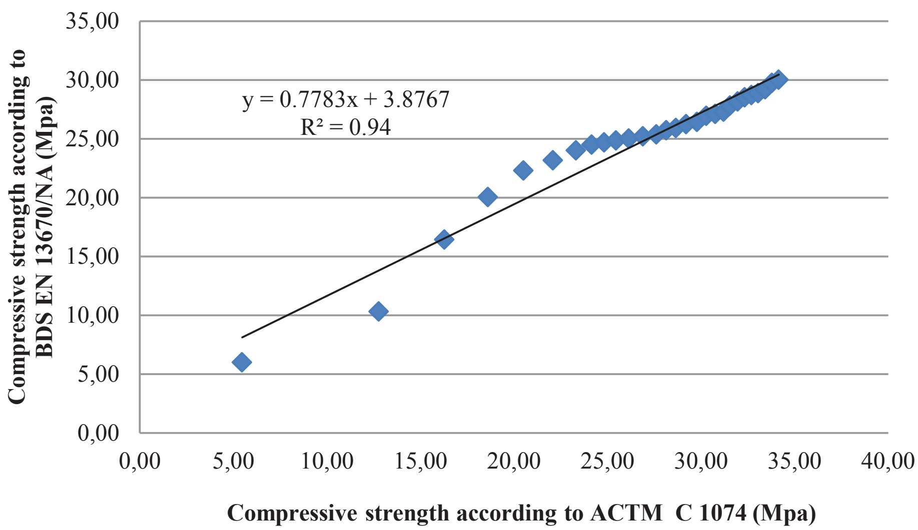


FIGURE 8. The strength correlation relationship obtained in point 1 of test specimen 1 according to ASTM 1074 and BDS EN 13791/NA (with BDS EN 12504-2).

CONCLUSION

The article presents the results from experimental study for the early-age compressive strength of concrete estimation using a maturity method based on in-situ temperature measurements and rebound hammer test. The maturity calculations are based on temperature measurements taken at a depth of 10 mm below the surface, according to requirements of standard EN 13670. Numerous conclusions can be made after the observation and the analysis of the results obtained.

A significant heat release in the first 48 hours after concreting in both tested specimens, which is mainly due to the heat release of the cement. With the increasing of age of the concrete, the temperature decreases. The temperature of the concrete follows the changes in the ambient temperature for all the tested specimens and this is more clearly expressed in the measuring points located near beneath the surface of the tested elements. In other words, for concrete and reinforced concrete members with dimensions similar to those of test specimens 1 and 2, the temperature of the concrete is largely influenced by the ambient temperature, environmental conditions and solar radiation. During the first 48 hours, higher temperatures were determined than those located on the surface at all the points located inside the elements. The effect of cement heat release decreases as the age of concrete increases. The lowest temperature of the concrete on the surface is practically equal to the ambient temperature during the night.

The comparison of the compressive strength obtained with the cubic test specimens, cured on site, and with the non-destructive methods - the Maturity method as per ASTM C 1074 and the rebound hammer test as per BDS EN 13791/NA, shows that the largest differences between the non-destructive methods and the destructive method were obtained at a concrete aged 1 day. With increasing the age, these differences decrease, and for the age of the concrete from 3 to 14 days, the differences are from 1% to 11% for the both non-destructive methods, compared to the destructive method.

The values of the compressive strength of the concrete obtained both as per BDS EN 12390-3 and in the surface layer as per FIB Model Code 2010 differ by up to about 68%÷71%, and these differences also decrease with increasing the concrete age. The mentioned differences are greater at the early age, and the strength differences with values of 12%, determined by both methods, are found only at a concrete aged 28 days.

The analysis of the determined values of the compressive strength according to ASTM C 1074 and rebound hammer test according to BDS EN 13791/NA and BDS EN 12504-2 shows that there is a correlation between two groups of the results. The high values of the correlation coefficient (R^2 = 0.94) are in evidence that allows the dependence to be assessed as very high.

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