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Surface-strength approach for concrete monitoring using sensors and shock-pulse method

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ABSTRACT

There are many methods used for temperature-strength control of reinforced concrete structures globally. Their majority is associated with the significant challenges of being time-consuming, costly and prone to errors. Therefore, this study investigated the potential applicability of the surface-strength approach of specimens using non-destructive testing methods to derive temperature-strength relationships as an alternative approach to the currently widely used methods. The studies were carried out by comparing the surface strength of small laboratory specimens (SS) and large specimens (LS), imitating building structures, obtained by the shock-pulse method and the strength obtained by the destructive method; and the obtained calibration dependencies were adapted to the results of specimens' thermal control. The temperature-strength dependence was corrected by comparing the strength and temperature parameters of SS and LS. The obtained nomograms make it possible to correct changes in the temperature regime of hydration of structures curing in real climatic conditions. The final adaptation of the temperature-strength dependence to the real erected structures showed a significant potential of this method in the construction industry. The difference between the actual strength of the drilled cores and the predicted strength of concrete at 28 days was only 1.02%.

Keywords: Concrete maturity, surface strength, shock-pulse method, operational control, sensor.

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Introduction

The concrete strength is the main characteristic that establishes the ability of a concrete or reinforced concrete structure (hereinafter – RCS) to bear the design loads [[1], [2], [3], [4], [5]]. Among the non-destructive methods of concrete strength control in the CIS countries, the most widespread is the shock-pulse method, implemented by a special device IPS MG4 [[6], [7], [8], [9]].

In contrast to the destruction of standard specimens [[10], [11], [12], [13], [14]] is faster, less labour-intensive, and relatively inexpensive. In contrast to CIS countries, these methods are regulated by state standards of several countries: the USA [15], Canada [16], the Netherlands [17], Germany [18], South America [19], Russia [[20], [21], [22], [23]]. According to these standards' requirements, concrete strength estimates can be performed according to the following basic methods: temperature graphs, concrete maturity, and analytical functions. Standards [[15], [16], [18], [24]] specify that there are four steps in the use of the method of calculating the current strength of concrete by its maturity:

i. Establishing the maturity-strength relationship in the laboratory;

ii. Embedding maturity sensors inside the formwork at the construction site;

iii. Sensor reading of concrete maturity at the construction site;

iv. Data analysis.

The method for concrete strength estimation by maturity is based on the "maturity index" concept. The maturity index is calculated using one of two measures: the temperature-time factor (TTF) or an equivalent age at 20 ^{o}C; due to the complexity of the calculation, the equivalent age is used infrequently compared to the TTF. The maturity method called “Weighted Maturity” [17] takes into account the “C” parameter specific to cement and is used depending on cement strength, although it also allows the use of additives. Previous studies have mainly focused on modifying maturity methods in the data analysis phase. This study investigates the potential applicability of the surface-strength approach of specimens using non-destructive testing methods to derive temperature-strength relationships. The general objective of this study is to express the maturity function based on the relationship between the curing temperature, time, and the surface strength of concrete [25]. In the future, this relationship can be used for prompt strength control using temperature sensors embedded in the concrete body [[2], [24], [26], [27], [28], [29]].

Experimental technique

The studies were conducted in two stages: at the first stage, the temperature-strength dependence of small cylindrical specimens (hereinafter – SS) was investigated; at the second stage, the same studies were conducted for large specimens (hereinafter – LS). The comparison of the results of studies of SS and LS shows the acceptability of strength control of RCS by measuring the thermal regime in the process of hydration. The important indicator of the study is the estimation of obtained temperature-strength dependence of SS adapted for real structures. Therefore, LS of imitating real RCS were used in the studies. The studies were carried out in the following sequence.

Stage 1 – Study of the SS (Figure 1a):

i. Preparation of 30 cylindrical SS with a height and diameter of 15 cm;

ii. Determination of the surface strength of SSs by the non-destructive shock-pulse method of control [[18], [19]], with measurements every 24 hours until the 28-day of curing of the specimens.

iii. Determination of the cylindrical strength of SS by destructive compression method [20] at curing ages of 1, 3, 7, 14, 28 days (six SSs for each age);

iv. Plotting the calibration dependence between the surface and cylindrical strength;

v. Measurement of concrete curing temperature in two SS for 28 days with 0.5-hour interval;

vi. Determination of the temperature-strength (surface) dependence according to ASTM [12].

Stage 2 – Study of the LS (Figure 1b):

i. Preparation of two LSs of cubic form with the size of 50x50x50 cm;

ii. Measurement of concrete curing temperature in two LS for 28 days with 0.5-hour interval;

iii. Determination of the temperature-strength (surface) dependence according to ASTM [12];

iv. Determination of the functional dependencies of SS and LS enabling correction of temperature-strength (surface) dependence;

v. Determination of the temperature-strength (cylindrical) dependence, taking into account the corrections.

All SS and LS were made with the same concrete mix B25 M350. The strength tests of the specimens by the non-destructive control method are performed using a shock-pulse device IPS MG4.

a b

Figure 1 – Experimental studies of specimens: a – SSs, b – LSs

This is an express method and being an indirect assessment of the strength characteristics of structures, it requires a calibration dependence on the destructive method [19] performed on a testing press (in this case, the Pilot Compact 500 kN automatic press was used).

A handmade measuring device consisting of the following components was used to measure the temperature mode of concrete curing:

i. Four DS18B20 type temperature sensors;

ii. Two lithium-ion batteries with a nominal voltage of 3.7V and a capacity of 3000mAh;

iii. Atmega328p microcontroller (this microprocessor is an 8-bit AVR microcontroller with 32KB of programmable Flash memory, it is relatively inexpensive compared to other energy-efficient microcontrollers but also has a compact TQFP32 package).

iv. 8GB memory card to store up to 28 days of recordings;

v. DS3231 timing module to periodically wake up the device and poll the connected sensors.

The processing of the temperature-strength dependence for predicting the concrete structure's strength was carried out in two stages. The first stage involved correcting the temperature-strength (surface) dependence of the LS to the temperature mode of the LS and the corresponding surface strength of the SS. This is because SS and LS were directly subjected to both temperature and surface strength control (unlike the strength by the destructive method), and the variables of the obtained dependences had a frequent periodicity of measurements (the measurement of surface strength every 24 hours, temperature - every 30 minutes). The second stage involved the correction of the obtained temperature-strength (surface) dependence for the transition from the surface strength to the cylindrical one, meaning from the indirect method to the direct destructive method. For the controlled assessment of the obtained temperature-strength dependence after 28 days, cores were taken from the LS to determine the actual strength. The obtained results of the actual strength were compared with the predicted strength obtained by the temperature-strength relationship.

Results and Discussion

2.1 Strength tests on specimens

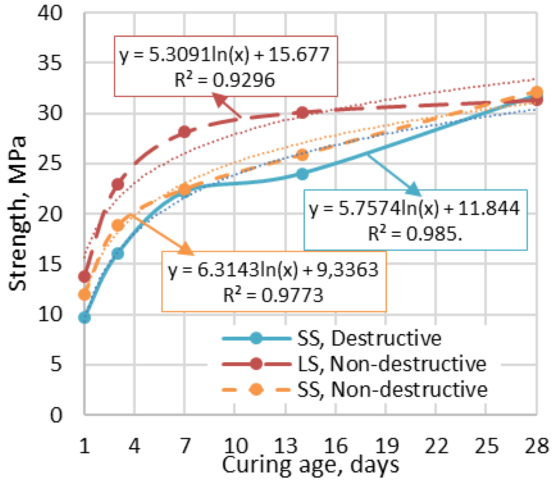
Figure 2a shows the dependence of measured non-destructive and destructive strengths on the age of concrete specimens (SS and LS). Before the tests, local measurement sites were prepared. The results of the non-destructive testing of the LSs are also shown in Figure 2a. Strength measurements were also performed on the side faces of the specimens. A total of 4 test measurements were made for each specimen, i.e., one test measurement was made from each of the side faces. Also, as in the case of SS, the control measurement included 15 particular strength measurements. The dependencies presented in Figure 2a are described by logarithmic functions having a close relationship with the specific values, whose coefficients of determination are more significant than 92%. Figure 2b shows a comparison of particular values of strength characteristics of LS and SS obtained by a non-destructive method. Figure 2c shows the calibration dependence or comparison of particular values of SS strength characteristics obtained by non-destructive and destructive methods.

According to the results of comparative analysis, the best convergence of values of strength is observed between the destructive and non-destructive methods of SS (the difference of particular values does not exceed 23%, on average 10%). It can be expressed by the corrective function, obtained from the correlation dependence between the surface and the cylindrical strength of SS (Eq. 1):

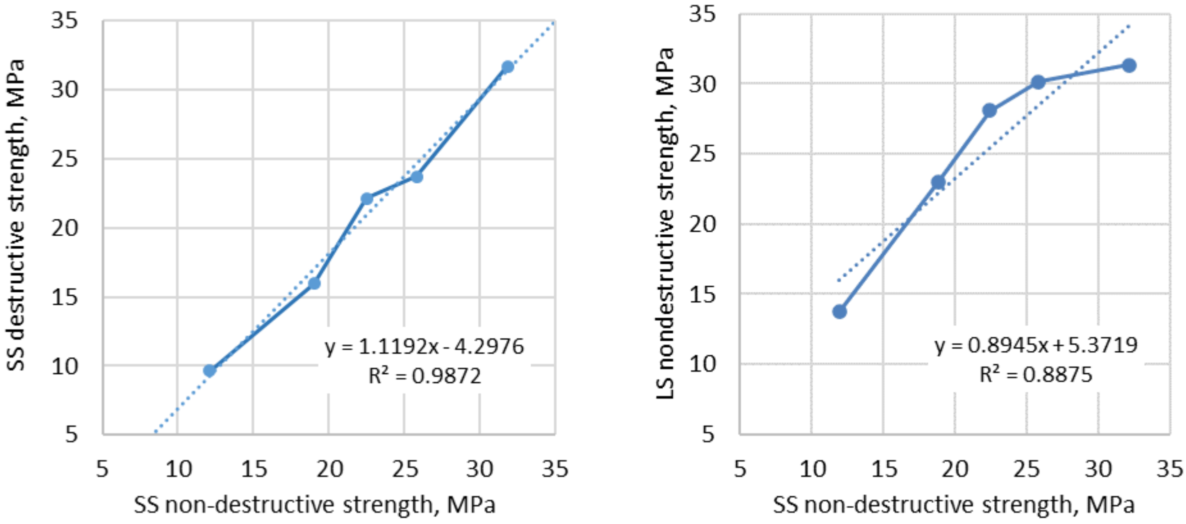
$$\sigma_{d}^{SS} = 1.1192\sigma_{nd}^{SS}, \tag{1}$$

The convergence of values between the non-destructive method of SS and LS also has a close relationship (the differences of particular values do not exceed 25%, on average 15%). It can be expressed by the following corrective function (Eq. 2):

$$\sigma_{nd}^{LS} = 0.8945\sigma_{nd}^{SS}, \tag{2}$$



a



b

c

Figure 2 – Results of strength measurements of SS and LS: a – Dependence of strength by age, b – Correlation between the surface and cylindrical strength of SS, c – Correlation between the surface strengths of SS and LS

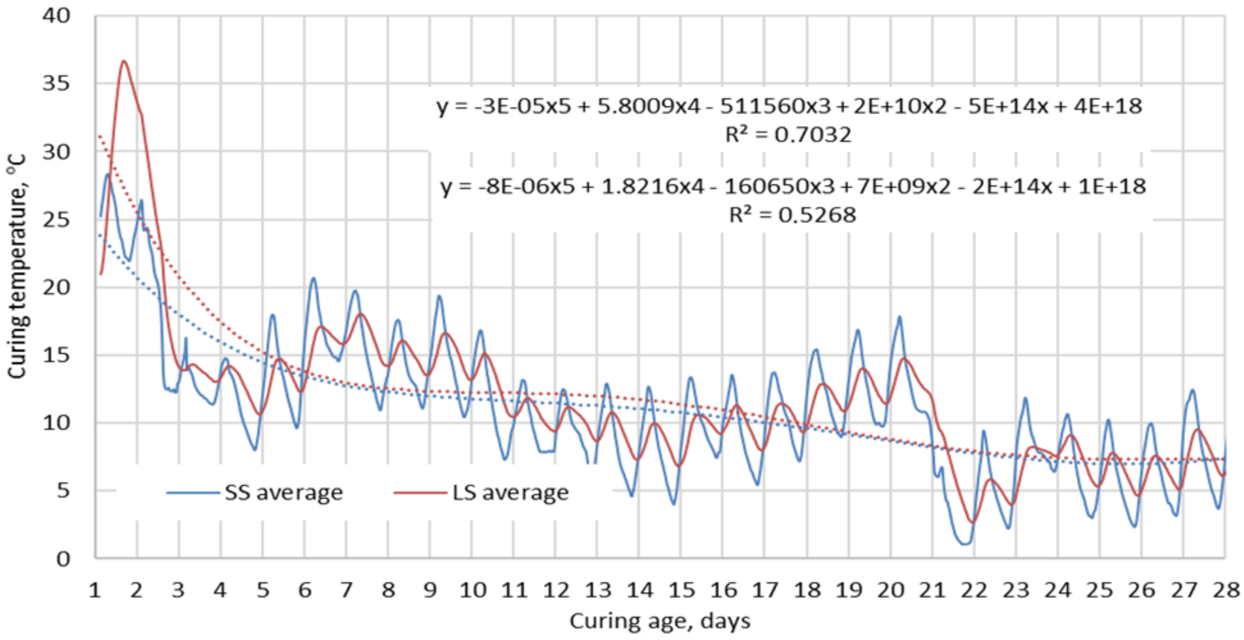


Figure 3 – Comparison of SS and LS temperature histories

According to the statistical analysis, particular values of strength measurements have close relations within the limits of control measurements, as well as control measurements among themselves: coefficient of variation of all related particular values on the average makes 0.02, lies in a range from 0.01 to 0.05; coefficient of reliability herewith makes 1.23 on the average, lies in a range from 1.01 to 2.46. It is necessary to note that extreme values of the range are out of general statistics and represent a single case, but they meet the requirements of statistical tests for exclusion of accidental errors and are within the acceptable 95% confidence level.

2.2. Thermal control of specimens

The data obtained for temperature changes by age showed a close relationship between SS and LS (Figure 3).

According to the obtained temperature regimes, the greatest thermal response of LS concrete was observed in the early period of its curing, after 13.5 hours of its pouring, with a temperature of 36.5 °C. The minimum LS temperature was observed after 22 days, amounting to 2.25 °C. A similar pattern of thermal fluctuation was observed in SS, where the maximum temperature of 28.27 °C corresponds to the curing age of 4.5 hours, the minimum temperature of 1.02 °C - after the same 22 days. The thermal fluctuation in both cases has a common pattern in the setting and curing of concrete.

In both cases, the maximum exothermic process occurs at the initial stage of concrete curing (due to three-calcium aluminate hydration). The difference in temperature at the initial stage of the hydration process may be explained by the massiveness of LS in relation to SS. The more massive the structure, the less convection surface heat removal; consequently, more time is needed to achieve thermal balance with the environment, as evidenced by the large amplitude of thermal cyclicity of the SS concerning the LS. Generally, the particular values of temperatures have high convergence (which can be observed when superimposing the dependencies on each other (Figure 4), numerically described by the dependency y=1.049x, which indicates deviations of particular values of SS from LS, on average, by 5%.

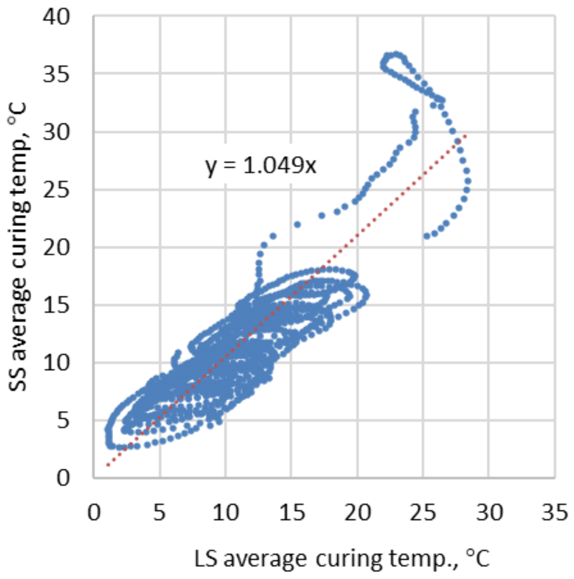
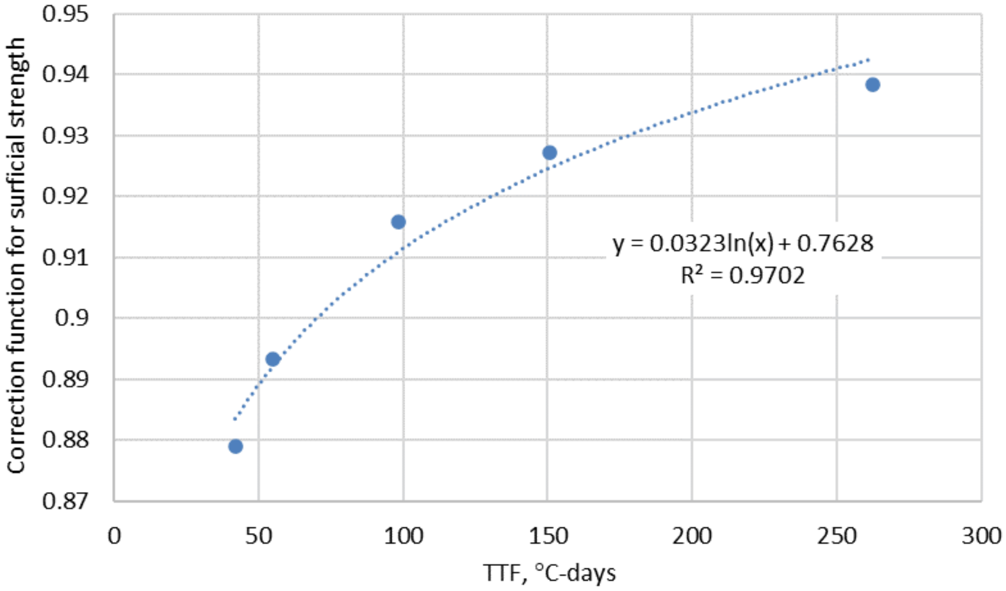


Figure 4 – Correlation of SS and LS temperature histories

It is necessary to correct the values of surface strength of large specimens from the available database of their temperature measurements as a result of the hydration process (Figure 5a). For the transition to the cylindrical strength of the LS concrete, we use the previously obtained function of the calibration dependence between the strength of non-destructive control and the cylindrical strength of the SS. Figure 5b shows the predicted dependence between LS's surface and cylindrical strength. The obtained dependence makes it possible to carry out indirect non-destructive strength control of reinforced concrete structures with the same mixture of concrete and kept in the same climatic conditions. The specimens were subjected to destructive strength tests. According to the results, the following was obtained: the average core strength was 32.9 MPa, with a quadratic deviation of 0.29 and a coefficient of variation of 0.01. Comparing the strength of the cores with the predicted strength calculated from the previously obtained dependence, it was found that the average actual core strength has a high convergence with the expected strength of 33.24 MPa. The error of the indirect method was: 1.02 %. In general, the studies to assess the strength characteristics of structures based on measurements of temperature conditions of concrete curing in the process of its hydration refers to indirect methods of strength control, so it requires a qualitative analysis of the data to be compared and considering regional characteristics of construction. According to the standard method [15], the transition to strength indexes of concrete is made by measuring the temperature regime and the control measurement of the cylindrical strength of concrete in different periods of its curing. The resulting pattern of temperature-strength dependence is subsequently adapted for strength control of real building structures. In the present study, in contrast to the standard method, it was decided to carry out strength control using the data on the surface strength of concrete by the shock-pulse method.

In the case of this study, the error of the obtained temperature-strength dependence, in comparison with the actual strength of four control tests of the strength (destructive method) of drilled cores, was 1.02%. It should be noted that comparisons with the actual strength of large specimens were made only after 28 days, which may not be sufficient for a complete conclusion about the reliability of this method. Also, the next study program will include an assessment of the influence of the temperature and humidity regime of the environment on the thermal changes in the concrete during the design period of hydration (up to 28 days).

In this case, the ambient temperature range will be within +5°C to +25°C, as exceeding this temperature range is not acceptable for curing the concrete without the use of additional measures. The obtained nomograms will make it possible to correct changes in the temperature regime of hydration of structures curing in real climatic conditions.



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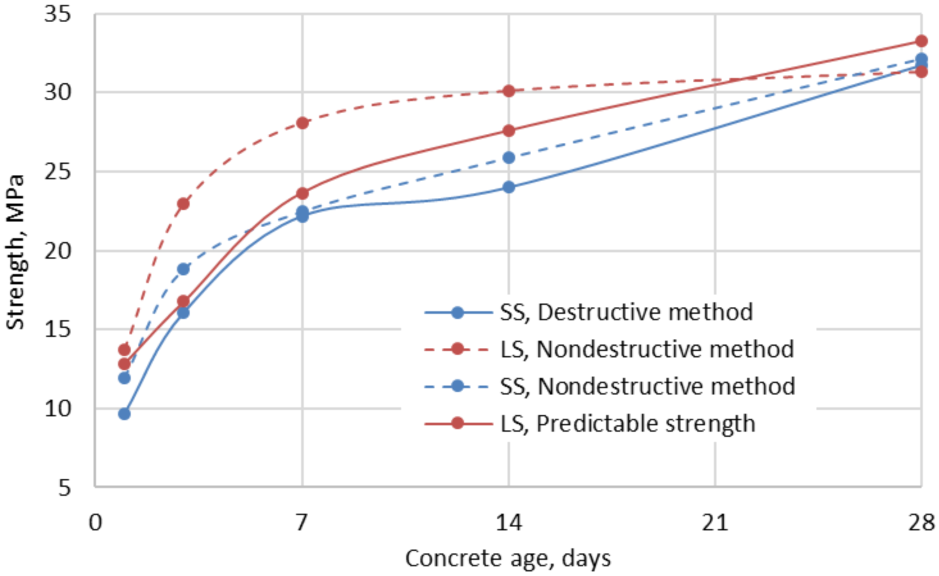

b

Figure 5 – Correction of the results of the temperature-strength dependence of LS: a – Correction function for surface strength, b – Corrected LS cylinder strength

Conclusion

A set of tests and strength measurements of small specimens (laboratory) and large specimens (imitating the relative massiveness of reinforced concrete structures in relation to the laboratory specimens), non-destructive and destructive tests were conducted. The following conclusions can be made based on the results of the studies; Firstly, the obtained particular strength values have a close relationship within the limits of the control measurements, have a high degree of reliability, as evidenced by high statistical indices and a large number of measurements: the coefficients of variation do not exceed 2%. Secondly, the average strength data of small and large specimens showed a remarkable convergence of the results, which is a positive indicator for further data reduction in the temperature-strength analysis and the error of indirect strength control. Thirdly, the temperature control results revealed the influence of the massiveness of large specimens on the amplitude of thermal cycling. Fourthly, the temperature-strength functional dependence was obtained, making it possible to perform strength control of reinforced concrete structures made of the same concrete mixture composition and kept under the same climatic conditions. The control method refers to the indirect one and has a high correlation with the actual strength of concrete. On the 28th day, the strength error made up 1.02% of the actual cylindrical strength of the collected core.

Conflict of interest. On behalf of all the authors, the correspondent author states that there is no conflict of interest.

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Датчиктер мен соққы-импульстік әдісті қолдана отырып, бетонның беткі беріктігі бойынша мониторингі

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ТҮЙІНДЕМЕ

Әлемде темір-бетон конструкцияларын температуралық-беріктік мониторингі және бақылау үшін пайдаланылатын көптеген әдістер бар. Алайда, бұл әдістер мен процедуралар маңызды мәселелермен байланысты, өйткені олар көп уақытты, шығындарды талап етеді және қателіктерге бейім. Сондықтан, бұл зерттеу қазіргі уақытта кеңінен қолданылатын әдістерге балама тәсіл ретінде температура мен беріктік арасындағы тәуелділікті алу үшін бұзылмайтын бақылау әдістерін қолдана отырып, үлгілердің беттік беріктігін анықтау әдісінің ықтимал қолданылуын зерттеді. Зерттеулер соққы-импульстік әдіспен алынған құрылыс конструкцияларын имитациялайтын шағын зертханалық үлгілердің (SS) және үлкен үлгілердің (LS) беткі беріктігін және бұзу әдісімен алынған беріктігін салыстыру арқылы жүргізілді. Алынған калибрлеу тәуелділіктері үлгілердің жылу бақылауының нәтижелеріне бейімделді. Температура-беріктік тәуелділігі SS және LS беріктігі мен температуралық параметрлерінің нәтижелерін салыстыру арқылы түзетілді. Нақты салынған конструкцияларға температуралық-беріктік тәуелділігінің түпкілікті бейімделуі құрылыс саласындағы осы әдістің елеулі әлеуетін көрсетті, мұнда бұрғыланған керндердің нақты беріктігі мен бетонның 28 күндік болжамды беріктігі арасындағы айырмашылық бар болғаны 1,02% - ды құрады. Алынған номограммалар нақты климаттық жағдайларда қататын құрылымдарды гидратациялаудың температуралық режиміндегі мүмкін болатын өзгерістерді түзетуге мүмкіндік береді.

Түйін сөздер: бетонның жетілуі, бетінің беріктігі, импульстік соққы әдісі, операциялық бақылау, сенсор.

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Мониторинг бетона по поверхностной прочности с применением датчиков и ударно-импульсного метода

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АННОТАЦИЯ

В мире существует множество методов, используемых для температурно-прочностного мониторинга и контроля железобетонных конструкций. Однако эти методы и процедуры связаны со значительными проблемами, поскольку требуют много времени, затрат и подвержены ошибкам. Поэтому в данном исследовании изучалась потенциальная применимость метода определения поверхностной прочности образцов с использованием методов неразрушающего контроля для получения зависимостей между температурой и прочностью в качестве альтернативного подхода к широко используемым в настоящее время методам. Исследования проводились путем сравнения поверхностной прочности малых лабораторных образцов (SS) и больших образцов (LS), имитирующих строительные конструкции, полученных ударно-импульсным методом, и прочности, полученной разрушающим методом. Полученные калибровочные зависимости были адаптированы к результатам теплового контроля образцов. Зависимость температура-прочность корректировалась путем сравнения результатов прочностных и температурных параметров SS и LS. Окончательная адаптация температурно-прочностной зависимости к реальным возведенным конструкциям показала значительный потенциал данного метода в строительной отрасли, где разница между фактической прочностью выбуренных кернов и прогнозной прочностью бетона в возрасте 28 дней составила всего 1,02%. Полученные номограммы позволят корректировать возможные изменения температурного режима гидратации конструкций, твердеющих в реальных климатических условиях.

Ключевые слова: зрелость бетона, поверхностная прочность, ударно-импульсный метод, оперативный контроль, датчик.

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