ЖЫЛУФИЗИКАСЫ ЖӘНЕ ТЕОРИЯЛЫҚ ЖЫЛУТЕХНИКАСЫ
ТЕПЛОФИЗИКА И ТЕОРЕТИЧЕСКАЯ ТЕПЛОТЕХНИКА
THERMOPHYSICS AND THEORETICAL THERMOENGINEERING

DOI 10.31489/2022PH1/66-74

UDC 691.328

Ye.B. Utepov[1,2], A. Aniskin[3], A.S. Tulebekova[1,2], S.B. Akhazhanov[4], Sh.Zh. Zharassov[*1]

[1]L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan,
[2]CSI Research & Lab, LLP, Nur-Sultan, Kazakhstan;
[3]University North, Varaždin, Croatia;
[4]Karaganda University of the name of academician E.A. Buketov, Kazakhstan
**E-mail: zhshzh95@gmail.com*

Evaluation of the Nurse-Saul method using maturity sensors for concrete strength control

The article presents the results of experimental studies on the strength of concrete grade B25 brand M350 by direct and indirect methods of control. To conduct tests, 17 cylindrical, 15 small, and 2 large cubic specimens were manufactured. 15 cylindrical specimens by 3 pieces were tested for compression in a hydraulic press on 1, 3, 7, 14, and 28 days of curing, and in the remaining two for 28 days the curing temperature was measured in order to obtain the strength-maturity relationship by the method of Nurse-Saul. The curing temperatures of the larger specimens were measured similarly, from which the concrete maturity and strength values on days 1, 3, 7, 14, and 28 were estimated. On the same days, compression tests were carried out on small specimens and by the shock pulse method on large specimens. As a result, the strength gain curves were obtained and calibration dependencies were plotted. The calibration dependencies showed a sufficiently close convergence of the results of the direct method of control (i.e., compression of small specimens) and the Nurse-Saul method of maturity, in contrast to those of the shock pulse method. The determination coefficients of these dependencies amounted to 0.9357 and 0.8965, respectively.

Keywords: maturity method, concrete strength, embedded sensors, compression test, curing temperature, shock-pulse method, calibration dependence.

Introduction

Inspection methods in modern construction increasingly overlap with information technology. Various methods and tools are used to figure out the compliance of the material with the design requirements [1, 2]. One of the frequently used and tested materials is concrete. There are many ways to determine its strength. The methods are regulated by various standards that contain a defined procedure for laboratory tests [3]. Different tools and devices can be used to identify the current and limited properties of concrete [4].

Nowadays, indirect methods of non-destructive concrete strength gain control are more popular than local destructive methods [5]. These methods give quick results and require minimal costs, with the result being made by the laboratory, but the curing time of the concrete requires intermediate solutions to complete the construction in a specified time or sooner than required by the customer [6]. Interim solutions can be formwork removal, structural loading, test scheduling, etc. The methods are based on parameters occurring during the concrete curing process, such as temperature, pressure, current conductivity, shock pulse impact, elastic rebound, plastic deformation, etc. [5].

Many standards of the CIS countries, regulating non-destructive control methods, are based on external influence. While in foreign countries, they practice such standards to determine the strength of internal parameters, which consider the temperature and curing time of concrete [7]. The method of temperature-strength control is widely used in the USA, Canada, South Africa, and European countries (Table 1).

Table 1

Foreign standards for methods of temperature-strength control of concrete [4]

No.	Standard indication	Name of the standard	Region
1	ASTM C1074	Standard Practice for Estimating Concrete Strength by Maturity Method	USA
2	ASTM C918	Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength	
3	ACI 318-6.2	Building Code Requirement for Structural Concrete and Commentary	
4	ACI 228.1R	In-place Methods to Estimate Concrete Strength	
5	ACI 306R	Guide to Cold Weather Concreting	
6	AASHTO T 325	Standard Method of Test for Estimating the Strength of Concrete in Transportation Construction by Maturity Tests	
7	CSA A23.1/A23.2	Concrete Materials and Methods of Concrete Construction/Test Methods and Standard Practice for Concrete	Canada
8	NCH 170	Hormigon-Requisitos generals (Concrete- General requirements)	South Africa
9	EN 206–1:2002	Concrete — Part 1: Specification, performance, production and conformity	Europe
10	BS EN 13670	Execution of concrete structures	
11	NEN 5970	Determination of Strength of Fresh Concrete with the Method of Weighted Maturity	
12	ST-NP SRO SSK-04–2013	Temperature and strength control of concrete during the construction of monolithic structures in winter	Russia

The study of temperature and strength control dates back to the 1970s by the American National Bureau of Standards. It was caused by the gradual collapse of a building under construction in Fairfax County, Virginia, which was not without casualties. According to the final inspection report, the problem was early removal of the formwork. The decision to remove the formwork was made 4 days after the concrete was poured, which was based on the average temperature readings [9]. Such cases prompted the American Occupational Safety and Health Administration to develop a standard for monitoring the curing rate over the entire 28-day period. Thus, this method has found use in several other countries, considering the specifics of the construction area and raw materials for concrete.

A good example of a country where the method of temperature-strength control regarding GOST has been developed is Russia. The standard was developed by the nonprofit partnership "Self-regulated Organization of the Union of Construction Companies of the Urals and Siberia", owned by the Urban Building Code of the Russian Federation [10]. This standard has been in use since 2013. As stated earlier, the specifics of the territory of construction require increased attention. If we compare countries with predominantly hot climates, it is only one temperature range that affects the strength gain, while countries with sharply continental climates also take into account negative temperatures. This point is considered in [11]. The basis for the creation of the standard [10] was the thermal stress state during curing or heat treatment of concrete. The standard has only recently been introduced and not all issues have yet been covered.

The maturity method regulated by the American standard is increasingly being used in the CIS countries as well. The applicability of this approach is already being tested on domestic construction sites [12, 13]. Thus, the authors of this study have developed a measuring complex for wireless temperature monitoring and estimation of the current strength of concrete "BDM-1" [14, 15], which implements the Nurse-Saul method [16]. An important principle of BDM-1 operation is automation of temperature data acquisition since the calculation method requires particular measurements, as well as individual calculation of number and location of maturity sensors, which are reflected in construction feasibility study. To test its performance and to assess the applicability of the standard [16], many tests were carried out in this work, applying different methods.

Based on the aforementioned, this study is aimed at assessing the applicability of the Nurse-Saul maturity method for Kazakhstan construction sites in conjunction with the BDM-1 measuring complex. Thus, the object of study is the curing temperature and strength of M350 B25 marketable concrete, produced by local manufacturers.

Experimental

The test program in this work was developed to study the process of concrete strength gain in the natural conditions using foreign [16, 17] and domestic standards [18, 19], applying different instrumentation (Table 2).

Table 2

Certified equipment used in the test program

No.	Equipment	No. of the certificate of type approval of measuring instruments	Equipment name
1	IPS-MG4.03	12148	Strength meter of building materials
2	HP-Testing	9885	Hydraulic press
3	BMD-1	3575	Wireless complex for concrete strength monitoring

Ready-mix concrete of grade B25 and brand M350 was tested (Table 3). Concrete of this grade and brand was chosen because of its wide use in the construction market [20].

Table 3

Composition of the tested concrete

No.	Component name	Consumption, kg/m^3
1	Portland cement	390
2	Washed sand	810
3	Crushed stone, fraction 5–20 mm	1080
4	Water	140
5	Chemical additive based on polycarboxylate esters HPS-3	2,73

The selected concrete mixture was used throughout the experiment. The data obtained in laboratory tests can only be used for a given concrete with the same consumable components [17, 21].

17 cylindrical specimens with a diameter and height of 15 cm each were prepared for testing by the method [16] (Fig. 1), of which 15 were tested in compression with a hydraulic press in the laboratory, by 3 specimens at 1, 3, 7, 14, and 28 days [17]. Sensors [22] were immersed in the remaining 2 specimens to measure the curing temperature of the concrete in the specimens at a frequency of 0.5 hours up to 28 days. The purpose of these tests was to derive the “strength-maturity” relationship of the concrete, where maturity is an index of temperature and time, according to the Nurse-Saul method [16, 23, 24]. This ratio was derived as a logarithmic function. It was used to calculate the current strength of concrete in a real structure, assuming the same composition was used.

Figure 1. Cylindrical specimens

The temperature-time factor was determined by the following equation [15]:

$$TTF = \sum (T_a - T_0)\Delta t; \quad (1)$$

where *TTF* — the time-temperature factor at age t (degree-days, degree-hours); Δt — time interval (days, hours); T_a — average concrete temperature during time interval (°C); T_0 — datum temperature, –10 °C.

To simulate a real structure made of the same concrete composition, two large cubic specimens sized 50x50x50 cm were prepared, in which temperature sensors were also immersed (Fig. 2 (a)). From the temperature history measured at a frequency of 0.5 hours, using the same Eq. 1, concrete maturity values (TTF) were calculated. Then, by applying these values to the derived logarithmic function, the strength values of the concrete in the structure on days 1, 3, 7, 14, and 28 of curing were estimated. On the same days, large specimens were subjected to non-destructive shock pulse testing [18] using the IPS-MG4 measuring device (Fig. 2 (b)).

In parallel with the previous tests there were molded 15 small cubic specimens of 10×10×10 cm in size, which were tested in compression by destructive method [19] on a hydraulic press, by 3 specimens on 1, 3, 7, 14, and 28 days of curing (Fig. 2 (c)).

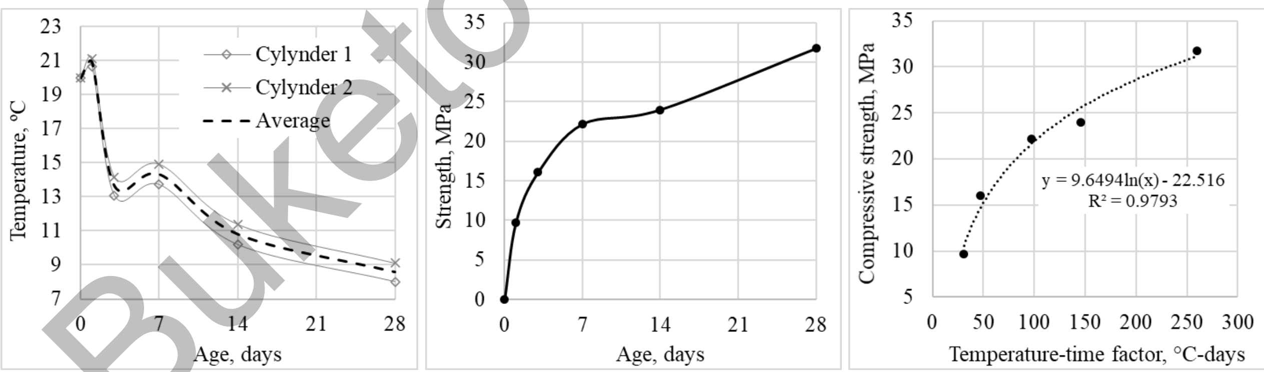
Then, using the average strength values obtained by the three different methods, the diagrams of concrete strength gain and calibration dependencies were plotted.

a) b) c)

Figure 2. Cubic specimens: a — large specimens, b — large specimens shock pulse testing, c — small specimens

Results and Discussion

Figure 3 illustrates the results of testing cylindrical concrete specimens using the maturity method.



a) b) c)

Figure 3. Results of tests of cylindrical concrete specimens: a — temperature mode of curing, b — concrete strength gain diagram, c — strength-maturity relationship

Using the Nurse-Saul method, the temperature of the two cylindrical specimens was monitored for 28 days. In Fig. 3 (a), one can notice the presence of the highest curing temperature in the first 3 days (21 °C), then, there is a sharp decline with a slight increase in temperature on the 7th day. Thus, the temperature on the 28th day is about 8 °C. Fig. 3 (b) shows a diagram of the strength gain in the cylinders. The trend increases sharply in the first 3 days, after showing a gradual rise. From the cylinder curing temperature history using the equation (1), concrete maturity values at days 1, 3, 7, 14, and 28 were calculated. By plotting these values against the strength values on the same days of curing, a strength-maturity relationship was plotted (Fig. 3

(c)). It can be seen from the Figure 3 that the obtained dependence has a fairly high coefficient of determination equal to 0.9793, which indicates its further applicability in estimating the strength of the real structure (i.e. large cubic specimens) from the same composition of concrete. The test results of the large specimens are shown in Figure 4.

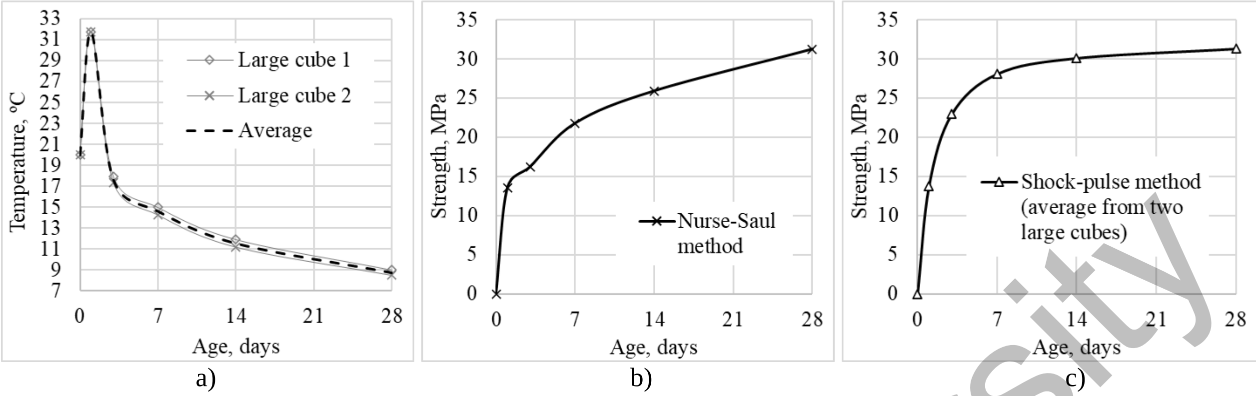


Figure 4. Results of tests of large cubic concrete specimens: a — temperature mode of curing, b — Nurse-Saul strength gain curve, c — shock-pulse strength gain curve

The curing temperatures (Fig. 4 (a)) of the two large cubes for 28 days provide the average value for the Nurse-Saul strength gain curve (Fig. 4 (b)). As shown in Fig. 4 (a), compared to the curing regime of the cylinders, the temperature increase on the first day of curing of large specimens are more intense. In the first 2 days, the temperature rose to 32 °C and then decreased smoothly to 8 °C. This can be explained by the massiveness of large specimens compared to small ones. Concrete maturity values on 1, 3, 7, 14, and 28 days were calculated in a similar manner for large specimens. By applying these values to the strength-maturity relationship obtained above, the strength values for the same days were estimated, from which the strength gain diagram was plotted (Fig. 4 (b)). According to the results of tests of large specimens by shock-pulse method (Fig. 4 (c)), during the first 7 days, the strength of concrete intensively increased, after that, it smoothly passed to stabilization.

To compare the results of the indirect methods obtained above with the direct ones, a diagram of the strength gain from the tests of small cubic specimens in compression in a hydraulic press was plotted as shown in Figure 5.

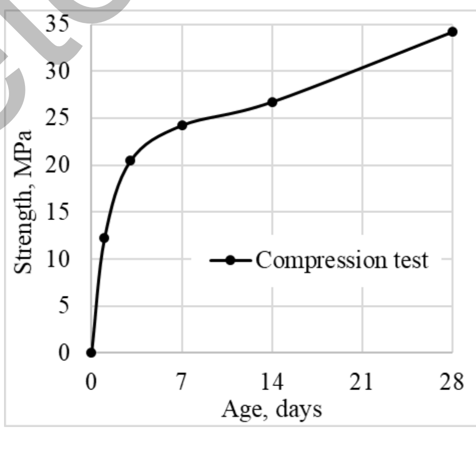


Figure 5. Results of tests of small cubic specimens by compression

The strength gain curve of small cubic specimens has a similar outline to the one obtained by the maturity method. However, the strength value at 28 days is higher. For visual comparison of the results of indirect (maturity method, shock pulse method) and direct (compression of cubic specimens) methods, their strength gain curves were combined into one diagram and calibration dependencies between these methods were derived (Fig. (6)).

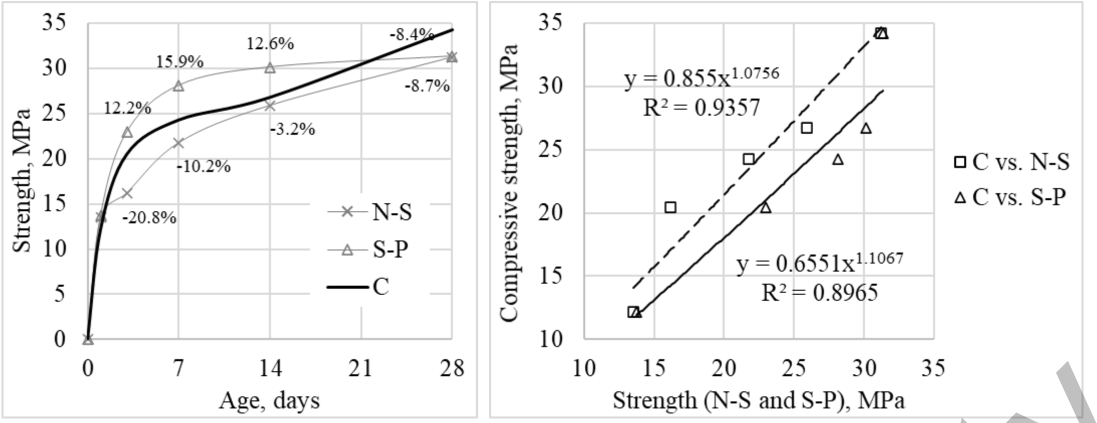


Figure 6. Comparative analysis of the results: a — strength gain curves, b — calibration dependencies, N-S, S-P, and C — Nurse-Saul, Shock pulse methods and Compression test, respectively

According to Fig. 6 (a), on the first day, there is no difference between the strength gains, however:

– on days 3, 7, and 14, the shock pulse method values are higher than those of the compression tests by an average of 13.5 %, while on 28 day, they are lower by 8.4 %.

– values from the maturity method beginning from day 3 up to day 28 were lagging the compression test by an average of 10.7 %.

Figure 6 (b) demonstrates the calibration dependencies between the direct and indirect methods used in this study. The power functions and their coefficients of determination were derived for each of the dependencies. One can notice from Figure 6 that the coefficient of determination of the dependence between the compression test and the maturity method, equal to 0.9357, is slightly higher than those between the compression test and the shock pulse method, equal to 0.8965. This indicates that the convergence of the first two methods is greater than that of the second.

Conclusions

In this work, the authors conducted several strength tests of concrete B25 M350 by direct and indirect methods and measurements of curing temperature with specialized instrumentation and equipment. According to the results of tests and measurements, the diagrams of strength gain and temperature curing for small (10x10x10 cm) and large specimens (50x50x50 cm) were obtained, strength-maturity relationships, as well as calibration dependencies between direct and indirect methods, were plotted. The following conclusions can be drawn from the analysis of the obtained results:

- The final compressive strength of the small specimens at 28 days was higher (34 MPa) than that obtained by the maturity and shock pulse methods on large specimens, although all the specimens were kept at the same temperature and humidity conditions. This is due to their lower massiveness.

- The shock pulse method, according to the strength gain curve, looks rather idealized and does not impress sufficient confidence. There are no drops; strength gain is smooth and stable.

- The strength gain curve obtained by the Nurse-Saul maturity method has a fairly realistic outline. There are small steps and unstable gains of strength. The strength values from the Nurse-Saul method were lower than those of the others. In this regard, it can be assumed that it is more reliable and has a potential margin of safety when controlling the strength by this method.

- Comparison of the direct and indirect methods by plotting the calibration dependencies revealed a greater convergence of the maturity method with the compression test in comparison with the shock pulse method; the determination coefficients of the obtained dependencies were 0.9357 and 0.8965, respectively.

Acknowledgments

This research was funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP08052033).

References

1 Liao C. Optimal Inspection Strategies for Labor Inspection in the Construction Industry / C. Liao // Journal of Construction Engineering and Management, 2015. – Vol. 141, Iss. 2. — P. 04014073.

2 Lin J. Understanding On-Site Inspection of Construction Projects Based on Keyword Extraction and Topic Modeling / J. Lin, Z. Hu, J. Li, L. Chen // IEEE Access, 2020. – No. 8. — P. 198503–198517.

3 Andersson N. Industrialization of construction: Implications on standards, business models and project orientation / N. Anderson, J. Lessing // Organization, technology and management in construction: an International Journal, 2020. – Vol. 12, No. 1. — P. 2109–2116.

4 Dovzhenko O.O. Use of extreme properties of deformation for estimation of strength of constructive concrete and reinforced concrete / O.O. Dovzhenko, V.V. Pohribnyi, Ye.V. Klymenko, M. Orešković // NEWS of the Academy of Sciences of the Republic of Kazakhstan, 2020. – Vol. 3, No. 441. — P. 32–39.

5 Malhotra V.M. Handbook on nondestructive testing of concrete / V.M. Malhotra, N.J. Carino. — CRC press. — Boca Raton. — 1991.

6 Zhang H. Building materials in civil engineering / H. Zhang. — Woodhead Publishing Limited. — 2011. — P. 440.

7 Hakan K. Determination of concrete quality with destructive and non-destructive methods / K. Hakan, T. Öztürk // Computers and Concrete, 2015. – Vol. 15, Iss. 3. — P. 473–484.

8 De Carufel S. Concrete Maturity From Theory to Application / S. De Carufel, A. Fahim, P. Ghods., A. Alizadeh. — Giatec Scientific Inc., 2018. — P. 20, 21.

9 Leyendecker E.V. Investigation of the Skyline Plaza Collapse in Fairfax Country, Virginia / E.V. Leyendecker, S.G. Fattal. — Washington D.C. — 1973.

10 СТ-НП СРО ССК-04–2013. Температурно-прочностной контроль бетона при возведении монолитных конструкций в зимний период. — УрСиб. — 2013.

11 Golovnev S.G. Normative regulation for concreting in winter / S.G. Golovnev // Academic Herald, 2014. — No. 2. — P. 70–71.

12 Lukpanov R. Performance of maturity method for estimation of concrete strength based on cubic specimens / R. Lukpanov, Sh. Zharassov, T. Mkilima, A. Aldungarova // Technobius. — 2021. — Vol. 1, No. 4. — P. 0008.

13 Utepov Y. Complex Maturity Method for Estimating the Concrete Strength Based on Curing Temperature, Ambient Temperature and Relative Humidity / Y. Utepov, A. Aniskin, A. Tulebekova, A. Aldungarova, S. Zharassov, A. Sarsembayeva // Applied Sciences, 2021. — Vol. 11, No. 16. — P. 7712.

14 Utepov Y. Prototyping an embedded wireless sensor for monitoring reinforced concrete structures / Y. Utepov, O. Khudaibergenov, Y. Kabdush, A. Kazkeev // Computers and Concrete. — 2019. — No. 24. — P. 95–102.

15 Utepov Ye. Prototyping of a concrete maturity sensor with hermetically sealed housing made of two-component plastic / Ye. Utepov, A. Tulebekova, S. Akhazhanov, Sh. Zharassov, D. Bazarbayev // Bulletin of the Karaganda University, Physics Series, 2021. — Vol. 103. — Issue 3. — P. 60–70.

16 ASTM C1074. Standard Practice for Estimating Concrete Strength by the Maturity Method. — Pennsylvania: ASTM International, 2019.

17 ASTM C192. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. — Pennsylvania: ASTM International, 2019.

18 ГОСТ 22690. Определение прочности механическими методами неразрушающего контроля. — М.: Стандартинформ, 2015.

19 ГОСТ 10180. Методы определения прочности по контрольным образцам. — М.: Стандартинформ, 2012.

20 HomeRenovates. Concrete grade M350 class B25. — Retrieved from https://homerenovates.com/en/records/11156.

21 Bassim R. Maturity-Based Estimates of Concrete Strength for Portland Concrete Cement Pavements and Patches at Early Age of Opening to Traffic / R. Basim, M.A. Issa // ACI Materials Journal, 2020. – No. 117. — P. 197–208.

22 Kumarapu K. Thermal Remote Sensing in Early Age Concrete Strength Estimation / K. Kumarapu, M. Shashi, K. Venkata Reddy. — Springer. — Roorkee. — 2020.

23 Zhenchao D. Discussion on the Problem of Standard Deviation of Concrete Strength / D. Zhenchao // ACI Materials Journal, 2020. – No. 117(1). — P. 25–35.

24 Soutsos M. Compressive strength estimates for adiabatically cured concretes with the Modified Nurse-Saul (MNS) maturity function / M. Soutsos, M. Kanavaris // Construction and Building Materials, 2020. – No. 255. — P. 119236.

Е.Б. Утепов, А. Анискин, А.С. Тулебекова, С.Б. Ахажанов, Ш.Ж. Жарасов

Бетонның беріктігін бақылау үшін кемелдену датчиктерін қолдану арқылы Nurse-Saul әдісін бағалау

Мақалада М350 маркалы және В25 класты бетонның беріктігін тікелей және жанама бақылау әдістерімен эксперименттік зерттеулердің нәтижелері келтірілген. Сынақ жүргізу үшін 17 цилиндрлік, 15 шағын және 2 үлкен текше үлгілер дайындалған. Әрқайсысы 3 данадан тұратын 15 цилиндрлік сынама гидравликалық престе сығымдалу үшін қатайтудың 1, 3, 7, 14 және 28-ші күндерінде сыналған, ал қалған 2-уі Nurse-Saul әдісі бойынша «беріктік-кемелдену» тәуелділігін алу мақсатында қатаю температурасы 28 күн бойы өлшенген. Үлкен үлгілердің қатаю температурасының ұқсас тәсілдері тіркелді, оған сәйкес бетонның жетілу деңгейлері және 1, 3, 7, 14 пен 28-ші күндегі беріктік мәндері есептелді. Сонымен қатар, көрсетілген тәулікте шағын үлгілерді сығуға және үлкен үлгілерді соққы-импульстік әдіспен сынау жүргізілді. Нәтижесінде беріктік қисықтары алынды және градуирлеу тәуелділіктері құрылды. Градуирлеу тәуелділіктері тікелей бақылау әдісі (яғни шағын үлгілерді сығу) нәтижелерінің және Nurse-Saul кемелдену әдісінің соққы-импульстік әдісімен салыстырғанда өте жақын ұқсастығын көрсетті. Осы тәуелділіктерді анықтау коэффициенттері сәйкесінше 0,9357 және 0,8965 болып шықты.

Кілт сөздер: кемелдену әдісі, бетонның беріктігі, кіріктірілген датчиктер, сығымдау сынағы, қатаю температурасы, импульстік–соққы әдісі, градуирлеу тәуелділігі.

Е.Б. Утепов, А. Анискин, А.С. Тулебекова, С.Б. Ахажанов, Ш.Ж. Жарасов

Оценка метода Nurse-Saul с применением датчиков зрелости для контроля прочности бетона

В статье представлены результаты экспериментальных исследований прочности бетона класса B25 марки M350 прямым и косвенным методами контроля. Для проведения испытаний было изготовлено 17 цилиндрических, 15 малых и 2 больших кубических образца. 15 цилиндрических образцов по 3 штуки испытывались на сжатие в гидравлическом прессе на 1, 3, 7, 14 и 28-е сутки твердения, а в 2-х остальных на протяжении 28-и суток измерялась температура твердения с целью получения зависимости «прочность–зрелость» по методу Nurse-Saul. Аналогичным способом фиксировалась температура твердения больших образцов, по которой вычислены уровни зрелости бетона и значения прочности на 1, 3, 7, 14 и 28-е сутки. Кроме того, в указанные сутки проводились испытания на сжатие малых образцов и ударно-импульсным методом больших образцов. В результате были получены кривые набора прочности и построены градуировочные зависимости. Градуировочные зависимости показали достаточно близкую сходимость результатов прямого метода контроля (т.е. сжатие малых образцов) и метода зрелости Nurse-Saul, в сравнении с ударно-импульсным методом. Коэффициенты детерминации данных зависимостей составили 0,9357 и 0,8965 соответственно.

Ключевые слова: метод зрелости, прочность бетона, встраиваемые датчики, испытание на сжатие, температура твердения, ударно-импульсный метод, градуировочная зависимость.

References

1 Liao, C. (2015). Optimal Inspection Strategies for Labor Inspection in the Construction Industry. *Journal of Construction Engineering and Management, 141(2),* 04014073.

2 Lin, J., Hu, Z., Lin, J., & Chen, L. (2020). Understanding On-Site Inspection of Construction Projects Based on Keyword Extraction and Topic Modeling. *IEEE Access, 8,* 198503–198517.

3 Andersson, N., & Lessing, J. (2020). Industrialization of construction: Implications on standards, business models and project orientation. *Organization, technology and management in construction: an International Journal, 12 (1),* 2109–2116.

4 Dovzhenko, O.O., Pohribnyi, V.V., Klymenko, Ye.V., & Orešković, M. (2020). Use of extreme properties of deformation for estimation of strength of constructive concrete and reinforced concrete. *NEWS of the Academy of Sciences of the Republic of Kazakhstan, 3(441),* 32–39.

5 Malhotra, V.M., & Carino, N.J. (1991). Handbook on nondestructive testing of concrete. *CRC press.*

6 Zhang, H. (2011). Building materials in civil engineering. *Woodhead Publishing Limited,* 440.

7 Hakan, K., & Öztürk, T. (2015). Determination of concrete quality with destructive and non-destructive methods. *Computers and Concrete, 15(3),* 473–484.

8 De Carufel, S., Fahim, A., Ghods, P., & Alizadeh, A. (2018). Concrete Maturity From Theory to Application. *Giatec Scientific Inc.,* 20, 21.

9 Leyendecker, E.V., & Fattal, S.G. (1973). Investigation of the Skyline Plaza Collapse in Fairfax Country, Virginia. *Washington D.C.*

10 ST-NP SRO SSK-04–2013. *Temperaturno-prochnostnoi kontrol betona pri vozvedenii monolitnikh konstruktsii v zimnii period* [*Temperature and strength control of concrete during the construction of monolithic structures in winter]* (2013). UrSyb [in Russian].

11 Golovnev, S.G. (2014). Normative regulation for concreting in winter. *Academic Herald, 2,* 70–71.

12 Lukpanov, R. Zharassov, Sh., Mkilima, T., & Aldungarova, A. (2021). Performance of maturity method for estimation of concrete strength based on cubic specimens. *Technobius, 1(4),* 0008.

13 Utepov, Y., Aniskin, A., Tulebekova, A., Aldungarova, A., Zharassov, Sh., & Sarsembayeva, A. (2021). Complex maturity method for estimating the concrete strength based on curing temperature, ambient temperature and relative humidity. *Applied Sciences, 11(16),* 7712.

14 Utepov, Y., Khudaibergenov, O., Kabdush, Y., & Kazkeev, A. (2019). Prototyping an embedded wireless sensor for monitoring reinforced concrete structures. *Computers and Concrete, 24*, 95–102.

15 Utepov, Ye. Tulebekova, A., Akhazhanov, S., Zharassov, Sh., & Bazarbayev, D. (2021). Prototyping of a concrete maturity sensor with hermetically sealed housing made of two-component plastic. *Bulletin of the Karaganda of University-Physics, 103, 3*, 60–70.

16 ASTM C1074. *Standard Practice for Estimating Concrete Strength by the Maturity Method* (2019). Pennsylvania: ASTM International.

17 ASTM C192. *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* (2019). Pennsylvania: ASTM International.

18 GOST 22690. Opredelenie prochnosti mekhanicheskimi metodami nerazrushaiushchego kontrolia (2015) [*Determination of strength of concrete by mechanical methods of nondestructive testing]*. Moscow: Standartinform [in Russian].

19 GOST 10180. Metody opredeleniia prochnosti po kontrolnym obraztsam (2012). [*Methods for concrete strength determination using reference specimens]*. Moscow: Standartinform [in Russian].

20 HomeRenovates. Concrete grade M350 class B25. *homerenovates.com*. Retrieved from https://homerenovates.com/en/records/11156.

21 Bassim, R., & Issa, M.A. (2020). Maturity-Based Estimates of Concrete Strength for Portland Concrete Cement Pavements and Patches at Early Age of Opening to Traffic. *ACI Materials Journal, 117,* 197–208.

22 Kumarapu, K., Shashi, M., & Venkata Reddy, K. (2020). Thermal Remote Sensing in Early Age Concrete Strength Estimation, Roorkee. *Springer.*

23 Zhenchao, D. (2020). Discussion on the Problem of Standard Deviation of Concrete Strength. *ACI Materials Journal, 117(1),* 25–35.

24 Soutsos, M., & Kanavaris, M. (2020). Compressive strength estimates for adiabatically cured concretes with the Modified Nurse-Saul (MNS) maturity function. *Construction and Building Materials, 255,* 119236.