Research article

Modulus of elasticity of concrete at an early age

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Abstract. Introduction. The assessment of the risk of early crack formation during hardening of massive monolithic reinforced concrete structures due to temperature gradients predetermines the relevance of studies aimed at increasing the reliability of methods for calculating temperature fields and stresses. When developing technological regulations for concreting, modeling methods are used to assess the risk of early crack formation, the implementation of which requires equations for changing the strength and deformation properties of concrete over time. Highly mobile and self-compacting concrete mixtures with modifiers, which are widely used in concreting the above structures, predetermine the relevance of clarifying known and identifying new patterns of change in the properties of concrete in the early period of hardening, in particular, obtaining equations for changing the E-modulus from prescription factors and temperature conditions. Purpose of the study: obtaining equations for changes in the early and subsequent periods of hardening of the E-modulus of concrete from highly mobile and self-compacting concrete mixtures depending on the prescription factors and temperature conditions during hardening. Methods. Analysis of known approaches to assessing changes in the E-modulus of concrete over time. Modeling using a three-component structural model "matrix – contact zone – aggregate." Experimental studies of the E-modulus depending on the compressive strength limit in the early and subsequent hardening periods of concrete from highly mobile and self-compacting concrete mixtures. Results: Equations are proposed that describe the change in time of the E-modulus of concretes from highly mobile and self-compacting concrete mixtures depending on the compressive strength limit, taking into account the maturity index. The possibility of using the equation EN 1992-1-1 for the change in E-modulus from compressive strength limit for the specified concretes is shown.

1. Introduction

When concreting massive monolithic structures, one of the important tasks is to prevent the risk of early crack formation due to temperature gradients in the early period of hardening caused by heat dissipation from the concrete. When concreting foundation slabs, Russian standard SP 70.13330.2012 allows, in the case of using self-compacting concrete mixtures, laying "simultaneously over the entire site of the structure" without the installation of working joints. Such practice takes place within the concreting section and when erecting massive foundation slabs with a volume of hundreds and even thousands of cubic meters when using self-compacting concrete mixtures of grades S4, S5 in a relatively short period of time [1]. As a result, significant temperature gradients are formed in the hardening concrete mass [2, 3]. The review presented in [4] shows that, based on the results of field observations in the period 2016-2022,

in structures with a top modulus of 1.4...2.4 made of concrete classes B25...B45, there were temperature differences between the center and the top of more than 20 °C at an initial temperature of the concrete mix of 8...29 °C and an ambient temperature of 4...30 °C. The time to reach the maximum difference ranged from 24 to 62 hours. The modeling data presented there [5–8] showed temperature differences of up to 30 °C and more, with a time to reach the maximum of 24...75 hours.

Russian standard SP 435.1325800.2018 prescribes "measures to reduce the influence of temperature and humidity fields and stresses associated with heat dissipation during concrete hardening" during the construction of massive monolithic structures, in connection with which the assessment of temperature fields and stresses to prevent early crack formation is an urgent task [8, 9], the solution of which, when developing technological regulations for concreting, is implemented by methods of modeling temperature fields and stresses [7, 10], including using numerical methods [5–7, 11]. As shown, for example, in [11], the most dangerous period is 1 ... 5 days, due to significant temperature changes. In [12], the effect of temperature conditions of hardening, different from normal, on the E-modulus of concrete is considered, and in [13], detailed studies of the effect of loading rate on the deformation diagram and the E-modulus of concrete under sulfate aggression are carried out. It is obvious that the study of the patterns of change in the E-modulus of concrete depending not only on the prescription factors but also on the temperature conditions during hardening, especially in the early period, and operation, and loading parameters, is a pressing task.

When studying crack formation processes in the early period of hardening of massive structures, methods of fracture mechanics are used, taking into account changes in heat dissipation and deformation properties of concrete over time [14].

Positive experience in constructing massive structures using prescription regulation of temperature fields [1] confirms the relevance of theoretical and experimental studies of the stress-strain state of structures in the early period of concrete hardening. When modeling, certain assumptions are often made regarding the kinetics of strength and E-modulus [11]. The authors [11] come to the conclusion that "the minimum thickness of a slab structure made of concrete classes B20...B50, above which it can be considered massive concrete, is about 0.6 m." A similar opinion is contained in [15].

Most software packages, including ANSYS, Abaqus, Lira-SAPR, SCAD, and a number of others, do not allow by default to specify the change in the E-modulus of concrete over time [16]. This problem is partially solved by developing and implementing user subroutines in FORTRAN and Python [17, 18], which requires a highly qualified programmer, as well as a deep understanding of the principles of operation of software packages. In the Midas Civil software package, the E-modulus of concrete can only be specified explicitly as a function of time [19], which predetermines the relevance of studies of dependencies $E_\tau = f\left(E_{28}\right)$. A thorough analysis of various equations describing the dependence of the E-modulus of concrete, including with mineral admixtures, on the ultimate strength is presented in [20].

In this regard, the purpose of this work is: obtaining equations for changes in the early and subsequent periods of hardening of the E-modulus of concrete from highly mobile and self-compacting concrete mixtures depending on the prescription factors and temperature conditions during hardening.

2. Methods

The assessment of the level of thermal stress state in the early period of hardening of concrete of a massive structure involves determining the magnitude of tensile stresses over time at each step of the calculations:

$$\Delta\sigma(z) = \frac{E(z,t)}{1-\upsilon} \cdot \left(\Delta\varepsilon - \alpha \cdot \Delta T(z) - \Delta\varepsilon_{cr}(z)\right), \qquad (1)$$

where $\Delta\varepsilon$ is the average increment of total deformation over the slab thickness; $\Delta T(z)$ is the difference between the temperature at the point at the current and previous time step; $\Delta\varepsilon_{cr}(z)$ is the increment of creep deformation; υ is the Poisson's ratio of concrete; α is the coefficient of linear thermal expansion of concrete; $E(z,t)$ is the E-modulus of concrete over time. The multiplier $(1-\upsilon)$ in the denominator in Eq. (1) takes into account the work of concrete under biaxial tension (compression) $\left(\sigma_x = \sigma_y = \sigma\right)$ [10].

In special cases, equations of the form [4, 21] are used:

$$\sigma_T = \frac{k_r \cdot E \cdot \alpha \cdot \Delta T}{(1+\varphi)} \qquad (2)$$

or [12]:

$$\sigma_{\varPi T} = \frac{\alpha_T \cdot E}{1-\upsilon} \cdot \left(T_{cp} - T_{\varPi}\right), \qquad (3)$$

where σ_T, $\sigma_{\varPi T}$ – tensile stress from temperature gradients, MPa; k_r takes into account the degree of restriction on the upper top of the slab (0.83 [16]); E – E-modulus of concrete, MPa; $\Delta T\left(T_{cp} - T_{\varPi}\right)$ – temperature difference between the center and the upper top of the slab at any time t, °C; φ – creep coefficient of concrete.

In any case, to determine the magnitude of tensile stresses, data on the kinetics of elasticity of hardening concrete are needed, taking into account the effect of changing temperature. Numerous dependences of the E-modulus of concrete on the compressive strength limit are known [20, 23]. In general, some of them can be presented as:

$$E_0 = k \cdot \frac{a \cdot (b \cdot R + c)}{d + e \cdot R}. \qquad (4)$$

The coefficients of some Eqs. (4) are given in Table 1.

Table 1. Coefficients of Eqs. (4).

Year	Author	Curve No. (Fig. 1)	Coefficients					
			k	a	b	c	d	e
1919	Uoker	6 [27]	53500	1	1	0	20	1
1937	Roš	5 [26]	55000	1	1	0	15	1
1988	Chistyakov	3 [27]	54000	1	1	0	20	1
1996	Karpenko	2 [28]	52000	1	1	0	18	1
1996	Nesvetaev	7	56700	1	1	0	22.5	1

Another group of equations has the general form:

$$E_0 = k \cdot \frac{a}{b + \dfrac{c}{d + R}}. \qquad (5)$$

The coefficients of some Eqs. (5) are given in Table 2.

Table 2. Coefficients of Eqs. (5).

Year	Author	Curve No. (Fig. 1)	Coefficients			
			k	a	b	c	d
1990	Kvirikadze	9	1000	60	1	29	3.8
1996	Nesvetaev	1	$456 \cdot E_a/67 + 544$	$0.05R + 57$			

E_a [GPa] – E-modulus of coarse aggregate.

According to EN 1992-1-1 and ACI 318-08, IS:456 (India), CSA (Canada), the relationship between the E-modulus and the compressive strength of concrete $\left(f_{cm}, f_c\right)$ is given by the equations:

$$\text{EN}: E_{cm} = 22000 \cdot \left(\frac{f_{cm}}{10}\right)^{0.3}; \qquad (6)$$

$$\text{ACI}: E_c = k \cdot \sqrt{f}. \qquad (7)$$

In Eq. (7), k = 4700 (ACI), 5000 (IS), 4500 (CSA), the value f is taken to be f_c (ACI, CSA) f_{ck} (IS).

All the above-considered dependencies are proposed for concretes at the design age; the possibility of their application for describing the dependence of the E-modulus on the compressive strength limit at an early age requires confirmation. In any case, the question of the patterns of change in the E-modulus of concrete over time is relevant.

3. Research Methodology

Modeling. There are two options for taking into account the change in the E-modulus of concrete over time. In the first option, the dependence of the E-modulus on time is determined as:

$$E_t = \beta \cdot E_{28}, \tag{8}$$

for example, according to equations similar to [29–31]:

$$E_t = E_{28} \cdot \left(\frac{t}{2.3 + 0.92 \cdot t} \right)^{0.4} = \beta_t \cdot E_{28}, \tag{9}$$

according to EN 1992-1-1:

$$E_{cm}(t) = \left(\frac{f_{cm}(t)}{f_{cm}} \right)^{0.3} \cdot E_{cm} \qquad \text{or} \qquad E_t = \left(\frac{R_t}{R_{28}} \right)^{0.3} \cdot E_{28}. \tag{10}$$

In the first case, the values of the coefficient β depend only on time, in connection with which, for concretes with different kinetics of compressive strength, it may be necessary to clarify the coefficients in Eq. (9). Eq. (10) is free of this drawback, but its applicability for temperature conditions other than normal may require correction of the numerical values of the coefficients.

In the second variant, the dependence of the E-modulus of concrete is determined at any moment of the given time as a function of the compressive strength limit.

The E-modulus of concrete depends on the E-modulus of the coarse aggregate E_{CA}, the solution component (matrix) and the E-modulus of the contact zone (transition zone) E_{tz}. Obviously E_{CA}, unlike E_m and E_{tz}, does not change over time, while it can change in a wide range of 40 ... 120 GPa. The use of structural models for the analysis of the E-modulus of concrete as a two-component system "matrix – aggregate" has been used for at least more than half a century [22]. In [23], various two-component models are analyzed and their applicability for determining the E-modulus of concrete under compression and tension is shown, and it is shown that at the age of 1 ... 3 days, there is a sharp increase in the E-modulus. In [24], a four-component model "coarse aggregate – contact zone – matrix – structural defects" is analyzed. The influence of porosity parameters on the E-modulus is considered in [25, 31].

In our studies, we used a three-component model of "matrix – contact zone – aggregate." The E-modulus of concrete during modeling was determined depending on the concentration V_m, V_a, V_{tz} and elastic properties E_m, E_{CA}, E_{tz} of the matrix, coarse aggregate and the contact zone between them, the influence of which on the result at a loading level of up to 0.4 is small, according to the equation:

$$E_H = \frac{2}{\dfrac{1}{E_a \cdot V_a + E_m \cdot V_m + E_{tz} \cdot V_{tz}} + \dfrac{V_a}{E_a} + \dfrac{V_m}{E_m} + \dfrac{V_{tz}}{E_{tz}}}. \tag{11}$$

By modeling the change in the E-modulus of the matrix over time, for example, using Eq. (10), it is possible to obtain the dependence of the E-modulus of concrete on time using Eq. (11). Modeling the dependence of the E-modulus on time using Eq. (11) is implemented using the following algorithm:

– according to the equation:

$$R_\tau = R_{28} \cdot \exp\left(s \cdot \left(1 - \sqrt{\frac{28}{\tau_m - \tau_i}}\right)\right), \tag{12}$$

at values of s 0.2, 0.25, 0.38, respectively, for fast (R), normal (M), and slow-hardening concrete (S), the values R_τ at τ_i 0.125 are determined. The values of τ_m, days, at a concrete curing temperature different from normal (increased when cured in massifs) are determined by the concrete degree of maturity M_b [10]:

$$\tau_m = \frac{M_b}{480}; \tag{13}$$

- the values of the coefficient β_{EN} in the equation $E_\tau = \beta_{EN} \cdot E_{28}$ are determined by equation (10);

- the values of the coefficient β_τ are determined by Eq. (9);

- for concrete of class, for example, B30 (C25/30), the value of the ultimate strength of the matrix at the design age is 40 MPa, the E-modulus E_m of the matrix is 28000 MPa, the values of the matrix at the age from 1 to 28 days are determined by Eq. (12);

- the value of the E-modulus E_m of the matrix at the age from 1 to 28 days is determined by Eq. (10);

- according to Eq. (11), the values of the E-modulus of concrete $E_{H,\tau}$ with the specified matrix were determined with the E-modulus of coarse aggregate E_{CA} = 40 (120) GPa and a volume concentration of coarse aggregate of 0.4, a volume concentration of the matrix of 0.6 (the volume concentration of the contact zone, due to the smallness of its effect on the deformation modulus at a loading level of up to 0.4, was taken to be equal to 0) at an age from 1 to 28 days;

- based on the obtained values $E_{H,\tau}$, the values were determined $\beta_H = {E_{H,\tau}}\big/{E_{H,28}}$.

Experimental studies

Experimental studies of changes in the E-modulus of concrete were performed using three Portland cements of class C42.5, one of which was admixtures-free (CEM I), two with different mineral admixture (CEM II). Concrete mixtures contained superplasticizing admixture PCE (L) or NF (C), or did not contain admixtures. Concrete curing conditions were normal, indoors in the laboratory, in the massif at a peak temperature of 39...42 °C. The compressive strength of concrete was determined at the age of 1, 2, 3, 28 days. For samples hardened in the massif, the reduced age was determined τ_m by the concrete degree of maturity M_b. The E-modulus of concrete was determined through the dynamic E-modulus. More than 65 years ago, it was shown that determining the dynamic E-modulus gives practically equal results regardless of the use of longitudinal or transverse vibrations, and the dimensions of the samples do not affect the result [32, 33]. Determination of the dynamic E-modulus allows obtaining results both at an early age and under various impacts on concrete on the same samples, which increases the reliability of the results [34]. Research in the field of improving the methodology for determining the dynamic E-modulus of concrete on various samples confirms the effectiveness of the method [35]. In this regard, in the work to determine the E-modulus of concrete on samples of 100×100×100 mm aged from 1 to 28 days, a method based on the use of longitudinal vibrations was used.

A total of 65 pairs of values "$E - R$" were obtained with a range of compressive strength of 9.3...69.2 MPa and E-modulus of 21.41...37.75 GPa.

4. Results and Discussion

Fig. 1 shows the dependence of the E-modulus of concrete on the compressive strength limit according to the equations in Tables 1 and 2.
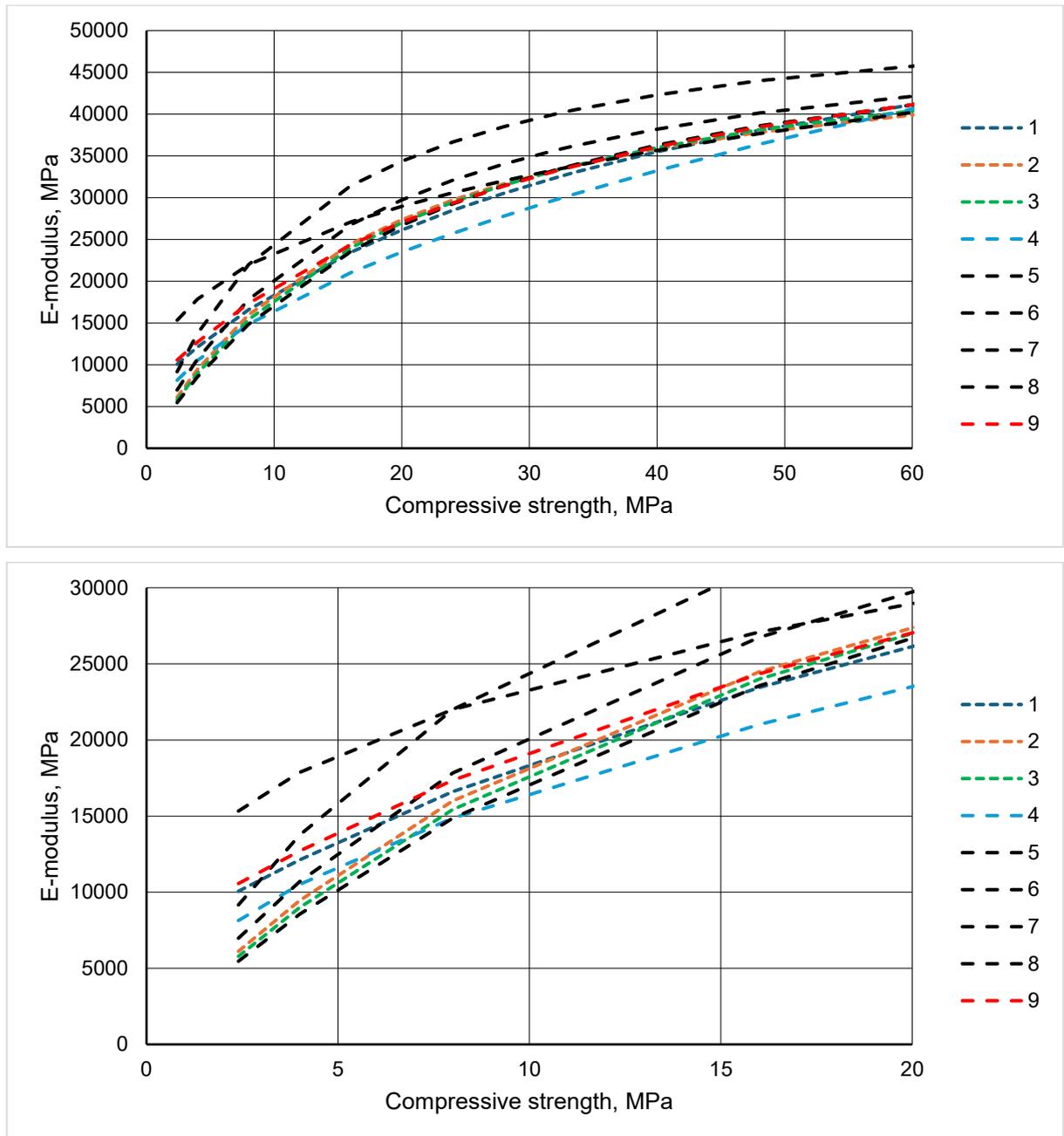
Figure 1. Dependence of the E-modulus of concrete on the compressive strength:
1–3, 5–7, 9 are indicated in Tables 1 and 2; 4 – according to Eq. (7); 8 – according to Eq. (6).

It is obvious that all dependencies in Table 1, except for Curve No. 5, provide relatively close values; at a strength value of more than 15 MPa, the difference does not exceed 5 %. At lower strength values, the difference increases and at a strength of 3 MPa, it reaches 2.5 times along Curves Nos. 2 and 8. Dependence EN 1992-1-1 (Curve No. 8) shows maximum values of the E-modulus at low values of the compressive strength, which can be considered as the early period of concrete hardening. As shown below, this is due to the influence of a constant value of the E-modulus of coarse aggregate over time.

Fig. 2 shows the calculated values of the coefficient β in Eq. (8).
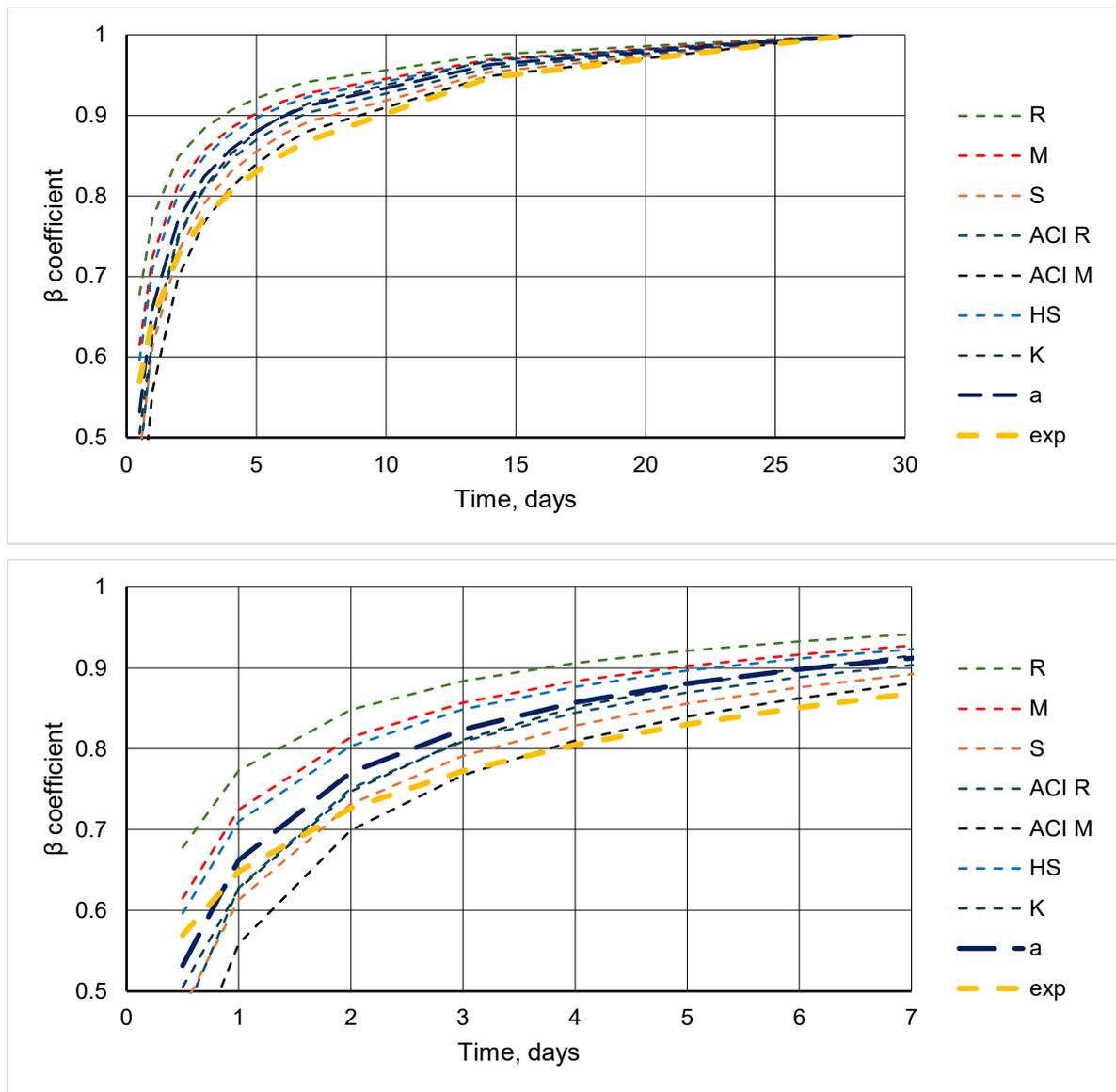
Figure 2. Dependence of the coefficient β on time.

Curves R, M, S – respectively, when determining the strength according to Eq. (12) for rapidly, normally and slowly hardening concrete β according to Eq. (10); Curves ACI R, M – respectively, when determining the strength according to Eq. (12) for rapidly and normally hardening concrete, the E-modulus according to Eq. (6), Curve K – β according to Eq. (9); Curve HS – when determining the modulus of the matrix according to Eq. (10), the E-modulus of concrete according to Eq. (11) with the E-modulus of coarse aggregate of 40 GPa; Curve a – is the average of all calculated values β; Curve exp – are the authors' experimental data.

At the age of one day, the difference in the calculated values β is 38 %, at the age of two days – 21 %, at the age of three days – 15 %. The dependence of the average calculated value of the coefficient β on time is described by the equation:

$$\beta = \exp\left(0.095 \cdot \left(1 - \sqrt{\frac{28}{\tau}}\right)\right). \tag{14}$$

The coefficients closest to the average value β are those according to Eq. (9) [29], as well as for quickly hardening concrete according to the ACI equation – Eq. (7).

The experimental values of the coefficient according to the authors' data β, obtained during tests of concrete with a fairly low E-modulus of coarse aggregate (siliceous sandstone with a E-modulus of 41.8...43.6 GPa) in principle fit into the overall picture.

Fig. 3 shows the dependence of the E-modulus on the compressive strength limit according to the authors' experimental data and some calculated dependencies. The calculated strength at the daily age of the studied concretes ranged from 5.1 MPa for slowly hardening concrete with a design strength from 27.1 to 29.3 MPa for quickly hardening concrete with a design strength of 69.2 MPa. The actual strength at the daily age ranged from 9.3 MPa with a design strength from 27.1 to 16.4 MPa with a design strength of 34.5 MPa (some samples were tested at the age of 2 days instead of 1 day). The E-modulus at the daily age ranged from 21140 to 24220 MPa, at the design age from 30515 to 37750 MPa.
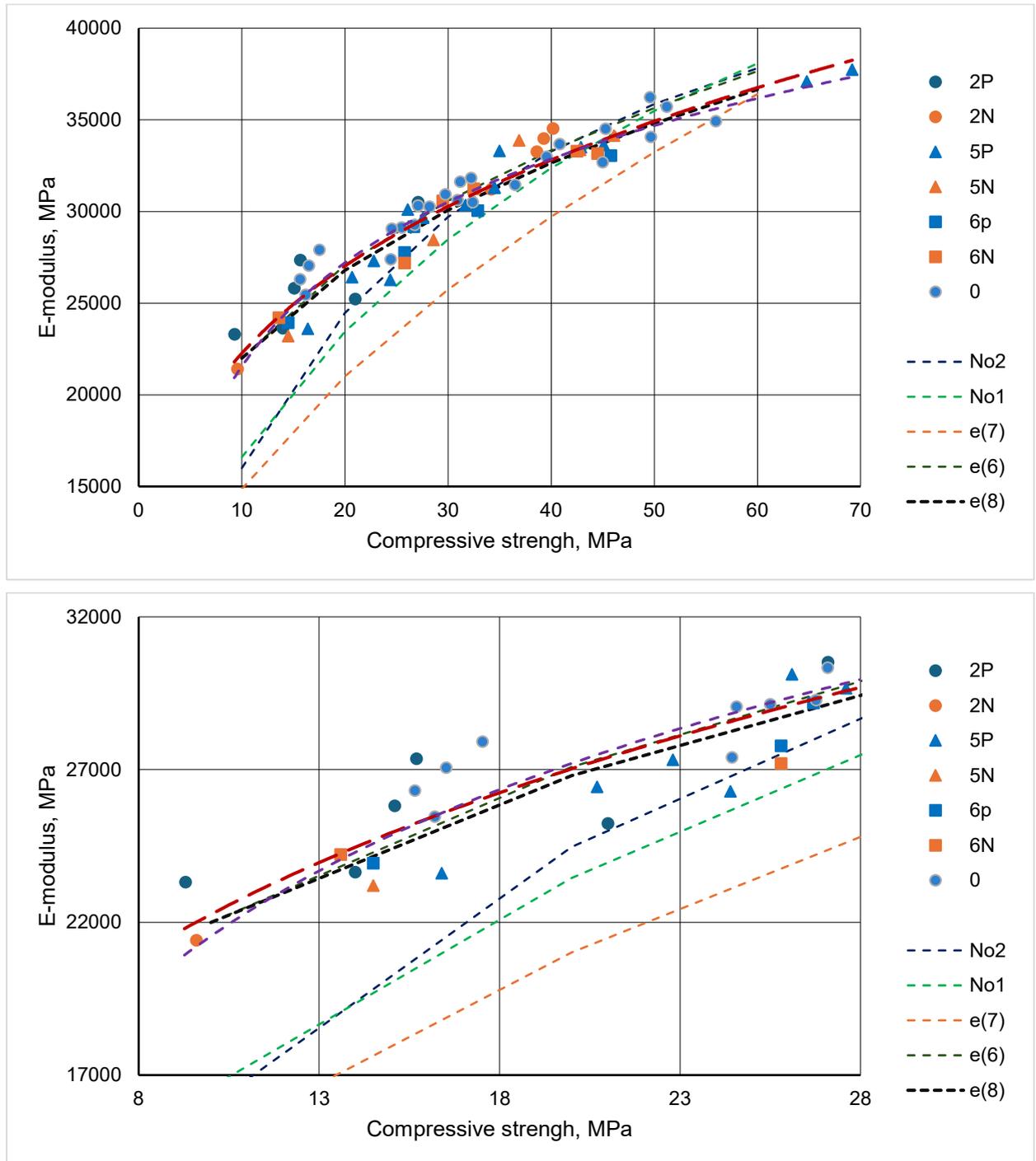

Figure 3. Dependence of the E-modulus on the compressive strength: 2, 5, 6 – cements;
P – PCE superplasticizer; N – NF superplasticizer; 0 – without admixtures;
Curves 1, 2 – curves in Fig. 1; e(6), e(7), e(8) – according to Eqs. (6), (7), (8).

It is obvious that Eq. (7) and Curves Nos. 1, 2 in Fig. 1, obtained for concrete of the design age, are not suitable for describing the dependence of the E-modulus of hardening concrete at an early age.

The dependence of the E-modulus of the concretes studied by the authors on the compressive strength limit is described by the equation:

$$E = 11685 \cdot R^{0.28},$$

(15)

with an approximation reliability index of R^2 = 0,923, which indicates good convergence and the possibility of using the equation for practical purposes.

Eq. (15), reduced to the form EN 1992-1-1, has the form:

$$E_t = 22265 \cdot \left(\frac{R_t}{10} \right)^{0.28},$$

(16)

the difference in values when calculating according to Eqs. (6) and (16) is less than 1 % in the range of compressive strength limits of 10…70 MPa.

Theoretical prerequisites for constructing a calculation method

The first option is the dependence of the E-modulus on the time of hardening of concrete at an early age is determined by Eq. (14) with the duration of the induction period in most cases being 0.15–0.25 days.

The second option is the dependence of the E-modulus on the time of hardening of concrete at an early age is determined by Eq. (16), while the strength value R_τ is determined at the given age τ_m depending on the degree of maturity of the concrete M_b.

5. Conclusions

1. Some dependencies have been analyzed $E_\tau = f(E_{28})$, it has been shown that the closest to the average value for all analyzed dependencies is provided by Eq. (9).

2. The dependence of the change in time of the E-modulus has been obtained taking into account the degree of maturity of hardening concrete with superplasticizing admixtures.

3. When calculating the time-varying values of the E-modulus of concrete based on the value of the compressive strength limit $E_\tau = f(R_\tau)$ it is advisable to use the dependence EN 1992-1-1.

References

1. Kaprielov, S.S., Sheinfeld, A.V., Kiseleva, Yu.A., Prigozhenko, O.V., Kardumyan, G.S., Urgapov, V.I Erection of Unique Structures Made of Modified Concrete and Used for Construction of the Complex "Federation" MMDTS "Moscow-City". Industrial and Civil Engineering. 2006. 8. Pp. 20–22.

2. Kuriakose, B., Rao, B.N., Dodagoudar, G.R. Early-age Temperature Distribution in a Massive Concrete Foundation. Procedia Technology. 2016. 25. Pp. 107–114. DOI: 10.1016/j.protcy.2016.08.087

3. Makeeva, A.V., Semenov, K.V., Makeev, A.A., Amelina, A.V. Crack resistance of massive concrete structures during the building period taking into account temperature effects. Bulletin of BSTU named after V.G. Shukhov. 2019. 8. Pp. 30–39. DOI: 10.34031/article_5d49408e0e0b61.97206550

4. Nesvetaev, G.V., Chepurnenko, A.S., Koryanova, Y.I., Sukhin, D.P. Evaluation of some methods for calculating thermal stresses during concreting of massive reinforced concrete foundation slabs. Engineering Journal of Don. 2022. 7(91). URL: http://www.ivdon.ru/en/magazine/archive/n7y2022/7817 (date of application: 22.01.26).

5. Fairbairn, E.M.R., Silvoso, M.M., Toledo Filho, R.D., Alves, J.L.D., Ebecken, N.F.F. Optimization of mass concrete construction using genetic algorithms. Computers & Structures. 2004. 82(2–3). Pp. 281–299. DOI: 10.1016/j.compstruc.2003.08.008

6. Agakhanov, E.K., Kurachev, R.M., Chepurnenko, A.S., Kulinich, I.I. Non-linear heat conduction problem for radiation-heat shield of nuclear reactor]. Engineering Journal of Don. 2015. 4. URL: ivdon.ru/ru/magazine/archive/n4y2015/3421 (date of application: 22.10012026).

7. Aniskina, N.A., Nguyen Trong Chuc, Bryansky, I.A., Dam Huu Hung. Determination of the Temperature Field and Thermal Stress State of the Massive of Stacked Concrete by Finite Element Method. Vestnik MGSU. 2018. 13(11). Pp. 1407–1418. DOI: 10.22227/1997-0935.2018.11.1407-1418

8. Semenov, K., Kukolev, M., Zaichenko, N., Popkov, S., Makeeva, A., Amelina, A., Amelin, P. Unsteady Temperature Fields in the Calculation of Crack Resistance of Massive Foundation Slab During the Building Period. Proceedings of EECE 2019. Springer. Cham, 2020. Pp. 455–467. DOI: 10.1007/978-3-030-42351-3_40

9. Bofang, Z. Thermal Stresses and Temperature Control of Mass Concrete. Elsevier/Butterworth-Heinemann. Amsterdam, Boston, 2014. 500 p.

10. Nesvetaev, G.V., Koryanova, Y.I., Chepurnenko, A.S., Sukhin, D.P. On the issue of modeling temperature stresses during concreting of massive reinforced concrete slabs. Engineering Journal of Don. 2022. 6. URL: ivdon.ru/ru/magazine/archive/n6y2022/7691 (date of application: 23.01.26).

11. Bolgov, A.N., Nevskii, A.V., Ivanov, S.I., Sokurov, A.Z. Numerical Modeling of Thermal Stresses in Concrete of Massive Structures during the Hardening Period. Industrial and Civil Engineering. 2022. 4. Pp. 6–13. DOI: 10.33622/0869-7019.2022.04.06-13

12. Klausen, A.E., Kanstad, T., Bjøntegaard, Ø., Sellevold, E.J. The effect of realistic curing temperature on the strength and E-modulus of concrete. Materials and Structures. 2018. 51. Article no. 168. DOI: 10.1617/s11527-018-1299-4

13. Liu, R., Mao, X., Li, B., Li, Y., Zhang, L. Experimental study on dynamic mechanical properties of concrete under sulfate attack. Frontiers in Materials. 2025. 12. Article no. 1560181. DOI: 10.3389/fmats.2025.1560181

14. Wang, Y.-S, Mo, L.-H., Xie, S.-X., Wang, C.-Y., Yu, X.-B. Early-age cracking in mass concrete: Modeling and case study of an extra-large exhibition pool. Journal of Building Engineering. 2023. 80. Article no. 108118. DOI: 10.1016/j.jobe.2023.108118

15. Abelev, M.Yu., Krasnovskiy, B.M. Technologies of Installation of Slab Foundations of 17-Storey Panel Buildings. Industrial and Civil Engineering. 2021. 4. Pp. 40–46. DOI: 10.33622/0869-7019.2021.04.40-46

16. Turina, V.S., Chepurnenko, A.S., Akopyan, V.F. Methodology for determining true temperature stresses during the construction of massive monolithic reinforced concrete structures. Construction Materials and Products. 2024. 7(3). Article no. 5. DOI: 10.58224/2618-7183-2024-7-3-5

17. Lin, Y., Chen, H.L. Thermal analysis and adiabatic calorimetry for early-age concrete members: Part 2. Evaluation of thermally induced stresses. Journal of Thermal Analysis and Calorimetry. 2016. 124. Pp. 227–239. DOI: 10.1007/s10973-015-5131-x

18. Mardmomen, S., Chen, H.L. Prediction of the early age thermal behavior of mass concrete containing SCMs using ANSYS. Journal of Thermal Analysis and Calorimetry. 2023. 148(15). Pp. 7899–7917. DOI: 10.1007/s10973-023-12243-9

19. Nikolenko, S.D., Sazonova, S.A., Zvyagintseva, A.V. Calculation of Crack Formation During the Thermal Stress State of Concrete Masses and Development of Measures to Improve the Operational Properties of Concrete. IOP Conference Series: Materials Science and Engineering. 2021. 1079(3). Article no. 032028. DOI: 10.1088/1757-899X/1079/3/032028

20. Qin, X., Xu, Z., Liu, M., Zhang, Y., Wang, Y., Yang, Z., Ling, X. Mechanical Properties and Elastic Modulus Prediction of Mixed Coal Gangue Concrete. Materials. 2025. 18(6). Article no. 1240. DOI: 10.3390/ma18061240

21. Kumar Mehta, P., Monteiro, P.J.M. Concrete: Microstructure, Properties and Materials. McGraw-Hill. USA, 2001. 239 p.

22. Popovics, S. Structural Model Approach to Two-Phase Composite Materials: State of the Art. American Ceramic Society Bulletin. 1969. 48(11). Pp. 1060–1064.

23. Yoshitake, I., Rajabipour, F., Mimura, Y., Scanlon, A. A Prediction Method of Tensile Young's Modulus of Concrete at Early Age. Advances in Civil Engineering. 2012. Article no. 391214. DOI: 10.1155/2012/391214

24. Li, X., Du, C., Li, C., Xu, Y., Gong, W. Effects of Initial Defects on Effective Elastic Modulus of Concrete with Mesostructure. Journal of Wuhan University of Technology – Materials Science. 2024. 39(6). Pp. 1484–1495. DOI: 10.1007/s11595-024-3018-z

25. Chen, H., Xu, F. Quantitative Characterization Model of Macroscopic Mechanical Properties of Recycled Concrete Based on Porosity and Pore Sizes. Advances in Materials Science Engineering. 2024. Article no. 5261052. DOI: 10.1155/2024/5261052

26. Roš, M. Versuche und Erfahrungen an ausgeführten Eisenbetonbauwerken in der Schweitz 1924–1937: Bericht Nr. 99. Eidgenössische Materialprüfungs u. Versuchsanstalt Zürich. Zürich, 1937. 405 S.

27. Mordovskiy, S.S. Initial Modulus of Elasticity of Concrete and Ways to Determine IT. Traditsii i innovatsii v stroitelstve i arkhitekture. stroitelstvo i stroitelnyye tekhnologii [Traditions and innovations in construction and architecture. Construction and construction technologies]. Samara: Samara State Technical University, 2022. Pp. 37–45.

28. Karpenko, N.I. Obshchiye modeli mekhaniki zhelezobetona [General models of reinforced concrete mechanics]. Moscow: Strojizdat, 1996. 412 p.

29. Karpenko, N.I., Travush, V.I., Kaprielov, S.S., Mishina, A.V., Andrianov, A.A., Bezgodov, I.M. The Research of Physical, Mechanical and Rheological Properties of High Strength Steel Fiber Reinforced Concrete. Academia. Architecture and Construction. 2013. 1. Pp. 106–113.

30. Singh, B.P., Yazdani, N., Ramirez, G. Effect of a Time Dependent Concrete Modulus of Elasticityon Prestress Losses in Bridge Girders. International Journal of Concrete Structures and Materials. 2013. 7(3). Pp.183–191. DOI: 10.1007/s40069-013-0037-0

31. Xu, F., Pan, H. Research on Quantitative Characterization Model of Compressive Strength or Elastic Modulus of Recycled Concrete Based on Pore Grading. Materials. 2025. 18(3). Article no. 3. DOI: 10.3390/ma18010003

32. Batchelder, G.M., Lewis, D.W. Comparison of Dynamic Methods of Testing Concretes Subjected to Freezing and Thawing. Proceedings, ASTM. 1953. 53. Pp. 1053–1068.

33. Woods, K.B., McLaughlin, J.F. Application of Pulse Velocity Tests to Several Laboratory Studies of Materials. Highway Research Board Bulletin. 1959. 206. Pp. 14–27.

34. Chen, D., Zou, J., Zhao, L., Xu, S., Xiang, T., Liu, C. Degradation of Dynamic Elastic Modulus of Concrete under Periodic Temperature-Humidity Action. Materials. 2020. 13(3). Article no. 611. DOI: 10.3390/ma13030611

35. Kim, M.S., Son, J.J., Chung, C.W., Lee, C.J. Factors Influencing Measurement of Dynamic Elastic Modulus from Disk-Shaped Concrete. Specimen International Journal of Concrete Structures and Materials. 2024. 18. Article no. 68. DOI: 10.1186/s40069-024-00710-y

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