

NUMERICAL MODELING OF CONCRETE CREEP UNDER VARIOUS STRESS STATES

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Abstract: The article addresses the problem of numerically modeling creep deformations in modern high-strength modified self-compacting concretes. The relevance of the research is driven by the imperfections in the regulatory framework, specifically SP 63.13330.2018, which offers an overly simplified and conservative approach to accounting for creep. This approach fails to consider the specific characteristics of modern concretes and does not enable reliable forecasting. Conversely, the existing, more detailed domestic recommendations from 1984 are technically obsolete and inapplicable to high-strength concretes.

The aim of the study is to assess the applicability of modern and outdated computational creep models for predicting deformations in high-strength concrete across different humidity conditions. The research was conducted using numerical modeling in the ATENA software complex, with verification of the results against experimental data.

The results demonstrated that the direct application of even the most modern models (B3, MC 2010) leads to significant errors (ranging from 13% to 130%), which vary depending on humidity. Models from the 1970s-80s (exemplified by ACI-78) proved entirely inapplicable, showing discrepancies of up to 600% compared to experimental data. The necessity of modifying models not only for the specific concrete composition but also for its curing conditions and humidity levels is demonstrated.

The study concludes that the verification and calibration of computational models based on experimental data are critically important before modeling complex stress-strain states. An action algorithm is proposed to enhance the accuracy of creep prediction under multiaxial loads, which includes mandatory experimental verification of boundary conditions.

Keywords: concrete creep, numerical modeling, high-strength concrete, ATENA, B3 creep model, fib Model Code, finite element method, stress-strain state

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПОЛЗУЧЕСТИ БЕТОНА ПРИ РАЗНЫХ ВИДАХ НДС

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Аннотация: В статье рассматривается проблема численного моделирования деформаций ползучести современных высокопрочных модифицированных самоуплотняющихся бетонов. Актуальность исследования обусловлена несовершенством нормативной базы, в частности, СП 63.13330.2018, который предлагает чрезмерно упрощенный и консервативный подход к учету ползучести, не учитывающий особенности современных бетонов и не позволяющий выполнять прогнозирование. Существующие более детальные отечественные рекомендации 1984 года, напротив, морально устарели и не применимы к высокопрочным бетонам.

Целью работы является оценка применимости современных и устаревших расчетных моделей ползучести для прогнозирования деформаций высокопрочного бетона класса в различных условиях влажности. Исследование проводилось методом численного моделирования в программном комплексе ATENA с верификацией результатов на экспериментальных данных.

Результаты показали, что прямое применение даже самых современных моделей (B3, MC 2010) приводит к значительным погрешностям (от 13% до 130%), варьирующимся в зависимости от влажности. Модели 1970-80-х годов (на примере ACI-78) оказались полностью неприменимы, демонстрируя расхождения с экспериментом до 600%. Показана необходимость модификации моделей не только под конкретный состав бетона, но и под условия его твердения и влажности.

Сделан вывод о критической важности верификации и калибровки вычислительных моделей на основе экспериментов перед моделированием сложного напряженно-деформированного состояния. Предложен алгоритм действий для повышения точности прогнозирования ползучести при многоосных нагрузках, включающий обязательную экспериментальную проверку граничных условий.

Ключевые слова: ползучесть бетона, численное моделирование, высокопрочный бетон, ATENA, модели ползучести B3, Model Code

INTRODUCTION

The main regulatory document that governs the calculation and design of reinforced concrete structures in our country is SP 63.13330.2018. It serves as the primary source for related documents such as SP 266.1325800.2016, which covers the design and calculation of steel-reinforced concrete structures; SP 430.1325800.2018, which regulates the design of cast-in-place structures; and the design code currently under development for reinforced concrete structures with external sheet reinforcement. Some formulas, tables, and provisions in these design codes are identical to those in SP 63.13330.2018. In particular, this applies to the description of the concrete creep process. However, the section on concrete creep accounting is very short. SP 63.13330.2018 does not provide any information on shrinkage accounting.

SP 63.13330.2018 does not offer a method for predicting creep. It only includes one formula, (1), for reducing the elastic modulus under prolonged loading while accounting for creep. Formula (1) includes only the initial modulus and the creep coefficient. Formula (2) accounts for inelastic deformations and rapid creep when specifying the elastic modulus under short-term loading. For shear, the code recommends taking the modulus of elasticity as 0.4 of the initial value, but does not specify whether this applies to long-term or short-term effects. This code does not provide any other recommendations for accounting for concrete creep. The creep coefficient, $\varphi_{b,cr}$, included in formula (1), is a tabulated value that depends only on the concrete class and ambient humidity. Furthermore, for high-strength concrete (with a compressive strength of 60 MPa and above, as per class designations), this coefficient is applied as a single, unified value. This approach is conservative and has been criticized

by many researchers [1, 2]. Its inclusion was not based on experimental or theoretical substantiation but rather on a review of foreign literature (American and European documents) conducted in the early 2000s during the development of the then-new Russian concrete design code, SP 52-101-2003. This was a practical solution, as the technology and industry were ready for the use of high-strength concrete, but its characteristics - particularly its deformation properties - were largely unstudied; nearly all scientific research in this area within the country had ceased.

Eurocode 2 (1992), which was thoroughly examined during the preparation of the 2001 Russian code, proposed the use of distinct creep coefficients for concrete grades up to class C100, with differentiation at five-class intervals. Currently, international research in this field has advanced considerably [3-5]. Studies now investigate the effects of creep not only under compression but also under other stress-strain state conditions, and there are ongoing efforts to utilize modern software for developing creep models, among other advancements [6-8]. In contrast, due to the fact that creep testing can only be conducted in a few organizations within our country, such research remains sporadic [9,10].

$$E_{b,\tau} = \frac{E_b}{1 + \varphi_{b,cr}} \quad (1)$$

$$E_{b,1} = 0.85 \cdot E_b \quad (2)$$

Before the publication of the design code SP 52-101-2003, which was used alongside the existing SNiP 2.03.01-84*, the Recommendations of the NIIZhB for Considering Shrinkage and Creep (1984) were also in effect. Interestingly, this document has never been officially revoked and, paradoxically, remains valid to this day. This was a fundamental body of work. A large number of

specialists participated in its development, and all its dependencies and tabulated values were based on an extensive array of experimental research conducted in the Soviet Union.

These recommendations allow predicting the creep and shrinkage deformations of concrete up to class B60, accounting for a wide range of input variables (such as concrete mix composition, loading age, and structure type). At the time of their release, these recommendations were not only highly relevant within the country but were also competitive on a global scale. The creep model they proposed was on par with leading European and American models of that era [11, 12]. Following the publication of these recommendations, some specialists continued in-depth research on creep [13-15], and there were attempts to introduce improved models [16, 17]. However, these subsequent studies were never incorporated into the regulatory documents. When attempts were made to apply both the models from the 1984 recommendations and those from other leading Russian and Soviet scientists to modern concretes, certain contradictions and inconsistencies were revealed [18]. Furthermore, direct attempts to predict the creep deformations of high-strength concrete using these models resulted in significant inaccuracies, to the point of complete inapplicability. This also applies to the accelerated method for determining creep deformations (which was present in GOST 24544-84) that was removed during the latest update of that standard. Later, this article will demonstrate the inadequacy of the 1978 American concrete creep model when applied to modern concretes.

Over the past 15 years, the author has conducted extensive experimental and theoretical research on the deformation characteristics of high-strength concretes. Some of these findings are presented in this article. The study examines an approach that combines the classical experimental evaluation of creep deformations according to GOST 24544-2020 with the use of modern computational tools based on advanced software complexes that have various built-in concrete creep models. This work is critically important because manually calculating the creep effects in

a complex structural element or joint is practically infeasible when such an analysis is required.

METHODS

To assess the applicability of existing creep theories, enable three-dimensional computer modeling of long-term experiments in analysis software, and evaluate the feasibility of computer modeling of complex stress-strain states under sustained loading, a numerical simulation was performed. This simulation imitated the deformation of prism specimens under three different humidity conditions using the most advanced creep models: B3, B3 improved, MC 2010, and the American ACI-78 model. The ATENA software package was used as the computational tool.

This particular software package was selected because its built-in model, which accounts for the physical nonlinearity of concrete properties—the Fracture–Plastic Constitutive Model CC3DCementitious2 developed by Červenka Consulting—has proven highly effective in modeling reinforced concrete elements under various stress-strain states. These include concentric and eccentric compression [19, 20], bending [21], biaxial compression, shear, punching shear [22], steel-concrete composite structures of varying complexity [23], and structures with external sheet reinforcement [24, 25], including those made of high-strength concrete. The model is based on a combination of a tensile fracture model (Rankine-Fracturing Model) and a compressive failure model for the material (Menétrey-Willam). A review of the literature indicates that calculation results obtained with the built-in CC3DCementitious2 concrete model generally show good agreement with experimental data—the discrepancy in results from various researchers, both Russian and international, typically remains within 10%.

For the computer simulation, a specific high-strength modified self-compacting concrete mix of class B75 (determined according to GOST 18105 and GOST 31914) was selected. Detailed

studies of modified high-strength concretes with similar characteristics, for which the authors of the report conducted concurrent tests to determine creep and shrinkage deformations under three different humidity conditions, are presented in [26]. The specimens were loaded at the age of 88 days. (For some modified concretes, achieving the design strength class at an age of 60 days or more is considered normal; the design age for this concrete was 90 days). Based on the test results for density and slump flow, conducted in accordance with the requirements of GOST 26633 and GOST R 59715, the mix can be classified as self-compacting. This particular composition was chosen for the computer study to evaluate the applicability of existing concrete creep models to modern high-strength modified self-compacting concretes. Given that practically all concretes with a strength class above B60 fall into this category, this research task is highly relevant. Predicting creep deformations under different humidity conditions for a single concrete mix is

an important task. This is because the same concrete, even within a single structure, can cure under various conditions (e.g., an enclosed steel section restricts moisture migration from the concrete, while exposed surfaces imply standard temperature and humidity conditions). Furthermore, when using creep coefficients in calculations, it is essential to know their potential maximum values for the concrete class in question, enabling a probabilistic forecast of worst-case scenarios. (Conversely, the worst-case design scenario may sometimes involve maximum stiffness of structural elements, which corresponds to minimum creep coefficients—see Formula 1). Figure 2 presents the experimental deformation curves for the concrete under sustained load at different humidity levels. This figure also shows the testing setups located in rooms with normal humidity; the tests at elevated and reduced humidity were conducted in separate climate-controlled chambers.

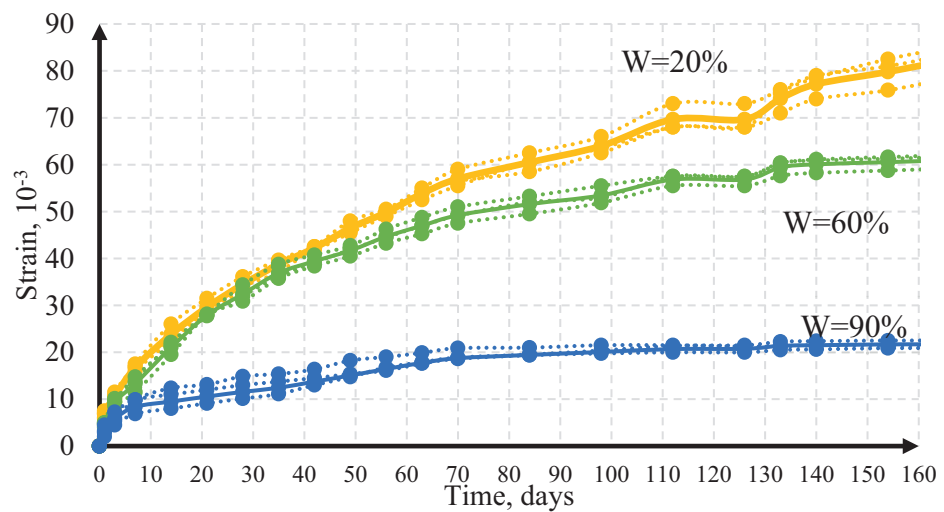


Figure 1. Experimental creep and shrinkage strains for various humidity conditions

The ATENA software package includes a built-in module for considering concrete creep. Within this module, it is possible to select virtually any modern creep model, and the proposed models can also be modified. The program allows for the full exploitation of the simulation capabilities inherent in the calculation

models. For example, it enables loading the specimen at any age, modeling various curing conditions prior to load application, and applying additional load during the test. Figure 2 (left) presents a diagram illustrating the algorithm for defining sustained load, alongside

the results of verification calculations performed using the B3, ACI, and CEB models (right), based on data from studies [26-30]. As can be seen from this table, the average error when using the ACI model reaches 58%. Furthermore, when evaluating individual experiments, the error can reach 100% or more. This assessment was conducted for each model

using data from 17 known experiments performed by various researchers on different concrete mixes.

Figure 3 shows the calculation model of the specimen with different configurations of the finite element mesh, which was used for a sensitivity test. Based on the results of this test, a mesh with an element size of 30×30×30 mm was selected for modeling the prism specimen.

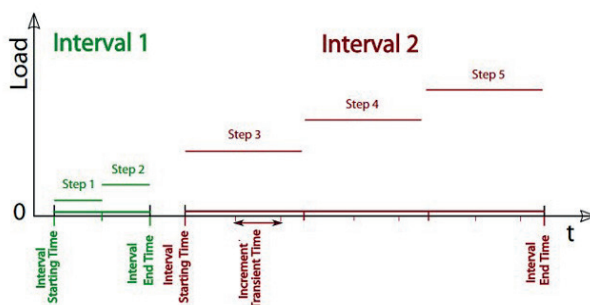
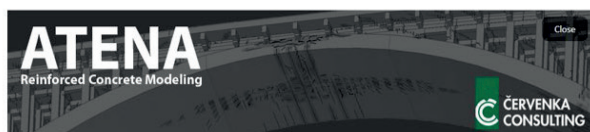


Table 2.1: Coefficients of variation of errors (expressed as percentage) of basic creep predictions for various models.

Model	B3	ACI	CEB
Test data	$\bar{\omega}$	$\bar{\omega}$	$\bar{\omega}$
1. Keeton	19.0	37.5	42.8
2. Kommendant et al	15.3	31.8	8.1
3. L'Hermite et al.	49.4	133.4	66.2
4. Rostasy et al.	15.2	47.6	5.0
5. Troxell et al.	4.6	13.9	6.2
6. York et al.	5.6	37.7	12.8
7. McDonald	6.9	48.4	22.2
8. Maity and Meyers	33.8	30.0	15.7
9. Mossiosian and Gamble	18.6	51.5	47.3
10. Hansen and Harboe et al. (Ross Dam)	14.1	51.2	31.1
11. Browne et al. (Wylfa vessel)	44.7	47.3	53.3
12. Hansen and Harboe et al. (Shasta Dam)	22.7	107.8	43.1
13. Brooks and Wainwright	12.6	14.9	15.4
14. Pirtz (Dworshak Dam)	12.5	58.2	32.5
15. Hansen and Harboe et al. (Canyon ferry Dam)	33.3	70.2	56.9
16. Russell and Burg (Water Tower Place)	15.7	19.3	31.5
17. Hanson	14.1	63.3	12.1
$\bar{\omega}_{all}$	23.6	58.1	35.0

Figure 2. Algorithm for modelling loading regime in creep analysis using ATENA software (left), comparison of various creep models with respect to experimental data (right)

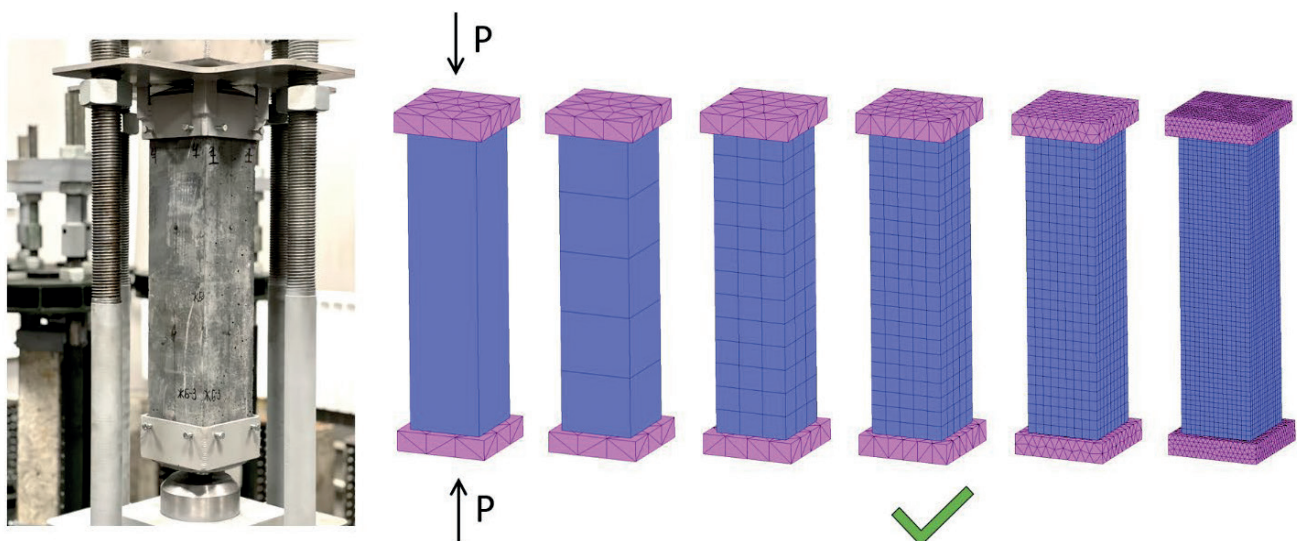


Figure 3. Finite element model of the tested specimen

RESULTS

Following the preparation of the computational model for a concrete prism specimen with dimensions of 150×150×600 mm as a standard specimen for creep tests according to GOST 24544-2020, restrained between two support plates with axial load transfer (simulating load application via a steel ball in a spring-loaded setup), a series of numerical analyses was performed. These analyses predicted creep deformations using four distinct models: MC 2010 (the current Model Code model), B3 (the most widely used creep model globally at present, proposed by Bažant in 1994), B3 improved (the latest enhanced B3 model, which allows for a greater number of input parameters, particularly for better accounting of early-age shrinkage), and ACI-78 (the now-outdated model from the American Concrete Institute). The 1978 ACI model was included in the comparison to provide a general assessment of the applicability of models from the 1970s and 1980s to modern modified self-compacting high-strength concretes. In this context, the calculation results obtained with this model indirectly reflect the

applicability of the domestic model from the 1984 Recommendations for Considering Shrinkage and Creep of Concrete. A direct verification of this latter model in any computer software is impossible because all advanced software packages capable of three-dimensional modeling of long-term concrete tests are foreign (e.g., Ansys, ATENA, Abaqus) and lack integration with Soviet and Russian scientific developments and regulatory documents. Figures 4-6 present the results of the computer-predicted creep deformations according to the considered models for humidity levels of 20%, 60%, and 90%. For ease of comparing the experimental and calculated curves, the deformation values are given in absolute terms. Next to the model’s name, the percentage deviation from the experimental results is indicated. Data for the modified model based on B3 are labeled "modify" on the graphs; the modifications to the B3 model were implemented by adding a set of coefficients to achieve the best possible fit between the modified model and the experimental results obtained under normal humidity conditions.

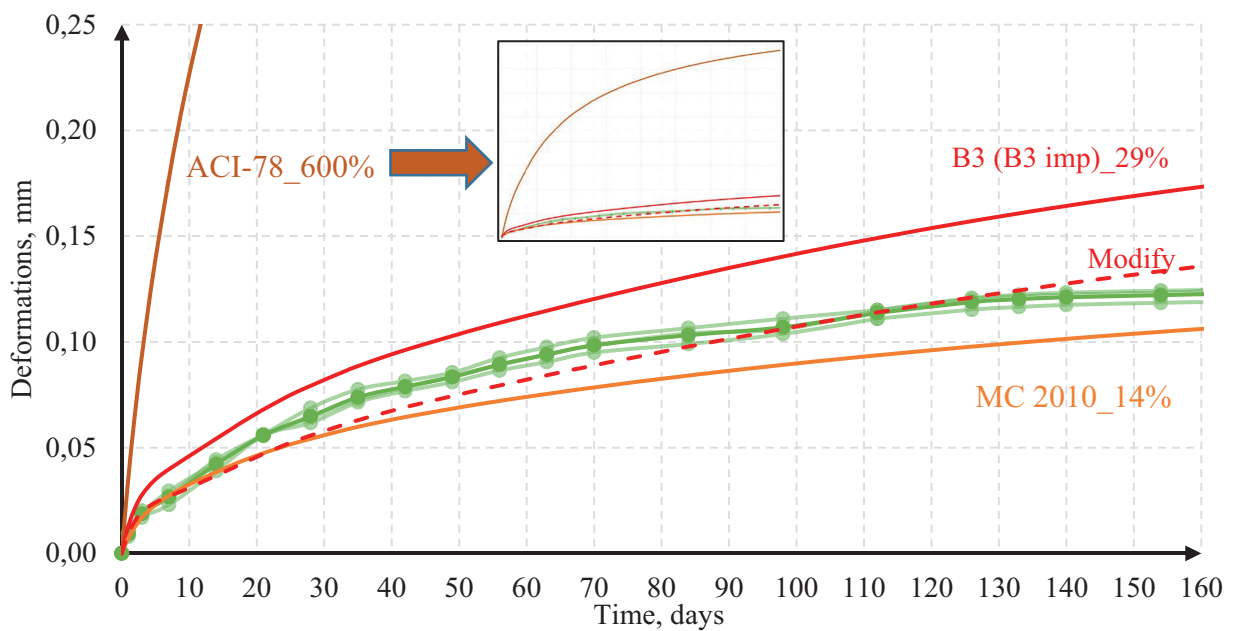


Figure 4. Calculated and experimental creep deformations at normal humidity conditions

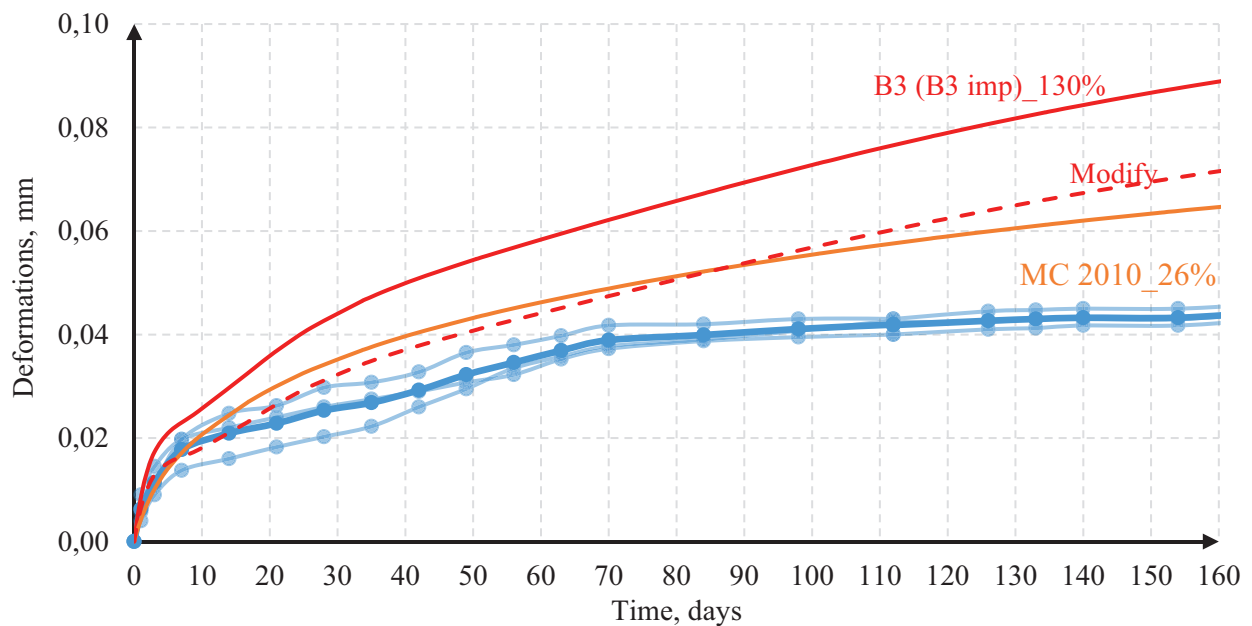


Figure 5. Calculated and experimental creep deformations at high humidity conditions

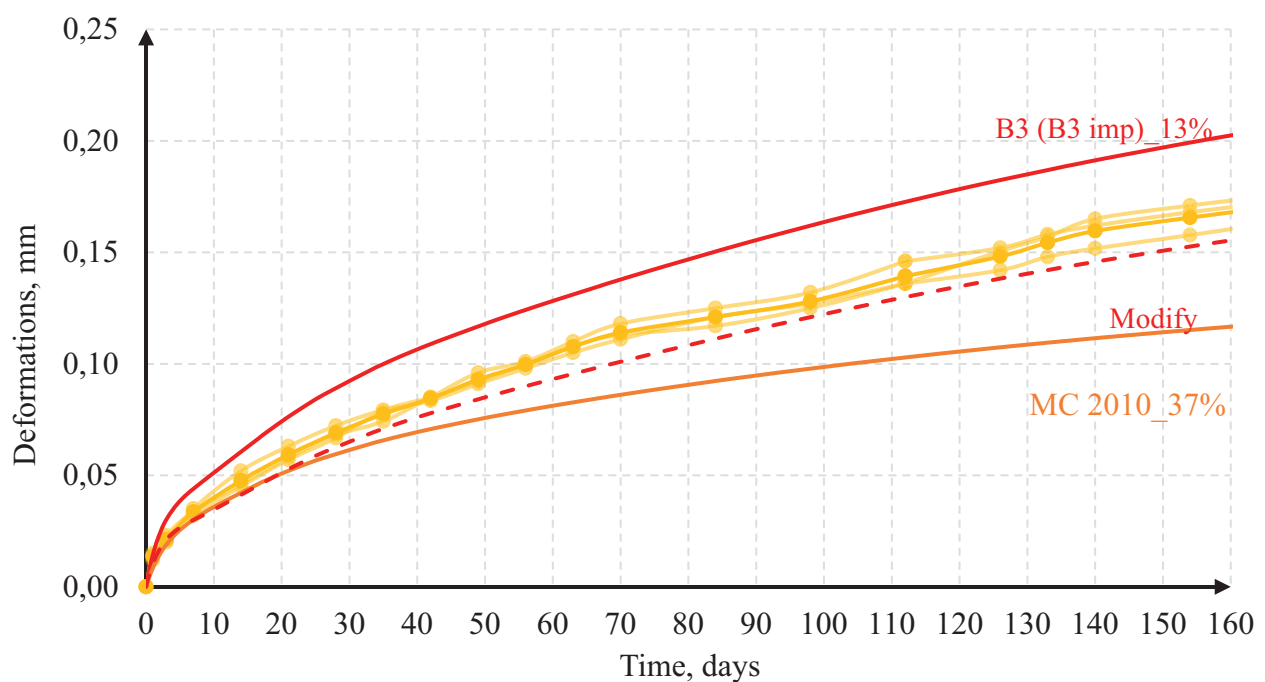


Figure 6. Calculated and experimental creep deformations at low humidity conditions

As can be seen from the calculation results, the direct application of any of the considered models for predicting the creep of modern concretes can lead to significant errors. Models from the 1970s and 1980s, exemplified by the ACI-78 model, are entirely inapplicable.

Another noteworthy observation is that when simulating the experiment in a high-humidity environment, all models showed a decreased level of agreement with the experimental data. It should also be noted that the results from the B3 model and the B3 improved model were virtually

identical. This is because the main enhancements in the more recent model are designed to more accurately capture concrete deformation during the first few months after loading. However, in the experiment under consideration, the specimens were loaded at the age of 88 days, which completely nullified the new algorithms of the B3 improved model. Furthermore, the experimental data recorded in normal and high-humidity conditions indicate an earlier stabilization (attenuation) of creep deformations—a phenomenon frequently observed in high-strength modified concretes—which none of the considered models account for.

The most significant outcome of this modeling effort, however, is the fact that the same model exhibits varying degrees of error under different humidity conditions. The creep curves that were closest to the experimental results were not consistently from a single model; this was also true for the modified model based on B3. Although this modified version was calibrated using data from normal humidity conditions, it showed considerable deviations from the experimental results in a high-humidity environment.

After performing these calculations with different models and ultimately selecting the one that most closely (perhaps after specific modifications) describes the experimental curve under the required temperature and humidity conditions, the software complex can be used to model long-term experiments of any complexity under various stress-strain states. However, the verification of any additional parameters is absolutely essential.

For example, if it is necessary to simulate a creep test under tension on a computer, but specialized lever-type testing machines are unavailable (such setups are currently very rare; according to the author's information, such tests within the Russian Federation can only be conducted at the Donbas National Academy of Civil Engineering and Architecture, where they have been preserved), it is possible to conduct a long-term verification test on concrete beam specimens under bending. Since the beams operate without crack-

ing—part of the beam is compressed while another part is tensioned—this can be done in accordance with Appendix E of GOST 24544-2020. The chosen creep model could then be further modified if necessary.

Consider another example: modeling triaxial long-term compression. This type of stress-strain state is relatively rare, but the construction projects for which experimental studies of concrete creep are typically undertaken are unique and extremely complex. In such structures, accounting for the actual stress-strain state under sustained loads in their structural elements can be critically important. Currently, there are no facilities in Russia for determining creep under triaxial compression (only a single such setup existed in the entire USSR). However, it is possible, for instance, to conduct long-term tests under biaxial compression. The capability for such testing exists at the Gvozdev Research Institute of Concrete and Reinforced Concrete (NIIZHB), and tests on high-strength concrete are currently underway there, with results to be published soon.

The importance of such additional verification can be demonstrated through computer modeling of biaxial compression in the ATENA software complex. Two additional distribution steel plates were added to the sides of the previously used model of a 150×150×600 mm concrete prism, which already had top and bottom distribution plates. These side plates were used to apply lateral pressure. Depending on the magnitude of friction at the interface between the side steel plates and the concrete prism, the results will vary significantly. Figure 7 shows the creep curve for biaxial compression in the limiting case where the steel plate is rigidly connected to the concrete. In such a scenario, the plate can absorb a portion of the compressive stresses from the longitudinal load, potentially leading to underestimated total creep deformations. The true interface condition that must be incorporated into the computational model for such an experimental setup can only be determined through physical testing.

A simplified approach could involve conducting a short-term biaxial compression test, simulating

it on a computer, calibrating the interface parameters based on that short-term test, and then using the calibrated model to simulate long-term tests. The result obtained this way would certainly be more accurate than one with no additional verification, but it could still differ somewhat from a real long-term biaxial compression test. The flowchart presented in Figure 8 illustrates the

recommended procedure for computer modeling of concrete creep under complex stress-strain states. Actions performed on the computer are shown in dark blue, while the experimental part of the work is shown in light blue. The more comprehensive this experimental part, the more accurate the final result will be.

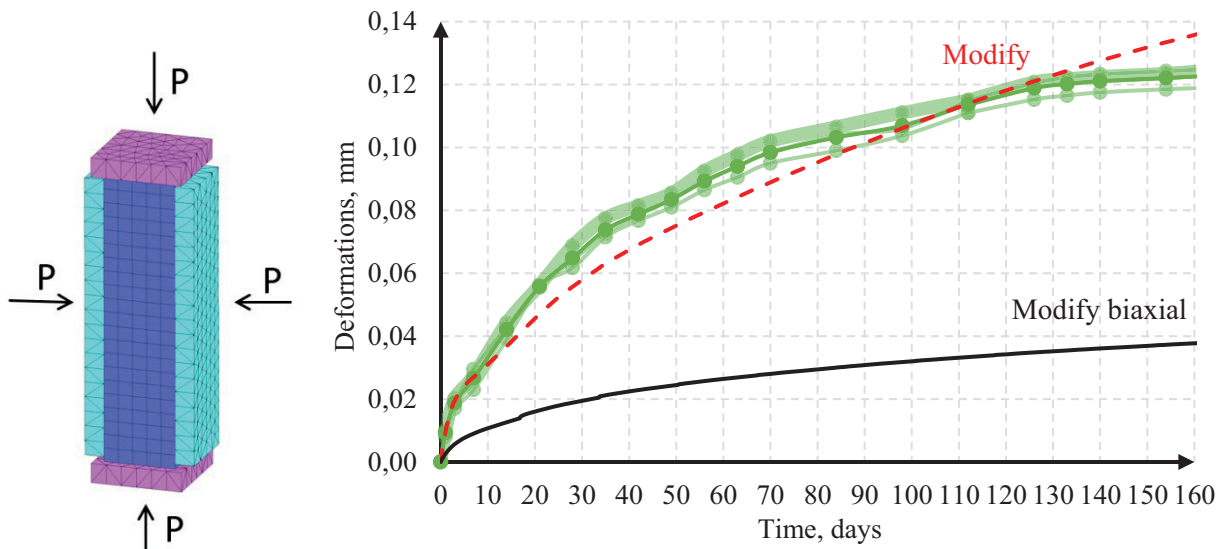


Figure 7. Calculated and experimental creep deformations at low humidity conditions

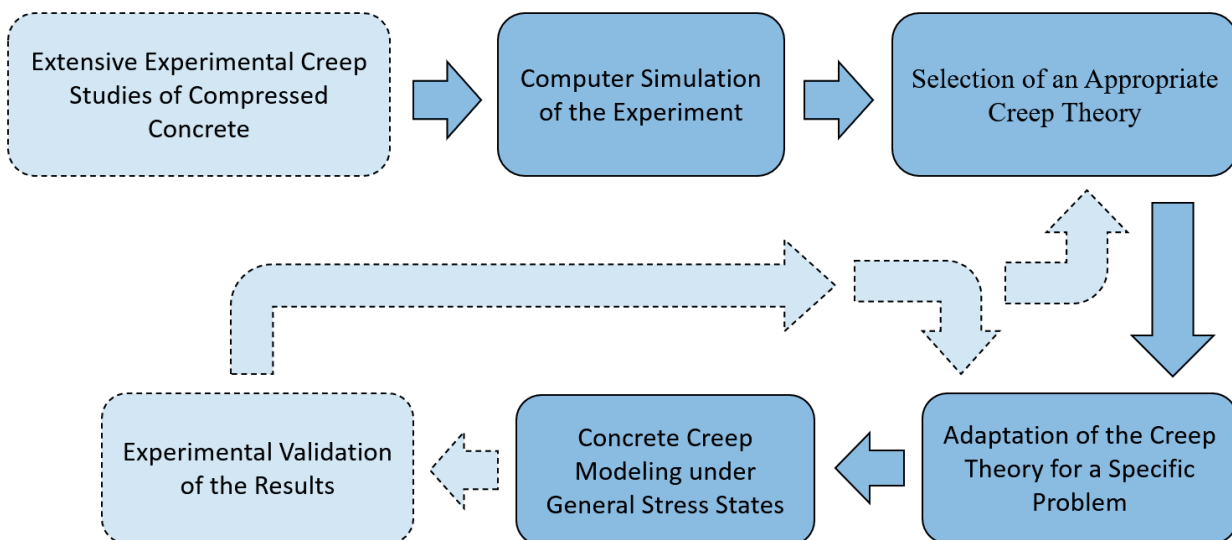


Figure 8. Flow-chart of the algorithm for concrete creep modelling at complex stress-strain state

CONCLUSIONS

Based on the results of the conducted work, the following conclusions can be drawn:

Using modern software, it is possible to predict concrete creep deformations based on advanced calculation models. When employing the B3 and Model Code 2010 models, the deviations from

experimental results obtained under normal humidity conditions (tests according to GOST 24544-2020 and corresponding international standards) were within 30% – which is considered an acceptable result for predicting long-term deformation.

Models from the 1980s, when applied to modern high-strength modified self-compacting concretes, can produce significant errors. For instance, using the ACI-78 model in calculations resulted in a deviation of 600% compared to experimental data. This indicates that predicting concrete creep processes using classical theories, which form the basis of current Russian codes and, to some extent, some foreign standards, can lead to critical inaccuracies. This pertains specifically to the Recommendations for Considering Shrinkage and Creep of Concrete from 1984, which currently remain the only regulatory document allowing for the prediction of creep deformations, as these recommendations have neither been reissued nor officially revoked.

Even the most up-to-date creep models, without modification for a specific experiment, can yield considerable errors. When using the three aforementioned theories (B3, MC 2010, ACI-78), the range of deviations varied from 13% (under reduced humidity) to 130% (under increased humidity). This is corroborated by the verification experiments conducted by the developers of these models, shown in Figure 2, where deviations ranging from 23% to 58% were considered acceptable outcomes.

The modification of creep models should be performed not only for a specific concrete mix composition but also for the specific temperature and humidity conditions of the test. A model modified based on normal humidity data can produce substantial errors when applied to conditions of reduced or increased humidity. This also applies to various loading scenarios that differ from standard tests according to GOST or international standards.

Prior to computer modeling of complex stress-strain states in any structural elements, besides verifying the creep models on simple prism spec-

imens under the relevant temperature and humidity conditions, the boundary conditions must also be verified. An example is the friction from lateral confinement plates when simulating biaxial or triaxial long-term experiments. In the case of lateral confinement, the distribution plates generating this pressure can act as an additional restraining factor against the vertical compressive forces, which can significantly influence the final result.

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