# Development of quality control methods for measurements and testing concrete structures

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**Abstract.** The development of building materials, structures, calculation and design methods, technologies leads to a significant lag in quality control methods, in particular, concrete. Modern control methods cannot guarantee the level of reliability of buildings and structures under construction. The standards for designing and controlling the compressive strength class of concrete, which are controlled according to various schemes, cannot meet the requirements for reliability during construction and operation. Goal. Give recommendations on the use of various concrete classes to ensure the required level of reliability and reliability of critical structures. Methods and materials. Standard concrete samples of classes B 30,50,100 in the form of 150 mm cubes were used as materials. Methods for estimating random variables for the load-bearing capacity and the load effect on the structure are used. Results. Different classes of concrete in terms of compressive strength provide different safety margins. With an increase in the concrete class, the safety factor increases, which ensures more efficient use of high-strength concretes in construction practice in terms of reliability. The probability of failure increases as the concrete class increases, which is due to different safety factors as the class increases. Practical significance. The development of control methods contributes to the level of development of engineering and technology of design and construction. The conducted research will improve the accuracy and quality of measurements and tests in the control of building materials and structures, even when using destructive methods.

## 1 Introduction

The current state of the construction industry requires a revision of the approach to quality control of construction products. This necessity arose in connection with the active development of both new technologies in the field of construction materials science and the emergence of new building materials, primarily related to the multicomponent nature of their compositions. The development of the industry of building materials, structures, calculation and design methods, modeling requires a more attentive attitude to the principles of quality control. Existing approaches cannot meet the requirements of

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sufficient guaranteed reliability and durability of buildings and structures under construction.

The problem is the inability to calculate and calculate numerical reliability indicators based on the properties of materials and structures obtained from real measurements and tests. The method of limit states or partial reliability coefficients used in calculations and design is a semi-probability method. It does not allow you to guarantee the level of reliability and confirm the results of technical control [1, 2]. In the European standards EN1990, it is assumed to switch to the design and calculation of structures, taking into account the required level of reliability according to the indicator "permissible probability of failure [3]". The basic principles of structural reliability are described in the international publications EN 1990 [4] and ISO 2394 [4]. The design must meet certain requirements during the expected service life, with an appropriate degree of reliability and economy [5]. The first requirement is the ability of the structure to withstand the load that can be applied during construction and operation. During the operation of structuresвыполняются, various works may be performed and external factors may affect them. The second requirement for building structures is to maintain suitability for the assigned function. The third requirement is to ensure the reliability of structures. Structural reliability covers areas such as structural load-bearing capacity, serviceability, and durability.

## 2 Materials and methods

Methods for analyzing probability distributions of systems of random variables are used. This approach is based on an assessment of the load-bearing capacity, the load effect on the structure, and the material used. They are accepted as random variables. Depending on the nature of the design, environmental conditions, and applied impacts, we can distinguish the following types of errors or uncertainties inherent in design and calculation methods [6]:

- random nature of external and climatic influences, material properties, and geometric parameters.
- limited amount of raw data for calculation and modeling.
- uncertainty of estimation using load-bearing capacity and impact models due to simplification of calculation models;
- inaccuracy in the description of operational requirements.
- gross errors in the design, control, construction and operation of the structure;
- measurement, testing, and control errors.
- lack of knowledge about the behavior of materials and some impacts in real conditions.

The random nature of errors (uncertainties) cannot be eliminated. They should be taken into account when planning and controlling construction. The load-bearing capacity of the structure randomly depends on the strength of the material, uniformity, deformability, geometric dimensions, reinforcement parameters, and other characteristics, each of which is a random variable and does not correlate with the others. The probability density distribution of these characteristics is assumed to be normal, since it is assumed that this will be true for a sufficiently large number of observations. The development of calculation methods and the transition to probabilistic methods implies a guarantee of the level of reliability of the constructed structures [1, 7].

The most important characteristic is the probability of failure of structures under construction, which determines the frequency of adverse conditions. This is determined by the condition of structural indestructibility [1, 7]:

$$\overline{R}-\overline{Q}\geq 0 \tag{1}$$

$$\overline{R}/\overline{Q} = SF \tag{2}$$

where $\overline{R}$ is the generalized structural strength.

$\overline{Q}$ - generalized load.

The "reliability index" characteristic is often used. It is determined by a standard variable distributed according to the normal law, corresponding to the probability of destruction of Pf.

$$\beta = -\Phi_U^{-1}(P_f) \tag{3}$$

where β is a safety characteristic or reliability index.

$$\beta = \frac{\overline{R} - \overline{Q}}{\sqrt{S_R^2 + S_Q^2}} \tag{4}$$

$S_r$; $S_q$- root-mean-square deviation of the strength properties of the structural material and loads.

Coefficients of variation of strength properties are determined by the formulas:

$$v_R = \frac{S_R}{\overline{R}} \tag{5}$$

$$v_Q = \frac{S_Q}{\overline{Q}} \tag{6}$$

Then, the probability of failure is determined by the dependency:

$$P_f = \frac{1}{\sqrt{2\pi}} \frac{\beta^2 - 1}{\beta^3} \exp(\frac{-\beta^2}{2}) \tag{7}$$

The required indicators of the European standards reliability index related to the probability of Pf failure are shown in Table 1.

**Table 1.** Classification of building reliability according to EN [4, 6].

| Reliability classes | Consequences of loss of human lives, economic, social and environmental consequences | Reliability index β | | Examples of buildings and civil engineering structures |
|---|---|---|---|---|
| | | βa for Ta=1 year | βd for Td=50 years | |
| 3-high | Significant | 5.2 | 4.3 | Bridges, public buildings |
| 2-normal | Medium | 4.7 | 3.8 | Residential and office buildings |
| 1 - low | Insignificant | 4.2 | 3.3 | Agricultural structures, greenhouses |

However, guaranteed reliability will not be achieved if there is no accurate and high-quality primary measurement information about the characteristics of material, structures, loads, etc. Collecting primary information, checking it during construction and operation is the task of technical control in construction and quality management systems in construction organizations. One of the most important control and measurement tasks in construction is to control the strength of materials, in particular, concrete.

Influence of control and measurement errors, using the example of concrete strength, we can imagine that assumptions are made that the results of concrete strength control due to systematic and random errors will be in the confidence interval, which affects the guaranteed strength value. The average value of a series of strength tests, on which the concrete class depends, and hence the calculated strength characteristics for groups 1 and 2 of limit states, will be in the interval, corresponding to the root-square arithmetic $mean\ Sx$. A graphical representation of the given hypothesis is shown in Fig. 1.

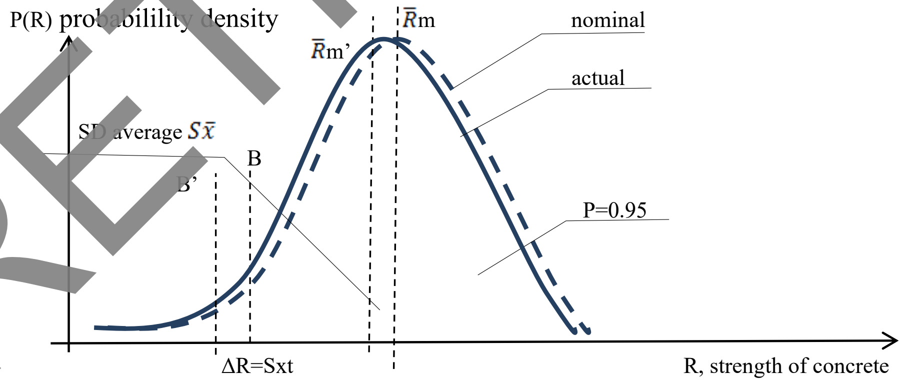

**Fig. 1.** Probability of concrete strength failure due to the error of the direct measurement method.

The value of the failure probability has an inverse relationship with the variability of the strength reserve. The greater the standard deviation of the average, the greater the deviation of the strength from the nominal guaranteed value due to measurement error. A smaller margin of safety due to falling within the minimum limits of the guaranteed interval leads to a decrease in the reliability index β and an increase in the probability of failure.

Improvement of concrete quality control methods will increase the accuracy, convergence and reproducibility of measurement information about the strength and uniformity of the material. If a lot of attention is paid to the accuracy of testing by various strength methods, then the quality of measurements: convergence and reproducibility leave much to be desired. EN12390-3 provides data indicating the importance of evaluating these indicators in accordance with ISO 5725-1 [8, 9].

The research was carried out on such samples as a 150 cube and a 160x320 cylinder. Compression tests were performed. The results for 2 cubic samples were in terms of convergence (repeatability) Sr =3.1%, reproducibility SR=4.7%. The first assessment was carried out in the UK in 1987 based on the results of tests in 16 laboratories. Concrete mixes were made using ordinary Portland cement, sand and coarse aggregate (10-20 mm) of the Thames River Valley. The probability of deviation of the test result by one operator r and in different laboratories R did not exceed the limits of 95% reliability [10]. The results for 3 cylindrical samples were in terms of convergence (repeatability) Sr =2.9%, reproducibility SR=3.1%. The second assessment was made in France during the Round Robin test in 1992 with the participation of 89 laboratories. Concrete mixtures were made on cement CPA55 (C EMI), sand of the river Seine and 20 mm coarse aggregate, the average value is 38.87 MPa. [10]

From the point of view of accuracy, the minimum achievable error can be obtained by standard destructive methods. Using these methods will provide measurement information. It will allow predicting the state and load-bearing capacity of structures throughout the entire life cycle for actively developing calculation and modeling methods.

## 3 Results

According to the authors, the quality of concrete assessed by destructive methods should be the basis of technical control. An important role is played by the shape and size of standard samples, normal hardening conditions and strength gain. Cubes with a base size of 150 mm are accepted as standard samples according to the ISO series documents. All other tests are linked to this type of sample [10]. Currently, for compression tests, standards use such samples as cubes, cylinders d<h, prisms 1:4. EN1390-1 assumes cubes and prisms h=2d, in ASMT [11] cylinders h=2d with a side size from 100 to 200 mm. Therefore, an unambiguous interpretation of the requirements for concretes according to different standards of a comparable class is difficult. For example, B30 and C25 / 30 are comparable at first glance, but analysis of control methods and requirements does not allow us to conclude that they are identical. The idea of concrete strength indicators also differs. In Russian standards, the actual concrete strength class is the estimated value of the concrete strength class calculated based on the results of determining the actual strength of concrete and its uniformity. The actual strength of concrete is the average value of concrete strength calculated from the results of its determination in batches of concrete mix, products or monolithic structures" [12].

In European standards, "the strength of concrete is a basic variable, which, within the framework of the method of partial coefficients, is represented by its characteristic value. The characteristic strength of concrete is the strength value established taking into account statistical variability with a security of 0.95 for a hypothetically infinite sample (population) of test results. The strength of concrete, as a physical quantity, is not determined by some deterministic value, but can only be represented as a continuous random variable (the probability of determining the exact value of such a value is zero).

The direct method is the most accurate destructive method of strength control. The geometrical dimensions of the samples and the breaking force are primary information. Measurement accuracy indicators are also provided for indirect methods. This ensures the accuracy of direct measurements :

– for geometric dimensions $\delta a'_{,b} - 1\%$;

– for the destructive force $\delta_{\delta p} - 2$ %.

The maximum allowable value of the coefficient of variation of concrete strength is 13% in Russian standards, and according to European standards it is equal to 15%. The influence of measurement and control errors significantly distorts the results. An unfavorable combination of events provides a significant increase in the probability of material failure in the structure. Reducing the level of reliability threatens to increase the cost of operation and repairs, an increase in the number of accidents of buildings and structures.

The errors of the indirect method of determining strength depend on the value of the errors of primary measurements, such as the breaking force (P) , geometric dimensions (a,b) and the loading speed (y).

Formula for determining the error of indirect measurement:

$$\delta_R = \sqrt{(\frac{\partial R}{\partial a})^2\ \delta_a^2 + (\frac{\partial R}{\partial b})^2 \delta_b^2 + (\frac{\partial R}{\partial P})^2 \delta_P^2 + (\frac{\partial R}{\partial v})^2 \delta_v^2} \quad (6)$$

where $\frac{\partial R}{\partial a}, \frac{\partial R}{\partial b}, \frac{\partial R}{\partial P}, \frac{\partial R}{\partial y}$ – coefficients of the importance of direct measurements.

The evaluation of the influence of the error during testing by destructive methods in standard samples of the base size on the example of concrete of class B 40 with an acceptable limit coefficient of variation of strength of 0.13 ($vk_\text{K}$) is shown below.

The concrete class is defined by the following dependency:

$$B = \bar{R}(1 - tvk_\text{K}) \quad (7)$$

B – concrete class.

$\bar{R}$ is the average strength according to the test results.

t=1.64 – Student's coefficient at one-sided opening of the interval (P=0.95, n=∞).

The error of the indirect method in determining the strength using a simplified formula will be:

$$\delta_R = \delta \text{a} + \delta b + \delta P + \delta v = 1+1+2+1=5\%$$

Errors in direct measurements are usually specified, except for the speed measurement error. It is accepted approximately 1%.

The results are as follows. The average strength according to the test results of the series is Rm=51.2 MPa, and the breaking force is approximately 1152 kN. The relative error is 5% of the average strength, and the absolute error is equal to the value of the confidence interval: 51.2*0.05=2.56 MPa. At the same time, the" hidden " instrumental strength reduction due to the control error will be: 51.2-2.56=48.64 MPa. Accordingly, the concrete class will be reduced relative to the nominal value to B35, instead of the required B40. The calculation results are in good agreement with the above results of convergence and reproducibility of concrete strength according to European standards.

The authors evaluated the possibility of using concretes of different classes for use in construction with different levels of responsibility, based on the possible random error and different number of samples in order to control the strength of concrete [13].

The reliability index was calculated for three concrete classes B30, B50, and B100, with an acceptable coefficient of concrete variation v=0.13 and a load $Vq_Q$. The value of the coefficient $\nu_Q$ is the same in all calculation scheme.

The root-mean-square deviation of different numbers of measurements was calculated with an acceptable coefficient of variation. The number of measurements (n=2...∞) is accepted both for a single series and for a batch of 2 to 6 tests. At the same time, the series is included in the volume of the batch with a large number of tests, and an infinitely large series, which is consistent with European standards. After determining the minimum allowable and average strength for the batch, the average square deviation of the test series and the average deviation of the average value are calculated.

$$Sx=\bar{R}m\ x\nu \tag{8}$$

$$S\bar{x} = Sx/\sqrt{n} \tag{9}$$

where
Sx – SKR of the measurement series.
$S\bar{x}$ – SKR of the average measurement series.

The possible decrease in Rm due to random error is equal to the average square deviation of the average for a particular concrete class. Reduction of the safety factor in comparison with RI (calculated strength of concrete for class I of group of limit states, equal to the design load at the time of failure) is determined by the formula:

SF= Rm/ RI (10);

Reliability Index:

$$\beta = \frac{SF-1}{\sqrt{(\nu_R^2 SF+\nu_Q^2)}} \tag{11}$$

For the sake of clarity, the calculation results are summarized in table 2.

**Table 2.** Results of application of different classes of concrete for strength control.

| Concrete class B | Minimum strength Rmin, MPa | Coefficient of variation of strength v | Average strength Rm average, MPa | SD measured Sx | numberof samples n | SD average at n | possible decrease in Rm due to random error, MPa | Calculated strength for group 1 LS RI, MPa (t. 6.8 SR) | SF, the guarantor | the reliability Index β | Coefficient of variation in load $v_Q$ | the Probability of failure by reducing the average Pf |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | 30 | 0,13 | 38,13 | of 4.96 | 2 | 3,50 | of 34.62 | 17 | of 2.04 | 3,957 | 0,185 | $3,76x10^{-5}$ |
| | | | | | 3 | 2,86 | 35,27 | 17 | of 2.07 | 4,082 | 0,185 | $2,21x10^{-5}$ |
| | | | | | 4 | of 2.48 | 35,65 | 17 | 2,10 | 4,157 | 0,185 | $1,6X10^{-5}$ |
| | | | | | 6 | of 2.02 | 36,11 | 17 | 2,12 | 4,244 | 0,185 | $1,09x10^{-5}$ |
| | | | | | 12 | 1,43 | of 36,70 | 17 | of 2.16 | 4,358 | 0,185 | $6,53x10^{-6}$ |
| | | | | | 15 | 1,28 | of 36,85 | 17 | 2,17 | 4,386 | 0,185 | $5,73x10^{-6}$ |
| | | | | | 30 | 0,90 | 37,22 | 17 | 2,19 | 4,457 | 0,185 | $4,12x10^{-6}$ |
| | | | | | ∞ | 0 | 38,13 | 17 | 2,243 | 4,628 | 0,185 | $1,84x10^{-6}$ |
| 50 | 50 | 0,13 | 63,55 | 8,26 | 2 | of 5.84 | 57,71 | 27,5 | 2,10 | 4,161 | 0,185 | $1,57x10^{-5}$ |
| | | | | | 3 | 4,77 | 58,78 | 27,5 | of 2.14 | 4,288 | 0,185 | $8,93x10^{-6}$ |
| | | | | | 4 | 4,13 | a 59.42 | 27,5 | of 2.16 | 4,364 | 0,185 | $6,35x10^{-6}$ |
| | | | | | 6 | 3,37 | 60,18 | 27,5 | of 2.19 | 4,453 | 0,185 | $4,21x10^{-6}$ |
| | | | | | 12 | of 2.38 | 61,16 | 27,5 | of 2.22 | 4,568 | 0,185 | $2,45x10^{-6}$ |
| | | | | | 15 | of 2.13 | 61,42 | 27,5 | of 2.23 | 4,597 | 0,185 | $2,1x10^{-6}$ |
| | | | | | 30 | of 1.51 | 62,04 | 27,5 | of 2.26 | 4,669 | 0,185 | $1. 5x10^{-6}$ |
| | | | | | ∞ | 0 | 63,55 | 27,5 | 2,311 | 4,842 | 0,185 | $6,38x10^{-7}$ |
| 100 | 100 | 0,13 | 127,10 | of 16.52 | 2 | 11,68 | 115,41 | 47,5 | of 2.43 | 5,211 | 0,185 | $9,37x10^{-8}$ |
| | | | | | 3 | of 9.54 | 117,56 | 47,5 | of 2.47 | 5,348 | 0,185 | $4,43x10^{-8}$ |
| | | | | | 4 | 8,26 | 118,84 | 47,5 | 2,50 | 5,430 | 0,185 | $2,82x10^{-8}$ |
| | | | | | 6 | 6,75 | 120,35 | 47,5 | of 2.53 | 5,526 | 0,185 | $11,9x10^{-8}$ |
| | | | | | 12 | 4,77 | 122,33 | 47,5 | of 2.58 | 5,650 | 0,185 | $8,02x10^{-9}$ |
| | | | | | 15 | 4,27 | 122,83 | 47,5 | of 2.59 | 5,681 | 0,185 | $6,67x10^{-9}$ |
| | | | | | 30 | 3,02 | 124,08 | 47,5 | of 2.61 | 5,759 | 0,185 | $4,22x10^{-9}$ |
| | | | | | ∞ | 0 | 127,10 | 47,5 | 2,676 | 5,945 | 0,185 | $1,38x10^{-9}$ |

Changes in the reliability index for different concrete classes and different numbers of samples are shown in Figure 2.

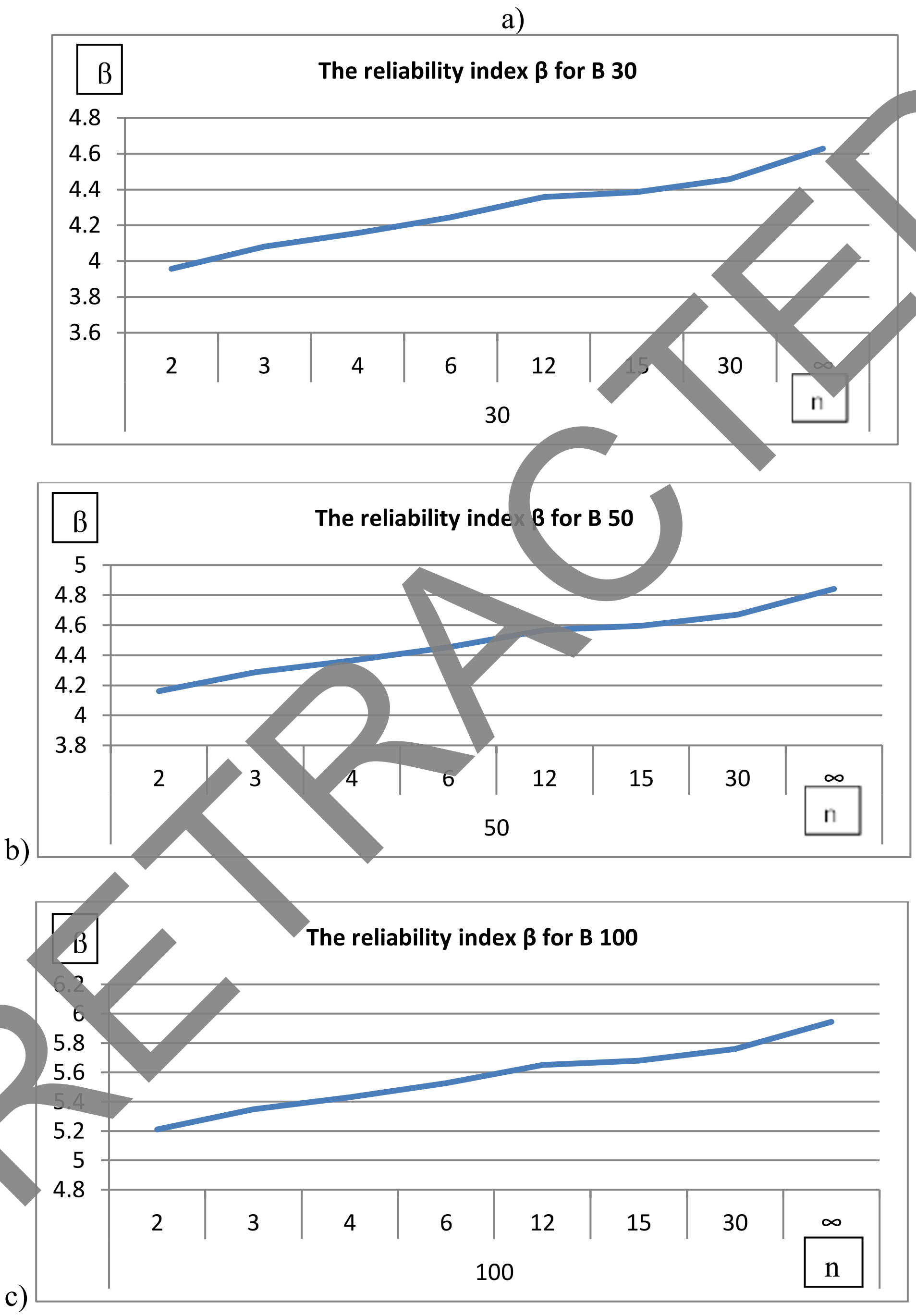

**Fig. 2.** Changes in the reliability index for different number of samples for concrete classes a) B30; b) B50; c) B100.

The results of calculating the minimum and maximum failure probability values for concretes of different classes are shown in Figure 3.

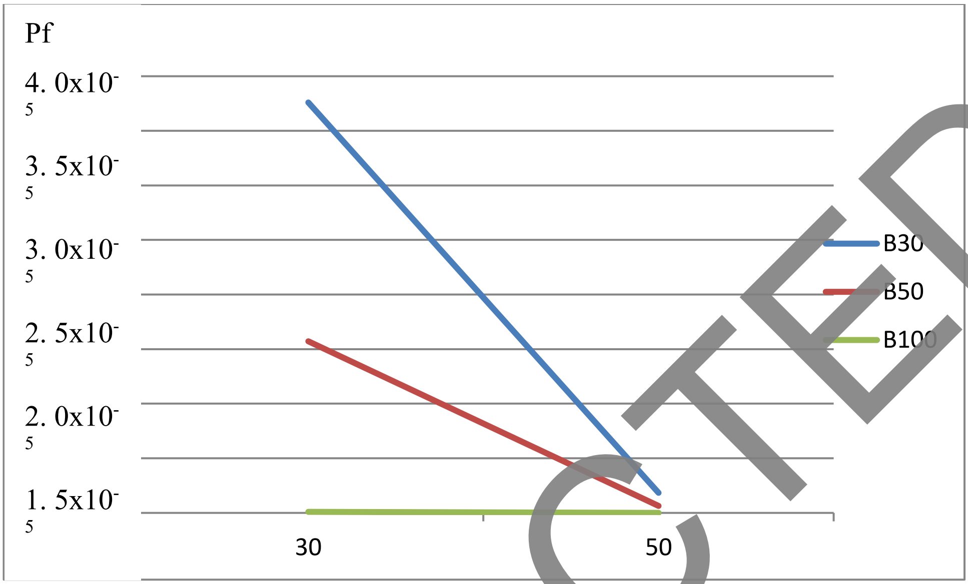

**Fig. 3.** Range of failure probability values for concretes of different classes under boundary conditions for determining strength.

## 4 Discussion

Based on the results described above, the following conclusions can be drawn:

- concrete classes B30 and B50 at v=0.13 cannot ensure the requirements for the reliability index for high-class reliability construction (Table 1). The reliability index indicator is provided for normal construction, including according to European standards;
- concrete class B100 at v=0.13 can ensure the requirements for the reliability index for construction of a high class of reliability under any type of control, including according to European standards;
- probability of failure as it increases the class of concrete increases, which is due to different safety factors as the class increases.

## 5 Conclusions

The development of control methods makes it possible to more effectively approach the design of concrete structures with a given level of reliability. This is reflected in the ratio of the actual strength of concrete and the calculated strength for one group of limit conditions. The Russian standards take into account the results of experimental Graph data. As the strength of concrete increases, the proportion of cubic and prismatic strengths, which are the basis for the calculated characteristics of concrete, decreases. When using high-strength concretes, the safety factor increases, and the probability of concrete failure in structures decreases. The problem with increasing the strength of concrete is an increase in the fragility of the material, which leads to the possibility of sudden destruction. Therefore, it is necessary to simultaneously increase both the strength of concrete and other physical and mechanical characteristics.

The authors recommend to solve the problem of construction with a high and normal level of reliability, the authors recommend improving the accuracy and quality of measurements and tests, including when using destructive methods in standard samples. It is necessary to strive for uniformity of concrete properties, which is achieved by increasing manufacturability and internal control.

The development of control methods should correspond to the level of development of engineering and technology of design and construction. The delay in control methods serves as a deterrent to the development of the building materials industry.

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