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Minimizing risks in conformity assessment of rebar in construction laboratories

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Abstract – The risks of making decisions on conformity assessment are analyzed using the example of rebar from a large Uzbek manufacturer and a small business. An interlaboratory comparison was organized using the capabilities of an accredited proficiency testing provider for the following indicators: cross-sectional area, yield strength and tensile strength of rebar (GOST 12004). The indicators are measured by a fixed value of steel density - 7850 kg/m^3. An analysis of the risks of using the measured and fixed value of rebar density for these indicators is carried out. An improvement of the measurement method, an analysis of the contributions to measurement uncertainty and the value of scatter are proposed. Further prospects for the development of certified reference material for the above indicators are also proposed

I. INTRODUCTION

Ensuring safety in construction is directly linked to the quality of the materials used. In the Commonwealth of Independent States (CIS) countries, and in particular in Uzbekistan, the requirements for rebars are established by GOST 34028 [1], and the methods for testing them are GOST 12004 [2]. To assess the quality indicators of rebar, such as “tensile strength”

$$\sigma_{\text{в}} = \frac{P_{max}}{F_0} \quad (1)$$

and “yield point”

$$\sigma_{\text{т}} = \frac{P_{\text{т}}}{F_0} \quad (2)$$

proceed from F_0 - the initial cross-sectional area, determined by the following formula (clause 1.4 of GOST 12004):

$$F_0 = \frac{m}{\rho * l} \quad (3)$$

where in the formulas (1), (2) и (3) m - mass of the test sample, kg;
l - length of the test sample, m;
ρ - density of steel, 7850 kg/m^3;
P_{max} and $P_{\text{т}}$ – load corresponding to rupture and yield of the sample, N.

It should be noted that the actual density of the rebar differs significantly from 7850 kg/m3.

Also in the international standard EN ISO 6892-1 [3] the initial cross-sectional area S_0 can be determined from the mass of a known length and its density using auxiliary formulas:

$$S_0 = \frac{1000 * m}{\rho * L_t} \quad (4)$$

where m - is the mass of the test sample in g;
ρ - is the density of the test sample material, in g/cm3;
L_t - is the total length of the test sample in mm.

Accordingly, if the samples are assessed based on (3) and (4), then metrological traceability and the validity of the test results can be challenged.

In model methods, the assessment of measurement uncertainty is carried out using the GUM Guide [4].

According to [3], when measuring the cross-section, it is necessary to ensure an accuracy of 1%. However, taking into account the contributions to the measurement uncertainty of the cross-sectional area according to models (3) and (4) leads to a decrease in the validity of the measurement results.

For example, in the section “Examples of calculation and assessment of measurement uncertainty” of the website of the Kyrgyz Accreditation Center “Assessment of uncertainty for determining the yield strength and tensile strength of reinforcing steel” [5], the uncertainty of the sample density is given as *U = 200* kg/m^3, with *k = 2, P = 0.95*.

This value can be based on OIML R 111-1 [6]. Because in [6] the uncertainty of the density of steel weights is given in exactly this way. In this case, the contribution of the expanded uncertainty exceeds 2.5% of the density. This reduces the validity of the results for determining the yield point and tensile strength of the rebar. Therefore, the development of an improved model for measuring the cross-sectional area of the rebar and the uncertainty budget based on this model remains an urgent task.

In GOST 12004, the precision and accuracy of the results of testing the rebars, which is used in monitoring to ensure the validity of measurements, is not regulated, based on this, it is important to reflect the results of precision in the proposed method based on the results of interlaboratory comparisons, as specified in Appendix L of the [3] standard.

When considering the available certified reference materials (CRM) [7], it was found that they are intended only for the mechanical properties of rebar, and the risks associated with determining the cross-section and density during characterization are not described. Evaluation of homogeneity and stability, as well as characterization of reference material (RM) based on the proposed model for measuring the cross-sectional area of rebar, lays the foundation for ensuring the validity of the results and allows minimizing the risk of decision-making when assessing the conformity of rebar.

II. THE STUDY CONDUCTED AND ITS RESULTS

A. Methodology and experiment

In the CIS countries, the outdated GOST 12004-81 standard (originally developed in the former USSR in 1966, re-approved in 1981, and last amended in 1985 and 1990, but still in effect today) is used to conduct mechanical testing of rebar, which, in modern construction conditions, does not meet the requirements of standardization and metrological traceability, and increases the risks when assessing compliance.

In order to study the issue in depth in order to assess the spread and study the validity of the results of these tests, we selected an accredited provider of qualification testing in the Uzbek Center for Accreditation (O‘ZAKK) system [8]. For the qualification tests, more than 60 samples of rebars from each of the two types of manufacturers were prepared: the manufacturer of the first group - a large enterprise that has implemented international quality management system standards (ISO 9001, ISO/IEC 17025); the manufacturer of the second group - a representative of a small business, whose products are freely available on the open market. The selected samples are shown in Figure 1.

Fig. 1. Research samples

In order to evaluate the homogeneity of the rebar in terms of cross-sectional area, ultimate strength and yield strength, 20 samples were tested. The homogeneity assessment was carried out based on the international standard ISO 13528 [9]. The values of the between-sample standard deviation (SD) are shown in Table 1:

Table 1. Results of homogeneity assessment (betw.sample)

Sample	Indicator Name	between-sample SD, s_s
First group	cross-sectional area F_0, mm^2	0.343
	tensile strength σ_B, N/mm^2	0.792
	yield point σ_T, N/mm^2	0.29
Second group	cross-sectional area F_0, mm^2	2.276
	tensile strength σ_B, N/mm^2	0.892
	yield point σ_T, N/mm^2	0

As it can be seen from the above results, when assessing the homogeneity of samples from group 1 - a manufacturer that has implemented ISO 9001 and has an accredited testing laboratory according to ISO/IEC 17025 - the homogeneity indicators are within the permissible measurement deviations and are minimal. While for samples from group 2, provided by a small business representative, the SD values are significantly higher, which requires separate consideration in comparative analysis and affects both the test results and the risk of decisions taken.

After obtaining the information on the dispersion values characterizing the homogeneity, the selected samples were sent by the proficiency testing provider to 14 accredited laboratories for the purpose of conducting comparative tests according to ISO 17043 [10], to evaluate the performance characteristics of the test method. The average values ($\bar{y}$) of two or three parallel tests submitted by the laboratories for the above indicators are given in Table 2.

Based on ISO 5725-2 [11], the values of SD were determined, and according to ISO 5725-6 [12], the repeatability limit and reproducibility limit were estimated and are presented in Table 3.

The obtained results show that the materials of group 1 in this case also demonstrate minimal deviations, which are within the permissible measurement error, whereas the materials of group 2 showed unsatisfactory results due to significant variation in both the indicators themselves and the results obtained by different laboratories.

As a solution to this problem, the hydrostatic method is recommended, which is capable of providing metrological traceability when measuring the cross-section of rebar and is economically accessible when organizing tests. Figure 2 shows the basic diagram of determining the volume/density/cross-sectional area of rebar.

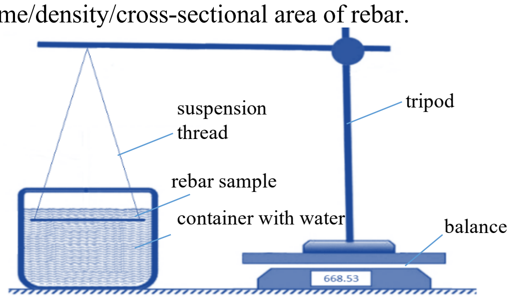

Fig. 2. Schematic diagram of the hydrostatic principle for measuring the volume/density/cross-sectional area of rebar

Table 2. Summary of laboratory results for interlaboratory comparison

Test indicators	Average results by labs ($\bar{y}$)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
First group														
F_0, mm^2	202.2	201.3	202.2	202.0	202.3	202.2	202.3	201.3	202.2	201.9	201.9	201.0	202.0	202.5
$\sigma_{\text{в}}$, N/mm^2	728.4	688.4	733.0	697.4	719.7	701.6	698.1	688.2	731.9	718.1	722.5	680.3	711.2	–
$\sigma_{\text{т}}$, N/mm^2	472.6	436.4	491.0	437.4	–	444.4	438.9	422.4	478.0	–	–	439.4	450.5	–
Second group														
F_0, mm^2	177.5	176.5	179.3	178.7	179.0	176.9	179.5	179.0	181.7	177.5	184.6	–	–	180.9
$\sigma_{\text{в}}$, N/mm^2	723.8	676.5	614.7	689.4	690.7	687.6	677.9	669.9	741.1	711.6	712.0	–	–	655.5
$\sigma_{\text{т}}$, N/mm^2	477.9	434.7	402.3	435.7	–	439.8	429.7	419.5	486.1	569.5	–	–	–	581.5

Table 3. Results of the method operating indicators (r, R) determined in the interlaboratory comparison

Sample	Test indicators	r	R
First group	F_0, mm^2	1.82	1.93
	$\sigma_{\text{в}}$, N/mm^2	14.45	53.23
	$\sigma_{\text{т}}$, N/mm^2	16.59	65.04
Second group	F_0, mm^2	9.36	9.62
	$\sigma_{\text{в}}$, N/mm^2	23.14	98.92
	$\sigma_{\text{т}}$, N/mm^2	21.08	180.31

That is, when using the proposed method, the initial cross-sectional area (S_0) of the steel rebar is determined by the following formula:

$$S = \frac{m_1 - m_2}{\rho * l} \tag{5}$$

where m_1 is the mass of the test sample in air, mg;

m_2 is the mass of the test sample in distilled water at 20 °C, mg;

l is the length of the test sample, mm;

ρ is the density of distilled water at 20 ° C, mg/mm^3

Fig.3. Practice of hydrostatic measurement of volume/density/cross-sectional area of rebar

In order to assess the effect of using actual or fixed values of the rebar cross-sectional area on the results, S_0 of the rebar of the first and second groups was additionally determined using the hydrostatic method. Figure 3 shows a drawing of the study for determining S_0.

The results of the study were obtained by measuring the cross-sectional areas of the rebar of the first and second groups according to models (3) and (5) with subsequent calculation and comparison of the ultimate strength (1) and yield strength (2) of the corresponding samples. The results obtained are presented in Table 4.

Table 4. Comparative table of mechanical properties of rebar obtained using a fixed density value (7850 kg/m³) and the hydrostatic weighing method.

Method	Test indicators	First group	Second group
GOST 12004	F_0, mm^2	202.1	178.7
	$\sigma_{\text{в}}$, N/mm^2	648.8	630.9
	$\sigma_{\text{т}}$, N/mm^2	399.4	395.0
hydrostatic method	S, mm^2	203.7	180.6
	$\sigma_{\text{в}}$, N/mm^2	636.1	615.5
	$\sigma_{\text{т}}$, N/mm^2	388.8	372.3
Comparison result, %	$\frac{S}{F_0}$, %	100.8%	101.1%
	by tensile strength	102.0%	102.5%
	by yield strength	102.7%	106.1%

As can be seen, the differences in the mechanical properties of the rebar are from 2 to 2.7 % for the samples of the first group and from 2.5 to 6.1 % for the samples of the second group. This, in turn, leads to a decrease in the validity of the measurement results when determining each indicators. Thus, the practical application of the results obtained using model (3) is questionable.

B. Analysis of the validity of measurement results

As noted above, when analyzing the uncertainty estimates of measurement results (see Table 5 and Fig. 4) of mechanical properties obtained in 14 laboratories, a decrease in the consistency of decision-making on compliance with a certain specificity is observed, which is due to the lack of a standardized methodology for assessing and taking into account contributions to uncertainty.

Table 5 and Figure 4 present the values of tensile strength and the corresponding uncertainties for the samples of the first group in the form of a diagram ordered in ascending order of the results obtained by the laboratories.

Table 5. Measurement results and uncertainty.

Laboratory ID	σ_B, N/mm^2	U (k = 2, $P \approx 0{,}95$), N/mm^2
12	680.3	0.9
8	688.2	2.5
2	688.4	5.6
4	697.4	2.3
7	698.1	10.0
6	701.6	2.5
13	711.2	17.5
10	718.1	1.8
5	719.7	2.5
11	722.5	0.0
1	728.4	5.6
9	731.9	0.3
3	733.0	16.9

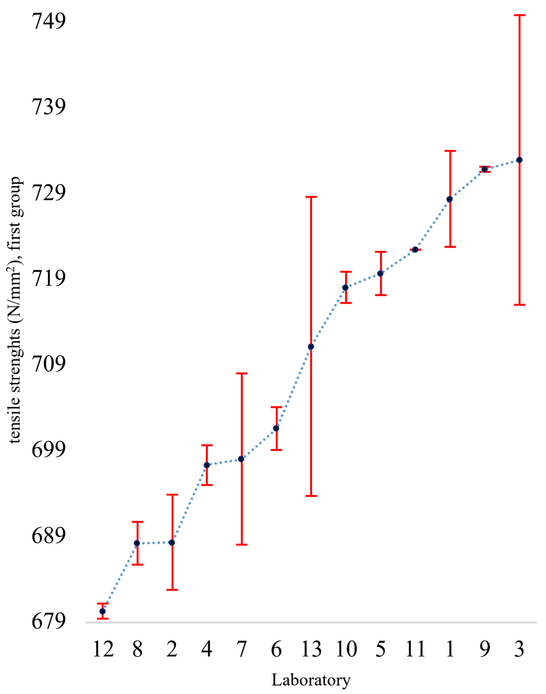

Fig. 4. Analysis of measurement results and uncertainties of laboratory participants in ascending order

As can be seen from Table 5 and Figure 4, laboratories use different approaches when taking into account contributions to the uncertainty assessment. This, in turn, leads to discrepancies when making decisions on compliance. Such circumstances necessitate the improvement of [2], as well as the clarification of the main sources of uncertainty in the assessment of measurements.

The most significant contributors to uncertainty include the following factors:

- homogeneity of samples;
- uncertainty associated with the measurement of the geometric dimensions of the sample;
- uncertainty arising from the calibration of the tensile testing machine and its drift over time;
- temperature sensitivity of the sample during testing;
- temperature of distilled water when using the hydrostatic method;
- loading rate during testing;
- duration and frequency of parallel tests;
- the method of gripping the test piece and the axiality of the application of the force [3];
- human factor and possible software errors;

and other sources.

It should be noted that similar categories of uncertainty sources are discussed in Appendix K of ISO 6829-1:2019, which confirms the relevance of an integrated approach to taking them into account when conducting tests and subsequent interpretation of the results.

The results of some laboratories show that the uncertainty values differ by several times. In general, in order to reduce the uncertainty in the process of its assessment, comparisons were made based on the model (3) and (5) using the GUM approach for assessing the sensitivity coefficient of partial derivatives, as well as on the basis of the correction specified in the literature EURACHEM/CITAC CG-4 [13] (see Appendix E.2 in the spreadsheet). These estimates were compared in Table 6. And for comparison, the results of measurements of the cross-sectional area of the rebar of the first group obtained using the hydrostatic method were used.

The comparison results show that the uncertainty obtained on the basis of partial derivatives and spreadsheets differs by up to 1 %. This means that when characterization RMs of rebar for construction laboratories, it should be taken into applied the spreadsheet method.

In addition, when evaluating using formula (5) based on the hydrostatic method, and considering the correlation between the masses and the differences between samples, the uncertainty obtained using the fixed density value according to formula (3) is 1.7 times greater (corresponding to a 70% increase) compared to the uncertainty obtained using the hydrostatic measurement method.

It should be particularly noted that the expanded uncertainty for the rebar density of 7850 kg/m^3, according to the reference [5] and [6], is 200 kg/m^3.

The uncertainty of the density of distilled water used in the hydrostatic method ranges from 0.1 to 1 kg/m^3 [14]. It is for this reason that there is a 70 % difference between the uncertainties obtained using these two methods.

Table 6. Comparative analysis of uncertainty assessment using the differential method and the spreadsheet method.

Name of row	Differential method (based on GUM)	Result	Spreadsheet method (according to EURACHEM/CITAC CG-4, Appendix E.2)	Result
Model	$S_0 = \frac{m_1 - m_2}{\rho * l}$			
Sensitivity coefficient for sample mass in air	$c_{m_1} = \frac{\partial S_0}{\partial m_1} = \frac{1}{\rho * l}$	*2 [g]*	$\frac{\partial S_0}{\partial m_1}(m_1; m_2; \rho; l) = \lim_{\Delta m_1 \to 0} \frac{S_0(m_1 + \Delta m_1; m_2; \rho; l) - S_0(m_1; m_2; \rho; l)}{\Delta m_1} =$	*2 [g]*
Sensitivity coefficient for sample mass in water	$c_{m_2} = \frac{\partial S_0}{\partial m_2} = -\frac{1}{\rho * l}$	*-2 [g]*	$\frac{\partial S}{\partial m_2}(m_1; m_2; \rho; l) = \lim_{\Delta m_2 \to 0} \frac{S_0(m_1; m_2 + \Delta m_2; \rho; l) - S_0(m_1; m_2; \rho; l)}{\Delta m_2} =$	*-2 [g]*
Liquid density sensitivity coefficient	$c_\rho = \frac{\partial S_0}{\partial \rho} = -\frac{m_1 - m_2}{\rho^2 * l}$	*-0.0002 [g/cm³]*	$\frac{\partial S}{\partial \rho}(m_1; m_2; \rho; l) = \lim_{\Delta \rho \to 0} \frac{S_0(m_1; m_2; \rho + \Delta\rho; l) - S_0(m_1; m_2; \rho; l)}{\Delta \rho} = -\frac{m_1 - m_2}{\rho * (\rho + \Delta\rho) * l}$	*-0.0002 [g/cm³]*
Sensitivity coefficient sample length	$c_l = \frac{\partial S_0}{\partial l} = -\frac{m_1 - m_2}{\rho * l^2}$	*-0.4 [mm]*	$\frac{\partial S}{\partial l}(m_1; m_2; \rho; l) = \lim_{\Delta l \to 0} \frac{S_0(m_1; m_2; \rho; l + \Delta l) - S_0(m_1; m_2; \rho; l)}{\Delta l} = -\frac{m_1 - m_2}{\rho * l * (l + \Delta l)}$	*-0.4 [mm]*
Combined standard uncertainty	*1.918 mm²*		*1.912 mm²*	
Model	$F_0 = \frac{m_1}{\rho_m * l}$			
Sample mass sensitivity coefficient	$c_{m_1} = \frac{\partial F_0}{\partial m_1} = \frac{1}{\rho_m * l}$	*0.261 [g]*	$\frac{\partial S}{\partial m_1}(m_1; \rho_m; l) = \lim_{\Delta m_1 \to 0} \frac{F_0(m_1 + \Delta m_1; \rho_m; l) - F_0(m_1; \rho_m; l)}{\Delta m_1} = \frac{1}{\rho_m * l}$	*0.261 [g]*
Sample density sensitivity coefficient	$c_\rho = \frac{\partial F_0}{\partial \rho_m} = -\frac{m_1}{{\rho_m}^2 * l}$	*-0.000026 [g/cm³]*	$\frac{\partial F_0}{\partial \rho}(m_1; \rho_m; l) = \lim_{\Delta \rho_m \to 0} \frac{F_0(m_1; \rho_m + \Delta\rho_m; l) - F_0(m_1; \rho_m; l)}{\Delta \rho_m} = -\frac{m_1}{\rho_m * (\rho_m + \Delta\rho_m) * l}$	*-0.000025 [g/cm³]*
Sensitivity coefficient sample length	$c_l = \frac{\partial F_0}{\partial l} = -\frac{m_1}{\rho_m * l^2}$	*-0.414 [mm]*	$\frac{\partial S}{\partial l}(m_1; \rho_m; l) = \lim_{\Delta l \to 0} \frac{F_0(m_1; \rho_m; l + \Delta l) - F_0(m_1; \rho_m; l)}{\Delta l} = -\frac{m_1}{\rho_m * l * (l + \Delta l)}$	*-0.411 [mm]*
Combined standard uncertainty	*3.231 mm²*		*3.201 mm²*	

C. Prospects for the production of CRM

Today, when organizing a quality control system for mechanical tests and ensuring the validity of measurement results in accordance with the requirements of the international standard ISO 17025 [15], it is necessary to conduct intermediate checks, calibrate measuring equipment, implement internal and external monitoring procedures, and implement personnel qualification assessment schemes. All these processes require the use of CRMs for mechanical properties. In particular, the availability of CRMs with certified values of such key characteristics of rebar as tensile strength and yield point with a minimum expanded uncertainty is essential for ensuring the quality and traceability of test results. The main problem in the production of CRMs for mechanical properties is the large expanded uncertainty of such samples [7]. Issues related to the development of such CRMs were also considered in [16]. According to ISO 33405 [17], the uncertainty of a CRM for mechanical properties should be estimated based on the following main contributions:

$$u_{\mathrm{CRM}} = \sqrt{u_{char}^2 + u_{hom}^2 + u_{trn}^2 + u_{lts}^2} \qquad (6)$$

u_{CRM} – denotes the standard uncertainty associated with the property value of the CRM;

u_{char} – denotes the combined standard uncertainty contribution from the characterization of the property value;

u_{hom} – denotes the uncertainty contribution from the assessment of homogeneity;

u_{trn} – denotes the uncertainty contribution from the assessment of the stability under transport conditions;

u_{lts} – denotes the uncertainty contribution from the assessment of the long-term stability under storage conditions at the RM producer's premises and the user's premises.

As noted above, there are certain approaches to reducing the uncertainty of the u_{char} property characterization. In particular, when determining the tensile strength and yield point, the main attention should be paid to the following measures to minimize the uncertainty of characterization:

- modification based on model (5) for measuring the cross-sectional area of a sample, allowing to increase the accuracy of determining the load per unit area;
- use of a spreadsheet-based uncertainty calculation method as recommended in the EURACHEM/CITAC guidelines, which provides a more detailed accounting of sensitivities and contributions;
- the use of high-precision scales of a "special" or "high" accuracy class, especially when using the hydrostatic method to determine the cross-sectional area through mass and density;
- use of high-precision testing machines that have undergone calibration with metrological traceability to the international SI, which helps to reduce the contribution of equipment to the overall uncertainty.

The implementation of the specified measures allows to significantly reduce the uncertainty of u_{char} and, as a consequence, to increase the reliability of the certified values of the mechanical characteristics of RM.

In the present study, commercially available rebar samples were used. Despite this, from the point of view of homogeneity, the achieved uncertainty (within 7–8%) can be considered sufficient for the purposes of developing the CRM. To further reduce the uncertainty associated with the homogeneity of u_{hom}, it is advisable to provide for strict quality control as in the manufacturer of the 1st group products, as well as the use of specially selected raw materials with a stable composition.

As for the uncertainty associated with transportation u_{trn} and long-term stability u_{lts} , under the specified conditions of transportation and storage, such contributions can be considered negligible for rebar samples and may not be taken into account in the final assessment.

III. Proposed measures and targeted conclusions

1. In order to increase the validity of the assessment of the characteristics of rebar that depend on the cross-sectional area, an improved mathematical model (5) was proposed, which is fundamentally different in its essence from the models presented in [2] and [3].
2. The developed model (5) allowed to minimize the discrepancy between the uncertainty estimated by GUM and spreadsheets based on increments [13].
3. The evaluation of homogeneity according to model (5) and the application of the proposed model in the certification of rebar "reference material" made it possible to achieve up to a twofold increase in confidence in the certified value compared to previous data [7].
4. The presence of multiple discrepancies in the results of studies indicates the absence of a unified methodology for assessing the uncertainty of measurements in [2]. In this study, a methodology is proposed that is subject to standardization and meets the requirements of [15], taking into account all significant contributions.
5. The use of the mathematical model (5) helps to increase the validity of measurement results, reduce uncertainty and, as a consequence, significantly reduce the risk when making decisions on the compliance of rebars with established requirements.
6. It is proposed to supplement GOST 12004 [2] with the results obtained within the framework of this study, in terms of presenting operational characteristics (repeatability and reproducibility), assessed in accordance with the requirements of [15], as well as according to the methods set out in [11] and [12].
7. In addition, the study demonstrated the practical significance of implementing quality management systems and production control in accordance with ISO 9001 and ISO/IEC 17025 using the example of the test results of the first group facility.

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