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CORRECTION FACTOR FOR HEAVY CONCRETE MIX DESIGN USING LOW-QUALITY AGGREGATES

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Abstract: This study investigates an experimental-analytical approach to improving the accuracy of calculating the nominal composition of heavy concrete using a database of test protocols from NEFU (2015–2025). Particular attention is paid to working with low-quality aggregates – sand with a fineness modulus below 1.4. Significant discrepancies between the calculated and actual concrete compositions were identified, reaching up to ±250 kg/m³. A corrective coefficient linking the cement-to-water ratio (C/W) with the proportion of aggregates is proposed. Its application reduced the error to ±60–150 kg/m³ and improved the convergence of results to 1.5% without loss of strength. It is shown that the strength of concrete incorporating very fine sand (fineness modulus ≤ 1.4) exhibits higher sensitivity to variations in the C/W ratio within a narrow range of 1.3–2.7. The discrepancy between calculated and actual concrete density varies widely, leading to material overconsumption and reducing the reliability of computational mix design methods. An empirical relationship has been established linking the key variable mix parameters (water-cement ratio and aggregate proportion), which can be used as a correction factor. Without the coefficient, the deviation range was 1.8–5.0%, while with its application it ranged from –0.6% to 1.5% without deterioration of concrete mixture properties or physical and mechanical characteristics.

Keywords: heavy concrete, mix design, experimental coefficient, experimental data, C/W ratio, database

ПОПРАВОЧНЫЙ КОЭФФИЦИЕНТ ДЛЯ ПОДБОРА СОСТАВА ТЯЖЁЛОГО БЕТОНА НА НИЗКОКАЧЕСТВЕННЫХ ЗАПОЛНИТЕЛЯХ

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Аннотация: В статье исследуется экспериментально-аналитический подход к повышению точности расчёта номинального состава тяжёлого бетона с использованием базы данных протоколов испытаний СВФУ за 2015–2025 гг. Особое внимание уделено работе с низкокачественными заполнителями – песком с модулем крупности менее 1,4. Выявлены существенные расхождения между расчётным и фактическим составами бетона, достигающие ±250 кг/м³. Предложен корректирующий коэффициент, связывающий цементно-водное отношение (Ц/В) с долей заполнителей. Его применение позволило снизить ошибку до ±60–150 кг/м³ и улучшить сходимость результатов до 1,5 % без потери прочности. Показано, что прочность бетона на очень мелких песках (Мкр ≤ 1,4) проявляет повышенную чувствительность к изменению Ц/В отношения в узком диапазоне 1,3–2,7. Расхождение между расчётной и фактической плотностью бетона варьируется в широких пределах, что ведёт к перерасходу материалов и снижает надёжность вычислительных методов подбора состава. Установлено эмпирическое выражение, связывающее варьируемые параметры смеси (водоцементное отношение и долю заполнителей), которое может использоваться в качестве поправочного коэффициента. Без коэффициента диапазон отклонений составлял 1,8–5,0 %, а с его применением – от –0,6 % до 1,5 % без ухудшения свойств бетонной смеси и физико-механических характеристик.

Ключевые слова: тяжёлый бетон, подбор состава, экспериментальный коэффициент, экспериментальные данные, цементно-водное отношение, база данных

INTRODUCTION

Modern construction technologies demand precise design of concrete mixtures considering multiple factors: strength, workability, durability and cost-effectiveness [1, 2]. However, traditional mix design methods based on manual calculations and trial batches remain labor-intensive and prone to errors, making experimental-analytical approaches incorporating statistical data processing and computer modeling particularly relevant [3, 4, 5].

Research across various scientific fields demonstrates that combining experimental data with mathematical modeling significantly improves calculation accuracy [6, 7]. Promising developments include integration of material databases [8], application of semi-empirical models [9] and automation of trial batches, which together with advances in artificial intelligence and big data open new possibilities for construction materials design [10, 11, 12]. In concrete science, the main challenges of manual mix design stem from component variability (cement, aggregates, admixtures), multiple influencing factors (water-cement ratio, curing conditions) and calculation complexity [12], prompting development of specialized software like the Borland Delphi 7 program automating heavy concrete mix design considering required strength and component properties [12]. Successful implementation of such methods requires comprehensive databases with well-defined dependencies for use as adjustment coefficients in calculated concrete mixes.

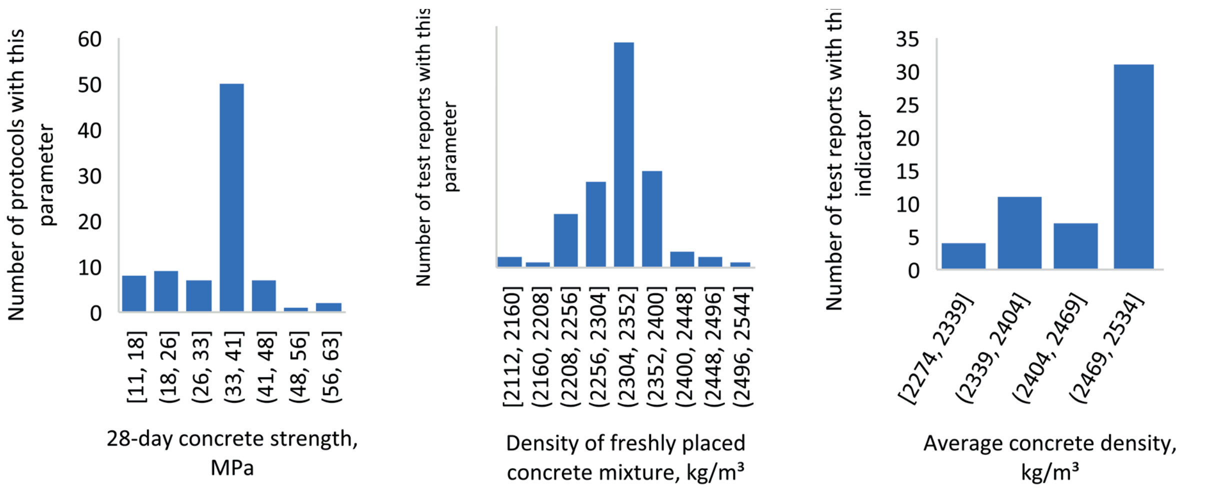
Practical experience in concrete design shows that when using low-quality aggregates (fine aggregate fineness modulus below 1.4), producing quality concrete mixtures requires high-performance chemical admixtures and reduced proportion of such inferior components. This aspect remains insufficiently addressed in scientific literature. While existing concrete design guidelines recommend decreasing fine aggregate content with increasing cement quantity, for concretes with fine aggregate fineness modulus below 1.4 this proportion must be further reduced to control workability - a non-standard case not covered by current recommendations, leading to significant discrepancies between design and actual compositions [13, 14]. It should be noted that concrete research advancements have introduced increasingly diverse components into concrete mixtures [15-18]. However, concrete theory considers water-cement ratio and aggregate proportions as primary variables significantly affecting concrete properties, meaning other mix parameters' influence can only be determined through data analysis.

This study aimed to improve accuracy of nominal concrete mix design calculations using an experimental-analytical approach incorporating database analysis. The research addressed the following tasks: compiling a database from concrete mix design protocols conducted at NEFU; analyzing data for compliance with formal logic and determinability through nominal mix design methods; deriving sufficiently reliable dependencies for use as adjustment coefficients in nominal concrete mix design calculations.

SUBJECT, OBJECTIVES, AND METHODS

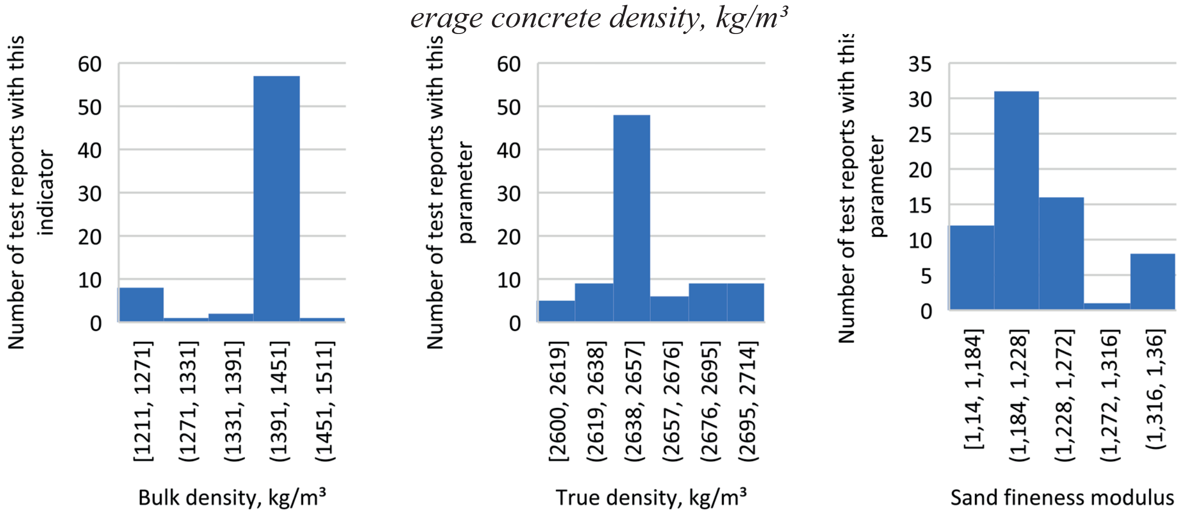
The database was compiled from records of mix design and testing of heavy concretes obtained at NEFU (North-Eastern Federal University) between 2015 and 2025. The dataset included 95 mix design protocols for heavy concretes, featuring concretes with compressive strengths ranging from 11 to 63 MPa, fresh concrete mixture densities from 2274 to 2534 kg/m³, and concrete slump values from 6 to 17 cm, corresponding to workability grades P2–P3 (Figure 1). According to the protocols, the concretes were produced using: sands with bulk density of 1211-1511 kg/m³, true density of 2600-2714 kg/m³ and fineness modulus of 1.14-1.34 (Figure 2); crushed stone with bulk density of 1366-1438 kg/m³, true density of 2600-2680 kg/m³ and fractional composition of 5-10, 5-20, 10-25 mm (Figure 3).

The heavy concrete mix design calculation is based on GOST 27006 and its methodological manual "Recommendations for mix design of heavy concrete and fine-grained concrete mixtures".



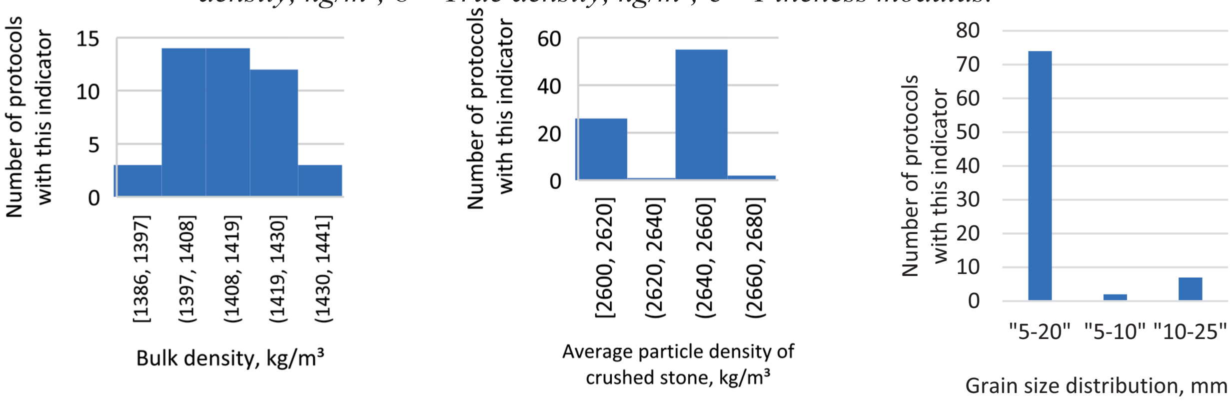
a) *b)* *c)*

<u>Figure 1.</u> Properties of heavy-weight concrete and concrete mixture in the studied test reports: (a) 28-day concrete strength, MPa; (b) density of freshly placed concrete mixture, kg/m³; (c) average concrete density, kg/m³



a) *b)* *c)*

<u>Figure 2.</u> Properties of fine aggregates in concrete mixes from the studied protocols: a – Bulk density, kg/m³; b – True density, kg/m³; c – Fineness modulus.



a) *b)* *c)*

<u>Figure 3.</u> Properties of coarse aggregates in the studied concrete mix protocols: a – Bulk density, kg/m³; b – Average particle density of crushed stone, kg/m³; c – Grain size distribution, mm

Equation (1) determines the cement-water ratio (C/W) that approximately provides the required average strength of concrete class at design age (28 days).

$$\mathrm{C/W} = \frac{R_b^{28} - 0{,}06 \times R_c^{28} + 13}{0{,}24 \times R_c^{28} + 13}, \qquad (1)$$

где C/W – the cement-water ratio providing the required concrete strength;
R_c^{28} – the cement strength (activity), taken equal to the cement class indicator upon its compliance after laboratory tests, MPa;
R_b^{28} – the required average strength of normally cured concrete class at 28 days age, MPa.
During mix design, the average class strength is set equal to the concrete strength at variation coefficient V_n = 13,5%. For this purpose, the specified concrete class is multiplied by the specified strength coefficient K_T equal to the specified variation coefficient (formula 2).

$$R_b^{28} = B \times K_T, \qquad (2)$$

где B – strength value corresponding to the adopted concrete class, MPa
K_T – specified strength coefficient.
The water consumption (W) is determined based on the water demand of the concrete mixture, depending on the required workability and the type of plasticizing admixture.
With known water content (W) and cement-water ratio (C/W), the cement content (C) per 1 m³ of concrete can be calculated.

$$C = (\mathrm{C/W}) \times W, \qquad (3)$$

where C/W – cement-water ratio;
W – water content.
The absolute volume of aggregates, V_a (L), is then calculated using the formula:

$$V_a = 1000 - (W/\rho_w) - (C/\rho_c), \qquad (4)$$

where p_c – true density of cement, kg/L;
p_w – density of water, taken as p_w = 1 kg/L.

The quantity of fine aggregate (S) in the absolute volume of aggregates is calculated by the formula:

$$S = V_a \times r_s \times \rho_s, \qquad (5)$$

where S – sand content, kg/m³;
r_s – proportion of sand in the aggregate mixture;
ρ_s – true density of sand particles, kg/L.
The quantity of coarse aggregate is calculated by the formula:

$$CA = V_a \times (r_{CA}) \times \rho_{CA}, \qquad (6)$$

Where CA – coarse aggregate content, kg/m³;
r_{CA} – proportion of sand in the aggregate mixture;
ρ_{CA} – average density of crushed stone particles, kg/L.
According to concrete mix design rules, after obtaining the nominal mix composition with specified properties, its average density is determined according to GOST 10181, and for each composition the actual material consumption per 1 m³ of concrete is calculated using the formula:

$$C, S, CA, W, Ad = \frac{\rho_{mix}}{\Sigma g} \times g_{c,s,ca,w,ad}, \qquad (7)$$

Where C, S, G, W, and Ad – actual consumption of cement, fine aggregate, coarse aggregate, water, and admixture per 1 m³ of concrete, respectively, kg;
g_c, g_s, g_{ca}, g_w, g_{ad} – mass of cement, fine aggregate, coarse aggregate, water, and admixture in the batch, respectively, kg;
ρ_{mix} – density of the concrete mixture, kg/m³;
Σg – total mass of all materials in the batch, kg.
The objective of this study was to derive an experimental coefficient that would allow for closer alignment between the nominal mix proportions and the actual material consumption per 1 m³ of concrete. This approach enables more accurate prediction of the physical and mechanical properties of concrete in non-standard mix designs.
To establish the relationships, a period was selected in accordance with GOST 18105, which requires at least 30 values obtained over a period not exceeding three months. For the experimental

validation of the analytical results, the following raw materials were used:

For heavy-weight concrete, in accordance with GOST 26633, Portlandcement grade CEM I 42.5N was used. The cement was produced by JSC "Yakutcement" and complies with the requirements of GOST 31108-2016 (Table 1).

Fine aggregate: Natural river sand from the floodplain of the Lena River was used. The properties of the sand are presented in Table 2.

Coarse aggregate: Limestone crushed stone (fraction 5–20 mm) produced by LLC "Yakutcement" was employed. The characteristics of the coarse aggregate are provided in Table 3.

Testing of the obtained concrete mixtures and hardened concrete was conducted in accordance with the following standards:

- GOST 10181-2000 "Concrete mixtures. Test methods" (controlled characteristics of fresh concrete)
- GOST 10180-2012 "Concrete. Methods for strength determination using control specimens"
- GOST 12730.1-78 "Concrete. Method for density determination"

Table 1. Properties of Portland cement

№	Cement quality parameter	Unit	Value
1	Cement strength class	MPa	42,5
2	Standard consistency	%	26,5
3	Mass fraction of sulfur (VI) oxide (SO_3)	%	2,55
4	Mass fraction of chloride ions (Cl^-)	%	0,026
5	Initial setting time	min	135
6	Signs of false setting	–	нет

Table 2. Characteristics of river sand

№	Parameter name	Unit	Requirements according to GOST 8736-2014	Actual values
1	Bulk density	kg/m³	Not standardized	1444
2	Fineness modulus	M	Over 1.0 to 1.5 (for "very fine" group)	1,09
3	Content of dust and clay particles	%	Max. 5 (for Grade II sand)	0,25
4	True density	g/cm³	2,0-2,8	2,62
5	Organic impurities content	Reference color	Lighter than reference	Lighter
6	Void content	%	Not standardized	44,89

Table 3. Characteristics of limestone crushed stone

№	Parameter Name	Unit	Requirements per GOST 8269.0-97	Actual Values
1	Grain size distribution, full sieve residues: - 10 mm - 15 mm - 20 mm - 25 mm	%	 90-100 30-60 ≤10 ≤0.5	 99 68 5 0,4
2	Content of dust and clay particles (by mass)	%	≤2	1
3	Content of flaky and elongated grains (by mass)	%	Group 2 (>10 to 15)	13
4	Crushability grade Mass loss during dry testing	%	Grade M600 (>12 to 16)	14
5	Content of weak grains (by mass)	%	≤10	2

RESULTS AND DISCUSSION

According to the initial mix design requirements (Table 4), a theoretical calculation of the baseline composition of heavy concrete was performed following the existing method described above. The calculation was carried out considering a sand ratio (r) taken as 0.41, as recommended by the manual, and as 0.35, based on experience in designing concrete mixes using the available sand. Using the calculated compositions, concrete mixtures were produced, and their technological properties—workability and density—were determined (Table 5). Subsequently, for each composition, the actual material consumption per 1 m³ of concrete was calculated. After that, the concrete mixture was molded into 100×100×100 mm cubes, with 6 specimens per composition. Following hardening under normal conditions for 28 days, the concrete properties—average density and compressive strength—were determined.

Table 4. Mix design requirements for heavy concrete

Parameter	Specifications
Compressive strength class	B25
Workability grade	P3
Production conditions:	
- Molding	Vibration
- Curing	Normal curing (28 days)
Raw materials:	
Binder:	Portland cement
-Type/grade	CEM I 42.5N
Fine aggregate	River sand
-Fineness modulus (Mk)	1.09
-Bulk density, kg/m³	1444
-True density, g/cm³	2.65
Coarse aggregate	Crushed stone
-Fraction, mm	5–20
-Bulk density, kg/m³	1425
-True density, g/cm³	2.65

Table 5. Properties of concrete mixture and concrete depending on the composition

№		1		2		3	
C/W ratio		2,2		1,9		2,5	
Sand ratio (r)		0,41	0,35	0,41	0,35	0,41	0,35
Water (W)	Calculated	200	200	200	200	200	200
	Actual	206	210	205	204	205	207
Cement (C)	Calculated	440	440	380	380	500	500
	Actual	455	463	390	387	513	518
Sand (S)	Calculated	728	622	762	650	694	593
	Actual	750	654	800	662	711	614
Coarse aggregate (CA)	Calculated	1048	1154	1096	1208	999	1101
	Actual	1121	1214	1150	1229	1023	1140
Density of concrete mixture, kg/m³	Calculated	2416	2416	2438	2438	2394	2394
	Actual	2532	2541	2545	2482	2452	2479
Δ, %		4,6	4,9	4,2	1,8	2,4	3,4
Workability (slump, cm)		9	13	6	15	11	15
Density of concrete, kg/m³		2335	2432	2330	2357	2327	2385
Compressive strength, MPa		32	33,1	23	22,7	33	36,7

Based on the test results, concrete mixtures obtained from compositions with a sand ratio (r) of 0.41, as recommended by the manual, did not meet the workability requirements of the mix design requirements. Compositions 1 and 3 with a sand ratio (r) of 0.35 fully complied with the design requirements; however, a significant deviation between the calculated and actual concrete compositions was observed, ranging from 1.8% to 3.4%. With such a deviation, the actual cement consumption may be 18 kg higher per 1 m³ than the calculated value, which is a substantial discrepancy. Therefore, our next task was to derive an experimental coefficient from the existing database that would allow the nominal composition values to approximate the actual material consumption per 1 m³ of concrete.

To establish the relationships, a period was selected in accordance with GOST 18105, comprising 30 values obtained over a three-month period. In general, the analyzed database supports the theory of a positive effect of the water-to-cement (W/C) ratio (or its inverse, C/W) on the 28-day compressive strength of concrete (Figure 4). Notably, the analyzed concrete compositions show a higher sensitivity of strength to the C/W ratio (C/W range: 1.3 to 2.7) compared to the relationship presented in the reference guidelines (C/W range: 0.9 to 2.9). This may be attributed to the poor quality of sand used in the concretes [13].

Furthermore, the deterministic relationship between the density of freshly placed concrete mixture and hardened concrete density (Figure 5) raises questions. The lack of a stable correlation may be attributed to air-entraining and foam-suppressing admixtures, which cause instability in the early-stage concrete mixture density (first 15 minutes). Since concrete mixture density values are crucial parameters for calculating actual mix proportions, subsequent work employed the calculated fresh concrete density determined by formula (8), which depends on the average hardened concrete density:

$$\rho_{\text{mix}} = 1{,}01 \times \rho_b - 0{,}26 \times \text{C+W} \quad (8)$$

Thus, more deterministic values of calculated fresh concrete density can be obtained from the recorded average hardened concrete density (Fig. 5).

The data show (Fig. 6) that the difference between the nominal composition and actual material consumption per 1 m³ in the analyzed protocols varies widely from -250 to 150 kg per 1 m³. This represents a significant error leading to material overconsumption and reduces the reliability of computational methods for obtaining concrete mix designs. Given the substantial discrepancy between nominal mix proportions and actual material consumption per 1 m³ of concrete, the critical task was to derive an experimental coefficient that would align these values and, consequently, enable more effective prediction of the physical-mechanical properties of concrete in non-standard mixes.

According to concrete theory, the water-cement ratio (W/C) and aggregate proportion are considered as the variable mix parameters that significantly influence concrete properties. However, there is a lack of research establishing the relationship between these parameters when determining concrete composition. We believe that establishing an empirical relationship between these parameters will allow more efficient calculation of concrete mix designs using the absolute volume method and reduce the error between nominal composition and actual material consumption per 1 m³.

To establish the actual proportions of sand and coarse aggregate in concrete compositions using derived equations (9) and (10) from formulas (5) and (6), we utilized the experimental data presented in Table 6.

$$r_S = \frac{S}{V_a \times \rho_S} \quad (9)$$

$$r_{CA} = \frac{CA}{V_a \times \rho_{CA}} \quad (10)$$

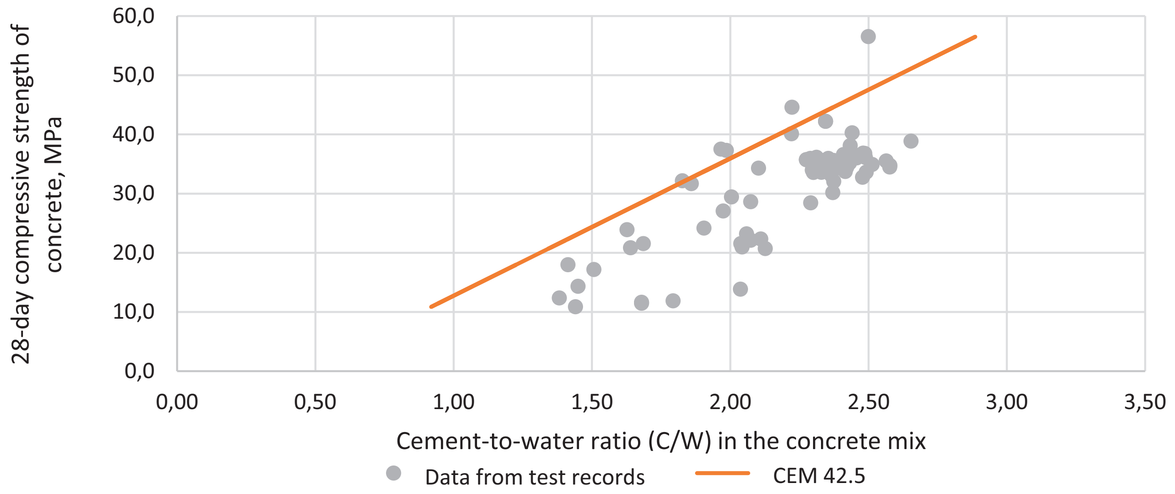


Figure 4. Effect of cement-water ratio (C/W) in concrete mix composition on 28-day compressive strength of concrete

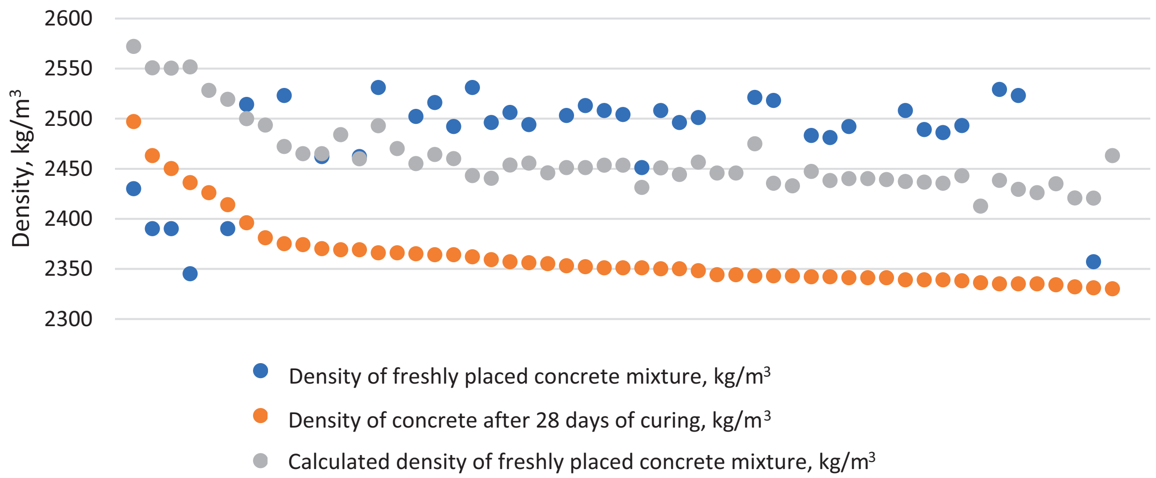


Figure 5. Correlation characteristics between average hardened concrete density and fresh concrete mixture density in the analyzed dataset

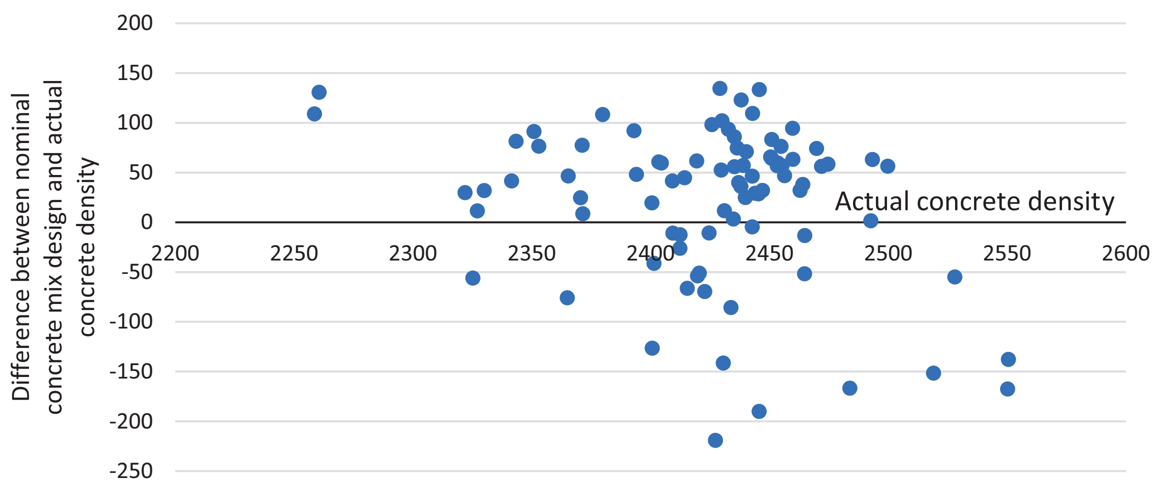


Figure 6. Discrepancy between nominal concrete mix design and actual material consumption per 1 m³ of concrete in the analyzed dataset

Table 6. Data used in calculations for determining aggregate proportions

№ mix	True density of sand, kg/m³	Bulk density of coarse aggregate, kg/m³	Mixture component mass, kg						Concrete density, kg/m³	28-day strength, MPa
			g_c	g_s	g_{ca}	g_w	g_{pl}	g_{ad}		
1	2640	2620	472	683	1186	203	-	-	2366	35,5
2	2650	2660	491	677	1186	185	3,4	9,8	2362	38,8
3	2650	2600	471	688	1172	190	2,8	-	2335	32,7
4	2700	2660	476	672	1183	197	-	-	2375	33,7
5	2620	2630	462	761	1138	200	-	-	2335	35,9
…	…	…	…	…	…	…	…	…	…	…
95	2680	2650	314	873	1020	182	-	-	2106	12,4

The analysis demonstrates that the total aggregate fraction does not consistently equal unity (Figure 7). Notably, a distinct correlation exists between the increased aggregate content and cement concentration in the mix. This relationship can be mathematically expressed by equation (11) and subsequently employed as a correction factor for mix design optimization.

$$K = (0{,}007 \times C + 0{,}731) \qquad (11)$$

A similar trend can be observed in external databases using coarser sands (fineness modulus of the fine aggregate greater than 1.4) (Figure 8) [19]. It is noticeable that the rate of increase in the aggregate fraction with higher cement content is greater when using fine sands.

The application of the derived coefficient to existing theoretical mix designs reduced the error range from -250 to 150 kg/m³ down to -60 to 150 kg/m³ (Fig. 9).

For practical validation, concrete compositions for class B25 were calculated according to the method using the obtained coefficient (Table 7).

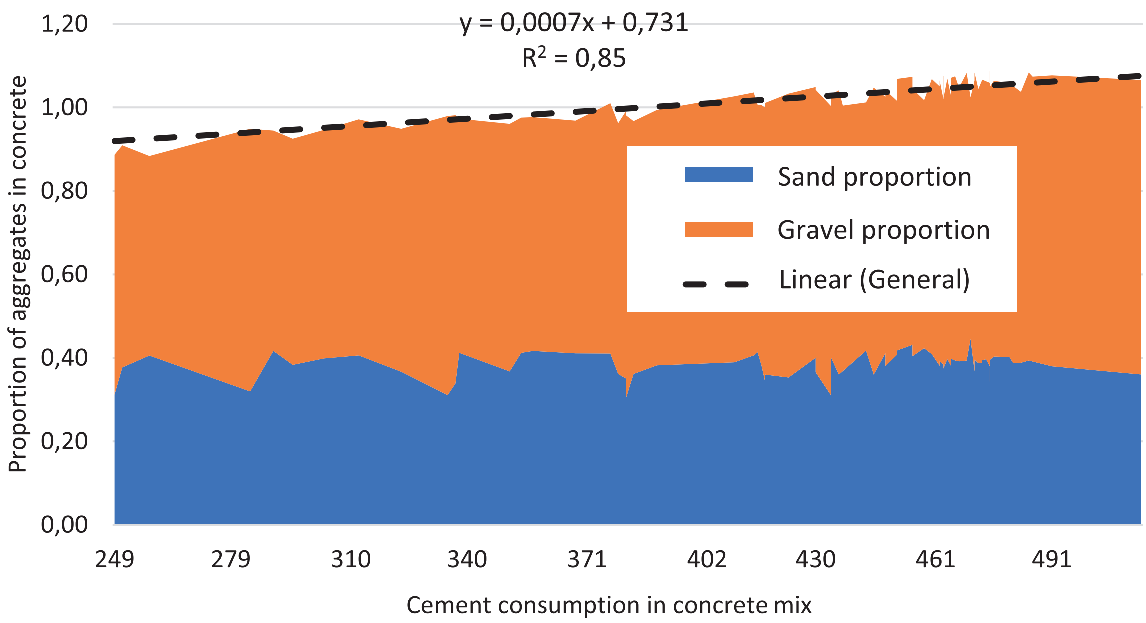


Figure 7. Aggregate content in concrete mixes as a function of cement dosage

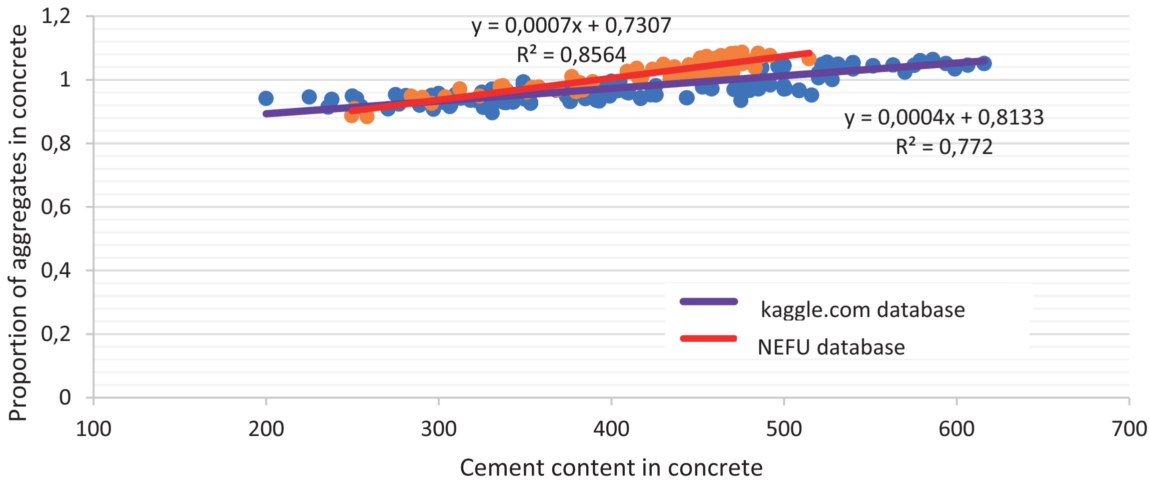


Figure 8. Proportion of aggregates in concrete compositions depending on cement content according to different databases

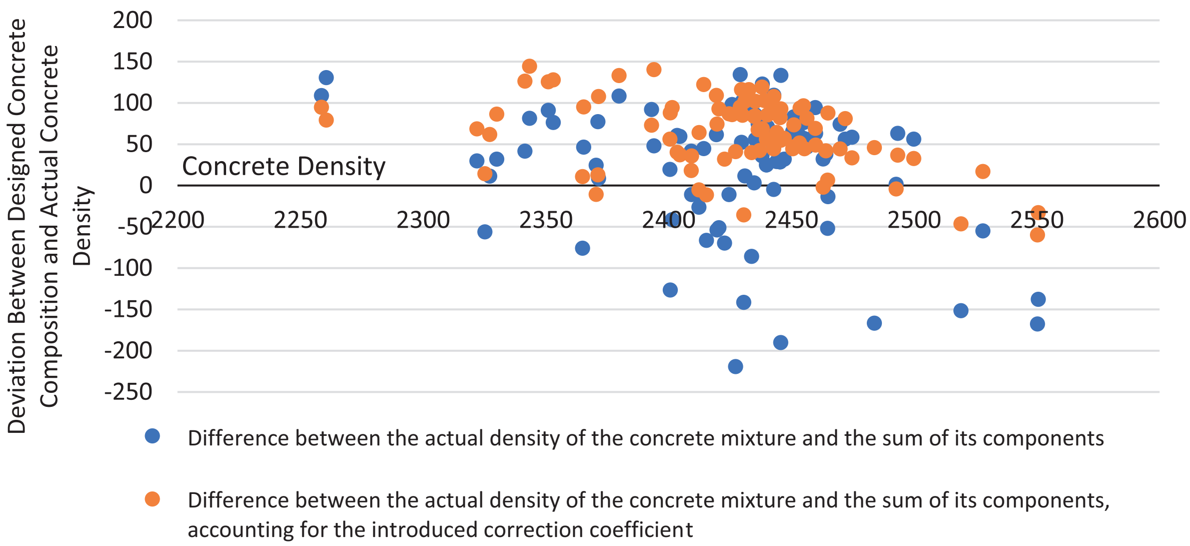


Figure 9. Deviation between designed concrete composition and measured concrete density

Table 7. Concrete properties depending on mix composition

#	C/W	Sand ratio (r)	Water (Calc/Act)	Cement (Calc/Act)	Sand (Calc/Act)	Coarse Agg. (Calc/Act)	Fresh Density, kg/m³ (Calc/Act)	Δ, %	Slump, cm	Hardened Density, kg/m³	Strength (28d), MPa
1	2.2	0.35	200 / 203	440 / 447	655 / 664	1154 / 1171	2449 / 2485	1.5	12	2432	33.1
2	1.9	0.35	200 / 203	380 / 386	659 / 670	1208 / 1229	2447 / 2488	1.7	14	2357	22.7
3	2.5	0.35	200 / 199	500 / 497	637 / 633	1101 / 1095	2438 / 2424	0.6	15	2385	36.7

According to GOST 27006-2019, the actual material consumptions of the concrete compositions were determined, and the average deviations between the calculated and actual component consumptions were obtained. Based on the obtained data, it can be seen that by applying the coefficient, better convergence between the actual and calculated compositions can be achieved. Without the coefficient, the range of deviations was from 1.8% to 4.9%; with the coefficient applied, the deviations ranged from -0.6% to 1.5%. Moreover, no deterioration occurs in the technological properties of the concrete mixture or the physical and mechanical characteristics.

CONCLUSION

This study aimed to improve the accuracy of nominal concrete mix design calculations using an experimental-analytical approach involving database analysis. The key findings are as follows:

1. The strength of concrete incorporating very fine sands (with a fineness modulus ≤1.4) shows relatively high sensitivity to variations in the C/W ratio within a narrow range of 1.3 to 2.7.
2. The discrepancy between the calculated density of concrete using very fine sands and its actual density varies significantly, ranging from -250 to 150 kg/m³. This substantial error leads to material overuse and reduces the reliability of computational mix design methods.
3. An empirical relationship has been established between the key variable mix parameters that significantly influence concrete properties - the water-cement ratio (W/C) and the proportion of aggregates in the concrete. This relationship is expressed as a formula that can serve as a correction coefficient when calculating sand and coarse aggregate quantities in concrete mixes. The data demonstrate that applying this coefficient yields better agreement between actual and calculated mix proportions. Without the correction coefficient, the discrepancy range was 1.8-5.0%, while with the coefficient it reduced to -0.6-1.5%, with no reduction in compressive strength observed.

The study thus demonstrates that concrete mix design efficiency can be improved and discrepancies between nominal compositions and actual material quantities per m³ reduced by establishing empirical relationships between key variable mix parameters. Future research should focus on developing numerical models to correlate concrete characteristics with the quantitative and qualitative composition of components, along with experimental validation, to establish a more reliable methodology for proportioning heavyweight concrete mixes when using aggregates of varying quality.

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