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A Standards-Informed Digital Platform for Exposure-Based, Performance-Oriented, and Low-Carbon Concrete Mix Design

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Abstract

Concrete proportioning in routine practice often relies on separate spreadsheets, code tables, and trial-batch records, making simultaneous control of strength, exposure resistance, workability, cost, and embodied carbon difficult. Although existing standards provide valuable guidance, a scientific and practical gap remains in converting fragmented provisions into an integrated workflow for performance-oriented and low-carbon mix design. This paper presents the EcoStruct platform, a thirteen-tab digital workflow for normal concrete mix design. The workflow integrates international guidance, including ACI 211.1, ACI durability provisions, EN 206, BS 8500, EN 197-1, ASTM C150, ASTM C33, ASTM C127/C128, EN 12620, EN 934-2, and DIN 1045-based aggregate gradation logic. The platform covers project definition, exposure limits, SCMs and admixtures, material characterization, target strength, aggregate grading, water–cement ratio, free-water demand, cement adjustment, absolute-volume aggregate calculation, performance prediction, laboratory trial, and reporting. A precast tunnel-lining segment was used to compare the platform with BRE and SP 23:1982. The platform mixture contained 440 kg/m³ cement and 190 kg/m³ water. Compared with BRE and SP 23:1982, it reduced free-water and cement demand while maintaining durability compliance and improving aggregate-skeleton continuity.

Keywords: concrete mix design; standards-informed workflow; digital concrete platform; performance-based design; aggregate-skeleton optimization; exposure-based durability; embodied carbon; tunnel-lining segments



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1. Introduction

Concrete mix design is a practical sequence of engineering decisions: the designer fixes the required strength and exposure class, selects a workable consistency, evaluates available cement and aggregates, and then adjusts water, binder and aggregate proportions through calculation and trial batching. In many batching plants, these steps are still distributed across separate spreadsheets, supplier datasheets and laboratory records. The separation becomes limiting for precast tunnel linings, bridge elements and low-carbon infrastructure, where permeability control, mold filling, vibration response, surface finish and embodied carbon must be considered together rather than after the mixture has already been proportioned.

The recent scientific literature shows that concrete mix design is increasingly moving from prescriptive proportioning to data-driven, multi-objective, and sustainability-oriented decision support. Zheng et al. [1] and Liu et al. [2] used machine learning and metaheuristic optimization to balance mechanical, economic, and environmental objectives in concrete proportioning. Golafshani et al. [3] linked recycled aggregate concrete design with strength, durability, cost, and embodied carbon, while Forsdyke et al. [4] used probabilistic machine learning to select mixtures under uncertainty. Bayesian and generative AI approaches have also been used to accelerate the search for mixtures with improved strength–carbon trade-offs [5,6].

Recent studies have further emphasized deployable digital tools and traceability. SmartMix Web3 combined ensemble machine learning and blockchain-based data reliability for low-carbon concrete design [7]. Other studies coupled machine learning estimators with genetic algorithms or explored model complexity and user-oriented optimization interfaces for concrete mixture selection [8,9]. Data-driven AI models have also been integrated into cement production decision making, showing the relevance of plant data for mixture design optimization [10].

Low-carbon and special-concrete studies confirm that strength, durability, workability, cost, and carbon should not be optimized separately. Reviews by Mahjoubi et al. [11] and Luo et al. [12] highlighted the need to integrate property prediction, multi-objective optimization, and quality-control logic. Recent applications to waste-glass-powder and manufactured-sand concrete show that machine learning optimization can include strength, permeability, cost, and CO₂ emissions in the same decision process [13,14]. Similar ML-based optimization has been applied to UHPC, geopolymers concrete, and reinforcement learning-based concrete proportioning [15–17].

Other recent studies highlight reliability, interpretability, and practical deployment. Liu et al. [18] emphasized external validation and user-oriented prediction tools, while Jing et al. [19] showed that ensemble learning and multi-objective optimization can reduce cost and CO₂ emissions for cement-based materials. Baten et al. [20] further introduced an open-source Bayesian optimization model for strength forecasting and mix optimization. Therefore, despite progress in AI-assisted concrete mix design, a gap remains for a transparent, standards-informed platform that connects project specification, exposure limits, aggregate-skeleton optimization, water and cement calculations, cost, embodied carbon, performance prediction, laboratory feedback, and reporting in one workflow.

The main technical basis for the proposed workflow comes from established standards and proportioning manuals, but these documents serve different purposes. ACI 211.1 supports proportioning by absolute volume [21]; ACI 318 and ACI 201.2R define exposure-related performance and durability limits [22,23]; and ACI 305R, ACI 306R, and ACI 306.1 address hot- and cold-weather concreting [24–26]. ASTM C150 defines Portland cement classification [27], whereas ASTM C33, ASTM C127, and ASTM C128 define aggregate quality and density/absorption properties [28–30]. EN 206 and BS 8500 specify European performance, exposure, consistency, conformity, and durability requirements [31–33], while EN 197-1, EN 12620, and EN 934-2 define cement, aggregate, and admixture classification [34–36]. DIN 1045-2 supports aggregate gradation and volumetric mix-design logic [37], and established concrete technology guidance supports dense grading and strength water/cement interpretation [38]. Environmental reporting is supported by the ICE database [39], ISO 14025 and ISO 21930 [40,41], and EN 15804 [42], while statistical strength evaluation follows ACI 214R [43], and life-cycle assessment follows ISO 14044 [44]. In North American practice, ACI 211.1 provides a rational procedure for selecting normal-density concrete proportions using tabulated estimates of water, coarse

aggregate and air content, whereas ACI 318 and ACI 201.2R complement the proportioning stage by imposing exposure-related strength and water–cement ratio limits [21–23].

European and British practice follows a different route. Eurocode does not provide a complete recipe-calculation procedure for concrete mixtures; instead, EN 206 defines concrete through strength class, exposure class, consistency class, and conformity rules, while BS 8500 provides national durability guidance for minimum cement content or combination content and maximum free-water/cement ratio [31–33]. Cement classification is standardized by EN 197-1, aggregate quality by EN 12620, and admixture classification by EN 934-2 [34–36].

Table 1 summarizes the key international standards and technical documents that informed the development rationale for the proposed platform. These documents do not provide the same type of guidance: some are primarily concerned with proportioning procedures, some with durability and exposure limits, some with material classification, and others with environmental assessment. Therefore, the platform does not rely on a single standard; instead, it integrates the strongest contribution of each framework into a unified workflow. ACI 211.1 supports the absolute-volume proportioning sequence; EN 206 and BS 8500 provide exposure-based durability constraints; ASTM and EN material standards define cement and aggregate characterization; and ISO/EN environmental standards support embodied-carbon and future EPD-related reporting. This combined approach allows the platform to translate fragmented standard provisions into a practical, transparent, and auditable mix-design process.

Table 1. Major standards and technical sources embedded in platform logic.

Standard/ Document	Main Area Concerned	Key Strength	Role in the Platform
ACI 211.1 [21]	Concrete mix proportioning	Provides a systematic procedure for selecting concrete proportions using the absolute-volume method, estimated water demand, aggregate volume, and trial adjustment.	Supports the general calculation sequence, especially water estimation, cement calculation, aggregate proportioning, and trial-batch refinement.
ACI 318 and ACI 201.2R [22,23]	Structural durability and exposure-related performance	Establish durability-oriented limits related to water–cement ratio, minimum strength, and protection against aggressive exposure mechanisms.	Used to support exposure-based checks, especially where durability limits override strength-based mixture selection.
ACI 305R and ACI 306R/306.1 [24–26]	Hot- and cold-weather concreting	Provide practical guidance for concrete production, delivery, placement, curing, slump retention, and protection against early-age freezing.	Used in the platform’s environmental limitation logic, especially for cold-weather and hot-weather mix adjustments.
EN 206 [31]	Concrete specification, performance, production, and conformity	Defines concrete through strength class, exposure class, consistency class, chloride class, production control, and conformity criteria.	Provides the main European framework for project specification, consistency selection, exposure classification, and compliance-oriented mix design.

Table 1. *Cont.*

Standard/ Document	Main Area Concerned	Key Strength	Role in the Platform
BS 8500 [32,33]	UK complementary standard to EN 206	Gives practical national guidance for minimum cement or combination content, maximum free-water/cement ratio, and exposure-based durability requirements.	Supports the platform's Durability Limit tab, especially minimum cement content and maximum water–cement ratio selection.
EN 197-1 [34]	Cement classification and conformity	Defines common cement types, compositions, strength classes, and conformity requirements in the European system.	Enables the platform to classify cement according to European cement types and strength classes.
ASTM C150 [27]	Portland cement classification	Defines Portland cement types based on intended performance, such as general use, sulfate resistance, and heat control.	Enables the platform to support American cement classification alongside EN 197-1.
EN 12620 [35]	Aggregates for concrete	Specifies aggregate properties, grading, quality requirements, and conformity criteria for concrete aggregates.	Supports aggregate input requirements, sieve grading, and material characterization.
ASTM C33, ASTM C127, and ASTM C128 [28–30]	Aggregate grading, specific gravity, and absorption	ASTM C33 covers aggregate quality and grading; ASTM C127 and C128 provide test methods for specific gravity and absorption of coarse and fine aggregates.	Supports aggregate property inputs, SSD/OD conversion, absorption correction, and absolute-volume calculation.
EN 934-2 [36]	Chemical admixtures for concrete	Defines admixture categories, performance requirements, conformity, and functional effects such as water reduction or air entrainment.	Supports the SCMs and Admixtures tab, particularly dosage range, water-reduction effect, and admixture selection.
DIN 1045 [37] inspired mix-design logic	Aggregate grading and volumetric mix design	Provides a structured and adaptable basis for grading envelopes, strength-oriented mix development, and volumetric consistency.	Serves as a foundation for the platform's combined aggregate gradation curves, water-demand calibration, and volumetric proportioning logic.
ICE database [39]; ISO 14025, ISO 21930, and EN 15804 [40–42]	Environmental assessment, LCA, embodied carbon, and EPD reporting	Provide a standardized basis for environmental product declarations, life-cycle assessment indicators, and embodied-carbon calculation.	Supports the platform's embodied-carbon calculation and future EPD-generation framework for optimized concrete mixes.

The present platform was developed by reviewing these major methods, experimentally assessing their strengths and limitations, and integrating the most reliable elements into a unified, user-oriented workflow. The gap addressed by the platform is not only computational but operational. Traditional standards tell the designer which limits must be obeyed, but they do not connect these limits to the full chain of project inputs, aggregate blend, moisture and absorption correction, automatic cement recalculation under durability constraints, sustainability reporting, or post-design trial-batch feedback. The EcoStruct platform was therefore developed as a standards-informed hybrid system that begins with project definition and concludes with a documented, traceable mix report. The

platform is intended for normal concrete up to about C50 MPa ACI 318, with slump values between 10 and 210 mm, and nominal maximum aggregate sizes from 9.5 to 38 mm while also laying the groundwork for future extension to SCC, lightweight concrete, and other advanced mixtures.

Figure 1 summarizes the thirteen-tab workflow examined in this paper. After the Introduction, the manuscript follows the exact sequence of the platform tabs. For each tab, the implemented function is described, the corresponding scientific reasoning is explained, and the platform logic is compared against relevant international standards. The final major section addresses the supplied case study on a precast tunnel-lining mix.

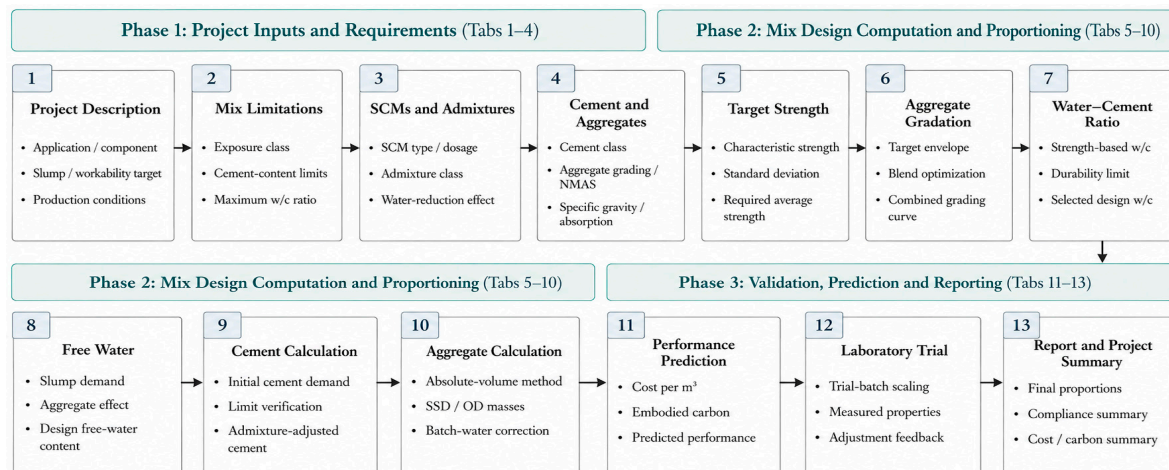


Figure 1. Thirteen-tab standards-informed workflow implemented in the EcoStruct platform.

2. Materials and Methods: Platform Architecture and Standards-Informed Mix-Design Workflow

The overall methodological scheme adopted in this study is presented in Figure 2. The research process begins with a review of the relevant literature, standards, and practical requirements, followed by the development of the platform architecture, material input definition, standards-informed mix-design computation, performance and carbon assessment, case-study comparison, and laboratory verification.

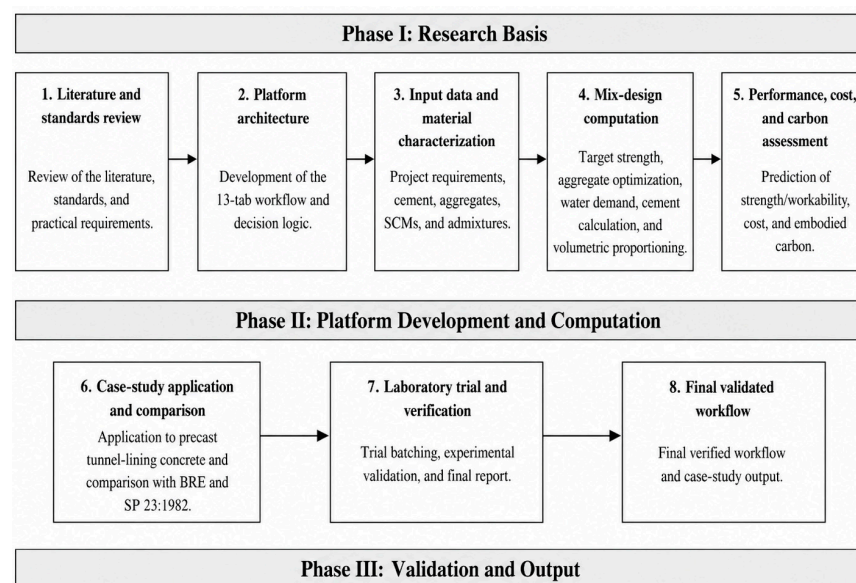


Figure 2. Methodological scheme of the study.

2.1. Tab 1—Project Description

Tab 1 defines the project-specific information required before mix proportioning begins. As shown in Figure 3, the platform records the application category, component type, workability class, target slump, aggregate gradation category, supply condition, batching facility, transport distance, ambient temperature, unit system, and currency. This structure follows the specification logic of EN 206, in which concrete is defined by performance, production, consistency, exposure, and conformity requirements [31]. BS 8500 further links intended use and exposure condition to durability-related limits, while ACI 211.1 requires that workability, aggregate characteristics, strength, and durability requirements be considered before selecting final mix proportions [21,32,33]. Therefore, this tab acts as the project-definition layer of the platform and provides the technical basis for later water demand, cement content, aggregate proportioning, and durability checks. Therefore, Tab 1 converts general project requirements into standards-aligned parameters for the subsequent mix-design workflow.

Precast Tunnel Lining Segments Mix Design Completed Viewing example (read-only) Edit Report Project Summary

2026 | 02 | 13 • buggy-tailgating

Project Description Need Help? < Previous Project Description < 1 of 13 > Next > Mix Limitations

Provide basic information about your concrete mix design project

1. Application and component definition

Application Type ①: Buggy or Tailgating Concrete
 Component Category: Standard Application
 Component Description: Precast Tunnel Lining

2. Aggregate gradation selection

Aggregate Gradation ①: Medium / Balanced - Well-graded

3. Workability requirements

Workability Class ①: S3 (100–150 mm) – Medium
 Target Slump (mm): 150
 Range: 100–150 mm ✓ Manual

4. Supply and production conditions

Supply Place: At Batching Plant (selected) | In Place
 Batching Facility: Holcim
 Distance (km): 1

5. Environmental condition

Temperature (°C): 10

6. Unit system and currency settings

Unit System: Metric (SI) (selected) | Imperial (US)
 Currency: Netherlands (EUR) (selected)

7. Intelligent selection guidance

Intelligent Selection
 The **Combined Aggregate Gradation** and **Workability Class** are automatically selected based on your chosen application type and component. However, you can manually adjust these selections if your specific requirements differ from the recommendations.

Figure 3. Annotated view of Tab 1: Project Description.

2.2. Tab 2—Mix Limitations

Tab 2 converts the selected exposure condition into governing durability limits before the mix-design calculations proceed. As shown in Figure 4, the platform allows the user to select the exposure category, including standard, cold weather, hot weather, chloride, freeze–thaw, and sulfate conditions, and then assigns the corresponding limits for minimum cement content, maximum cement content, maximum water–cement ratio, and minimum early-age strength. This logic follows the durability-based specification approach of EN 206 and BS 8500, in which exposure conditions are linked to limiting values such as minimum cement or binder content, maximum free-water-to-cement ratio, and required strength class [31–33]. ACI-based practice follows the same principles through durability provisions and exposure-related guidance [22,23], while ACI 305R, ACI 306R, and ACI 306.1 address the effects of hot- and cold-weather concreting, including slump loss, rapid setting, curing temperature, and protection against freezing [24–26]. The platform mainly considers the following constraints:

$$C_{min,E} \leq C \leq C_{max,E} \quad (1)$$

$$\left(\frac{W}{C}\right)_{design} \leq \left(\frac{W}{C}\right)_{max,E} \quad (2)$$

$$f_c(t_f) \geq f_{c,min,E} \quad (3)$$

where E represents the selected exposure condition, C is the cement content, $\left(\frac{W}{C}\right)_{design}$ is the adopted water–cement ratio, and $f_c(t_f)$ is the concrete compressive strength prior to freezing exposure. Therefore, Tab 2 serves as the platform’s durability-control layer: it ensures that later strength- or workability-based calculations do not exceed the limits required for environmental resistance.

Precast Tunnel Lining Segments Mix Design Completed Viewing example (read-only) Edit Report Project Summary

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Mix Limitations Need Help? Select exposure conditions to determine mix design limitations

< Previous Project Description Mix Limitations < 2 of 13 > Next > SCMs & Admixtures

1. Exposure category selection

Exposure Category

Standard Cold Weather Hot Weather Chloride Freeze-Thaw Sulfate

2. Exposure-based durability requirements

Cold Weather Requirements

Mix design limitations and requirements for selected exposure conditions. All values are automatically calculated but can be edited to match your specific project requirements.

3. Cement content limits

Minimum Cement Content (kg/m³) 400 Maximum Cement Content (kg/m³) 450

4. Maximum water-to-cement ratio

Maximum Water-To-Cement Ratio 0.45

5. Minimum pre-freezing strength

Minimum Compressive Strength Before Exposure To Freezing (MPa) 3.5 (ACI 306) to 7.0 (CSA)

6. Workflow navigation and actions

Save Save & Continue >

Figure 4. Annotated view of Tab 2: Mix Limitations.

2.3. Tab 3—SCMs and Admixtures

As shown in Figure 5, Tab 3 provides a structured interface for selecting SCMs and chemical admixtures and for defining their dosages and water-reduction effects before subsequent mix-proportioning calculations. From a standards perspective, supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GGBFS), and silica fume must be selected based on verified material properties, replacement levels, durability contributions, and compatibility with the selected cement system. This requirement is consistent with ASTM C618, ASTM C989, and ASTM C1240 for fly ash, slag cement, and silica fume, respectively [45–47]. EN 206 also supports the use of additions and equivalent performance concepts in concrete specification [31]. On the platform, SCM selection is therefore not treated only as a material substitution; it is linked to strength development, durability, resistance, water demand, cement reduction, and embodied-carbon reduction. The equivalent binder contribution may be expressed using the value concept:

$$B_{eq} = C + K_f F + k_L L + k_M M \quad (4)$$

$$\left(\frac{w}{b}\right)_{eq} = \frac{W_f}{B_{eq}} \quad (5)$$

where C is the Portland cement content; F , L , and M are the masses of fly ash, GGBFS, and silica fume, respectively; K_f , $k_L L$, and $k_M M$ are their corresponding activity factors; and W_f is the free-water content. This formulation enables the platform to assess whether the selected binder system meets both strength and durability requirements while reducing clinker demand.

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2026 | Q2 | 13 • buggy-tailgating

SCMs & Admixtures Need Help? Configure SCMs and chemical admixtures for your mix

Supplementary Cementitious Materials (SCMs)
Choose an SCM and fine-tune its properties.

Without SCMs Fly Ash GGBFS Silica Fume

Select an SCM option to view and configure its parameters.

1. SCM Selection

6. Tab Navigation

< Previous Mix Limitations SCMs & Admixtures < 3 of 13 > Next > Cement & Aggregates

Admixture
Configure optional chemical admixtures for your mix.

Without Admixture Water Reducing Admixture Air-Entraining Admixture

2. Admixture Type

Product / Manufacturer
Sica

3. Manufacturer / Product

Note: Confirm dosage and water-reduction values with the manufacturer's TDS and trial mixes.

Dosage (% by cement mass)
0.1% 0.4%–1.5% 6%

4. Dosage Range

Water Reduction Range (%)
1% 12%–35% 35%

5. Water-Reduction Range

Save Save & Continue >

Figure 5. Annotated view of Tab 3: SCMs and Admixtures.

The same tab also defines the admixture system, including water-reducing and air-entraining admixtures and their dosage ranges. This follows the functional classification adopted in standards such as ASTM C494/C494M, ASTM C260/C260M, and ACI 212.3R for chemical and air-entraining admixtures [48–50]. EN 934-2 provides the corresponding European classification for concrete admixtures [36]. In the case shown on the platform, no SCM is selected, whereas a water-reducing admixture is activated to reduce the demand for free water and maintain the required workability. The effect of a water-reducing admixture can be expressed as:

$$W_{adj} = W_f \left(1 - \frac{R_w}{100} \right) \quad (6)$$

$$M_{adm} = \frac{d_{adm}}{100} B \quad (7)$$

where W_{adj} is the adjusted free-water content, R_w is the water-reduction percentage, M_{adm} is the admixture mass, d_{adm} is the dosage expressed as a percentage of binder mass, and B is the total binder content. The PCE-based water-reduction effect is treated as a bounded first-order correction for preliminary mix proportioning, not as a universal linear rheological law. The adopted reduction must remain within the recommended dosage range and be verified by trial batching, slump retention, air content, setting time, segregation tendency, and compressive strength testing. Therefore, Tab 3 provides a controlled interface for selecting SCMs and admixtures while ensuring that their effects are carried forward into the water demand, binder calculation, durability compliance, and final mix optimization stages.

2.4. Tab 4—Cement and Aggregates

Tab 4 establishes the platform's material characterization layer by defining the cement system and the physical properties of each aggregate fraction prior to volumetric proportioning. As shown in Figure 6, the platform allows for cement classification according to either ASTM C150 [27] or EN 197-1 [34], enabling the user to select the cement type, strength class, density, and nominal maximum aggregate size. This is consistent with ASTM C150, which classifies Portland cement by performance type, and EN 197-1, which classifies common cements by composition and strength class.

Precast Tunnel Lining Segments Mix Design Completed Viewing example (read-only) Edit Report Project Summary

2026 | 02 | 13 • buggy-tailgating

Cement & Aggregates Need Help? < Previous Cement & Aggregates Next > SCMs & Admixtures < 4 of 13 > Target Strength

Select cement type and define aggregate properties

1 Cement classification and cement type

Cement Properties

Cement Classification: ASTM C150 EN 197-1

Cement Type: Type I

2 Cement strength class and density

Cement Strength Class (MPa): 32.5 MPa 42.5 MPa 52.5 MPa

Density (g/cm³): 3.1

Typical range: 3.14 - 3.15 g/cm³

3 Nominal maximum aggregate size

Nominal Maximum Aggregate Size (mm): 19 mm

Used to auto-fill sieve rows above the selected size.

Aggregate Properties Add to library Aggregate Library + Add Aggregate

Capture density, manage aggregate columns, and complete the property table.

PROPERTY	COARSE GRAVEL Coarse	FINE GRAVEL Coarse	SAND Fine
Specific Gravity (SSD) (g/cm³)	2.589	2.652	2.675
Water Absorption (%)	0.8	1	1.8
Moisture (%)	0	0	0
Percent Crushed / Fractured Faces	100	100	100
Percentage Passing Through 38 mm Sieve	100	100	100
Percentage Passing Through 25 mm Sieve	100	100	100

4 Aggregate library and material-entry controls

6 Specific gravity (SSD)

7 Water absorption and moisture content

8 Fractured faces and shape-related input

9 Sieve passing / grading data

Figure 6. Annotated view of Tab 4: Cement and Aggregates.

The aggregate part of Tab 4 records the SSD specific gravity, water absorption, fractured-face percentage, moisture content, and sieve-passing values for coarse gravel, fine gravel, and sand. These parameters follow the material-control logic of ASTM C33 and EN 12620, which address aggregate grading and quality requirements [28,35], while ASTM C127 and ASTM C128 define relative density and absorption for coarse and fine aggregates, respectively [29,30]. The sieve data are also consistent with ASTM C136/C136M, where particle-size distribution is determined by sieving and used to evaluate grading compliance [51]. Mathematically, the moisture and absorption data are required to convert aggregate masses between SSD and oven-dry conditions and to correct batch water:

$$M_{OD} = \frac{M_{SSD}}{1 + A} \quad (8)$$

$$W_{corr} = M_{OD}(A - MC) \quad (9)$$

where M_{SSD} and M_{OD} are the saturated-surface-dry and oven-dry aggregate masses, A is the absorption, and MC is the actual moisture content. Thus, Tab 4 provides the platform with the essential material properties required for aggregate gradation, water correction, absolute-volume proportioning, and reliable plant batching.

2.5. Tab 5—Target Strength

As shown in Figure 7, Tab 5 provides a structured procedure for selecting the calculation method, defining the strength input parameters, and determining the target mean compressive strength. In concrete mix design, the specified characteristic strength cannot be used directly as the design mean value because of production variability, batching accuracy, curing conditions, and testing scatter. This follows the statistical basis of ACI practice, in which the required average strength is set higher than the specified strength by an amount determined by the standard deviation of prior concrete test results; ACI 214R also provides statistical procedures for interpreting variability in concrete strength-test results [43]. EN 206 and BS 8500 apply the same quality-control principle through compressive strength

classes and conformity assessment [31–33]. On the platform, when statistical data are available, the target mean strength is obtained as:

$$f_{cm} = \max(f_c + 1.34s + 1.5, f_c + 2.33s - 4) \quad (10)$$

where f_{cm} is the target mean compressive strength, f_c is the specified characteristic compressive strength, and s is the standard deviation of compressive strength results. This ensures that the selected mix is not only designed to reach the specified strength but also to achieve it reliably under expected production variability.

Precast Tunnel Lining Segments Mix Design Completed Viewing example (read-only) Edit Report Project Summary

2026 | 02 | 13 • buggy-tailgating

Target Strength Need Help? Calculate target strength with safety margins

< Previous Cement & Aggregates Target Strength < 5 of 13 > Next > Aggregate Gradation

1. Calculation method

Select Calculation Method
Choose the method based on available data and project requirements

Method
2. Based on Statistical Data

How do we calculate this?

2. Strength input parameters

Characteristic Compressive Strength (f_c) MPa
45
This is the specified characteristic strength from project requirements or codes

Standard Deviation (σ) MPa
3.5
Enter the standard deviation from laboratory test results or previous similar projects

Calculation

Formula 1 Result
51.19 MPa
 $f'_{c,m} = f'_c + 1.34s + 1.5$
Recommended

Formula 2 Result
49.16 MPa
 $f'_{c,m} = f'_c + 2.33s - 4$

3. Target strength outputs

4. Recommended target mean strength

Calculation Steps

1	Characteristic Strength (f'_c) = 45.0 MPa	1	Characteristic Strength (f'_c) = 45.0 MPa
2	Standard Deviation (σ) = 3.50 MPa (user input)	2	Standard Deviation (σ) = 3.50 MPa (user input)
3	Margin = $1.34 \times \sigma + 1.5 = 1.34 \times 3.50 + 1.5 = 6.19$ MPa	3	Margin = $2.33 \times \sigma - 4.0 = 2.33 \times 3.50 - 4.0 = 4.16$ MPa
4	Target Strength (f'_{cm}) = $f'_c + \text{Margin} = 45.0 + 6.19 = 51.19$ MPa	4	Target Strength (f'_{cm}) = $f'_c + \text{Margin} = 45.0 + 4.16 = 49.16$ MPa

5. Step-by-step calculation

Figure 7. Annotated view of Tab 5: Target Strength.

When sufficient strength-test records are available, the platform allows s to be calculated from previous or similar production data as:

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}} \quad (11)$$

where x_i is an individual compressive strength result, $\bar{x}$ is the mean strength, and n is the number of test results. If reliable statistical data are not available, the platform permits alternative routes, including direct input, estimation from similar projects, plant-quality classification, or use of a conservative safety margin:

$$f_{cm} = f_c + SM \quad (12)$$

where SM is the adopted safety margin. Therefore, Tab 5 serves as the platform's statistical safety layer: it converts the specified design strength into a target production strength for subsequent calculations of the water–cement ratio and cement content. This reflects the same practical logic used in international concrete standards, where mix proportions must account for both structural strength requirements and the variability of concrete production.

2.6. Tab 6—Aggregate Gradation

Tab 6 controls the aggregate grading and optimizes the proportions of each aggregate fraction to achieve the desired particle-size distribution. As shown in Figure 8, the platform presents the individual gradation curves for coarse gravel, fine gravel, and sand, along with reference grading Curves A, B, and C. These curves are based on the German DIN 1045/DIN 1045-2 aggregate grading envelope concept, which has been widely used in concrete mix proportioning to define acceptable granulometric boundaries for combined aggregates [37]. In this framework, Curve A generally represents the coarser side of the

grading envelope, Curve B represents an intermediate or well-balanced grading region, and Curve C represents the finer, more cohesive side of the grading envelope. The recommended grading domain is commonly described in the literature as the region bounded by these DIN-based boundary curves, whereas Fuller-type grading concepts are used to achieve dense packing and reduced void content [38].

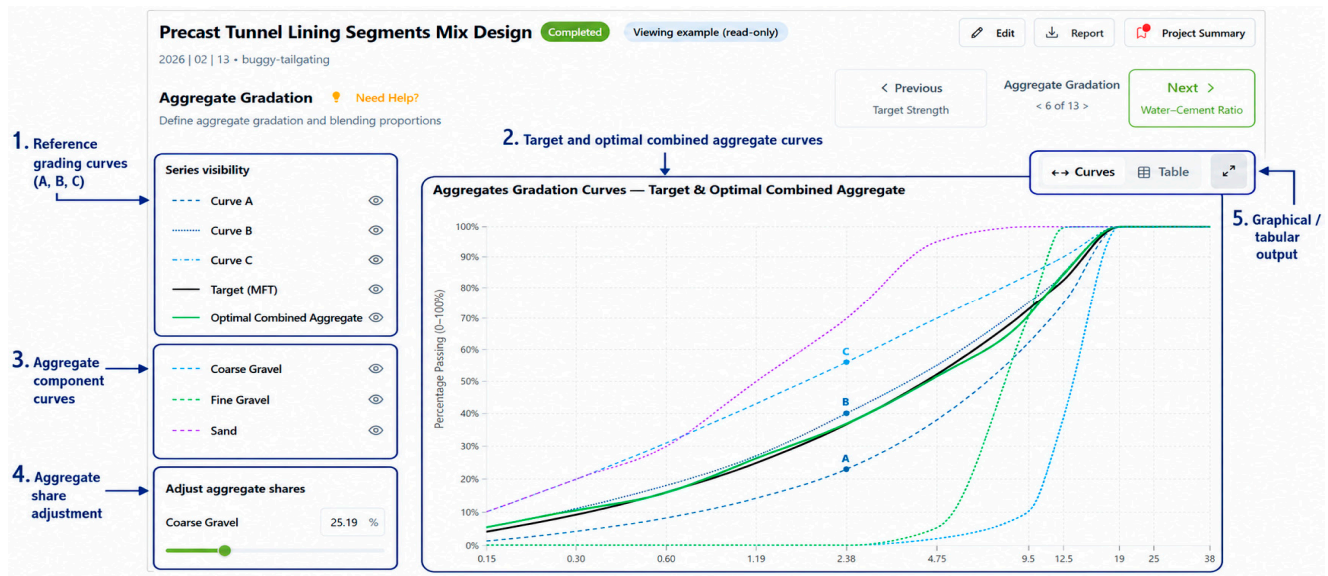


Figure 8. Annotated view of Tab 6: Aggregate Gradation.

Mathematically, the platform determines the combined aggregate curve by calculating the weighted contribution of each aggregate fraction at every sieve size:

$$P_{com}(dj) = \sum_{i=1}^n x_i P_i(d_j) \quad (13)$$

This is subjected to

$$\sum_{i=1}^n x_i = 1, 0 \leq x_i \leq 1 \quad (14)$$

where $P_{com}(dj)$ is the combined passing percentage at sieve size dj , $P_i(d_j)$ is the passing percentage of the aggregate fraction i , and x_i is the selected mass fraction of that aggregate. The target grading curve may be expressed using a Fuller-type relationship:

$$P_{tar}(d) = 100 \left(\frac{d}{D} \right)^n \quad (15)$$

where D is the nominal maximum aggregate size and n controls the fineness or coarseness of the grading curve. The platform intelligently adjusts the aggregate percentages by minimizing the deviation between the combined grading curve and the selected target curve:

$$\min \sum_{j=1}^m [P_{com}(d_j) - P_{tar}(d_j)]^2 \quad (16)$$

The minimization in Equation (16) is performed using a deterministic constrained least-squares optimization. The aggregate mass fractions are treated as design variables, subject to non-negativity constraints and the condition that their sum equals 1. Because the number of aggregate fractions is limited and the objective function is smooth, a deterministic least-squares/nonlinear programming routine was adopted rather than a genetic algorithm.

Therefore, Tab 6 does not only visualize aggregate gradation; it automatically identifies aggregate proportions that best match the desirable grading curve according to the required workability, placement method, and performance demand.

2.7. Tab 7—Water–Cement Ratio

Tab 7 determines the design water–cement ratio from the required target compressive strength, cement strength class, aggregate shape, and the durability limit defined in the previous exposure-control stage. As shown in Figure 9, the platform first evaluates the strength-based water–cement ratio from the selected performance curve and then compares it with the maximum allowable durability value. This approach is consistent with the classical Abrams' law concept, in which the compressive strength of fully compacted concrete is governed primarily by the free-water–cement ratio for a given cement type, test age, and curing condition [52,53]. ACI 211.1 similarly treats the water–cement ratio as a key proportioning parameter for estimating strength [21]. ACI 318 requires the final selected value to satisfy exposure-related durability limits [22], while EN 206/BS 8500 apply comparable exposure-based limits [31–33].

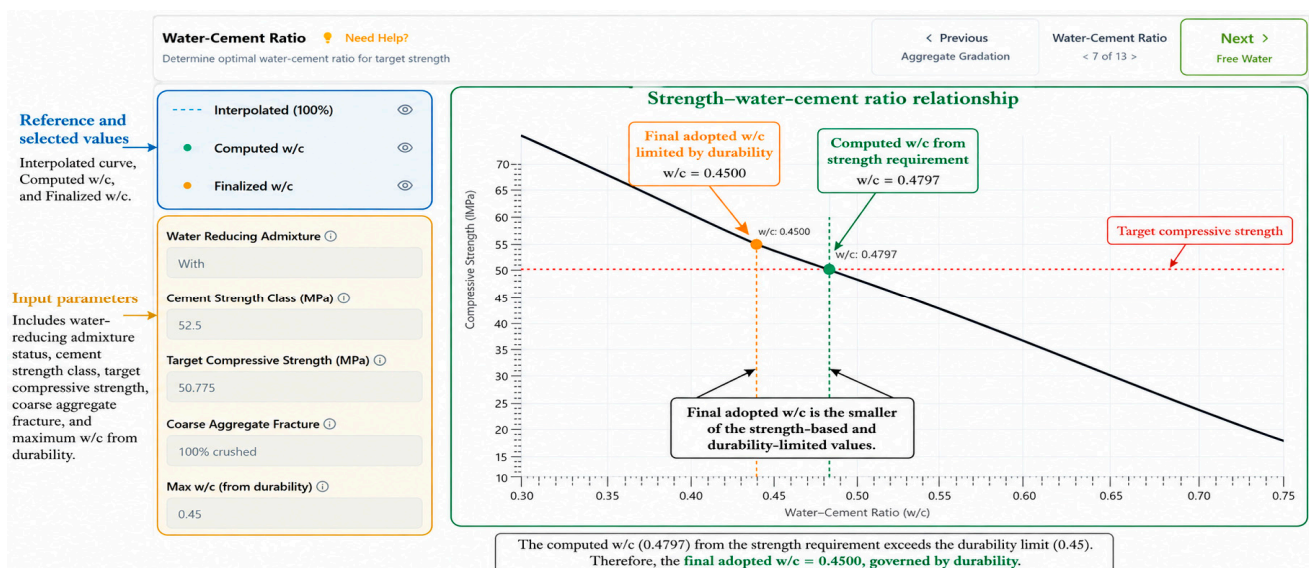


Figure 9. Annotated view of Tab 7: Water–Cement Ratio.

Mathematically, the strength-based relationship may be expressed in general form as $f_c = F\left(\frac{w}{c}\right)$ or, using an Abrams-type expression, as:

$$f_c = AB^{-\left(\frac{w}{c}\right)} \quad (17)$$

where f_c is the compressive strength and A and B are material-dependent empirical constants. On the platform, the calculated value is obtained from the calibrated strength – $\left(\frac{w}{c}\right)$ curves and may be interpolated according to aggregate shape or fracture percentage. The strength–water/cement relationship is selected according to cement strength class and aggregate condition. Separate calibration for CEM I, CEM II, CEM III, or SCM-rich systems is recommended when project-specific test data are available; otherwise, the calculated value is treated as a preliminary estimate requiring trial-batch verification.

For partially crushed aggregate, the interpolated value can be expressed as:

$$\left(\frac{w}{c}\right)_\alpha = (1 - \alpha)\left(\frac{w}{c}\right)_R + \alpha\left(\frac{w}{c}\right)_C \quad (18)$$

where $(\frac{w}{c})_R$ and $(\frac{w}{c})_C$ are the values corresponding to the rounded and crushed aggregate curves, respectively, and α is the normalized fracture ratio. The final adopted value is then governed by:

$$(\frac{w}{c})_d = \min \left[\left(\frac{w}{c} \right)_{strength}, \left(\frac{w}{c} \right)_{max,durability} \right] \quad (19)$$

2.8. Tab 8—Free Water

Tab 8 estimates the free-water content required to achieve the selected workability, considering the combined aggregate grading and particle shape. As shown in Figure 10, the platform relates to the fineness modulus, target slump, and average aggregate fracture condition. This follows the proportioning logic of ACI 211.1, in which the water required to achieve a given slump depends on the nominal maximum aggregate size, particle shape, surface texture, grading, concrete temperature, air content, and the use of admixtures [21]. EN 206 and BS 8500 also define workability through consistency classes, with the S3 class corresponding to a slump range of approximately 100–150 mm [31–33]. Therefore, the platform treats free water not as a fixed tabular value, but as a workability-controlled design variable:

$$W_f = f(S_t, FM, \alpha, A_{air}, Ad) \quad (20)$$

where S_t is the target slump, FM is the fineness modulus of the combined aggregate, α is the aggregate angularity or fracture index, A_{air} is the air content, and Ad represents admixture effects.

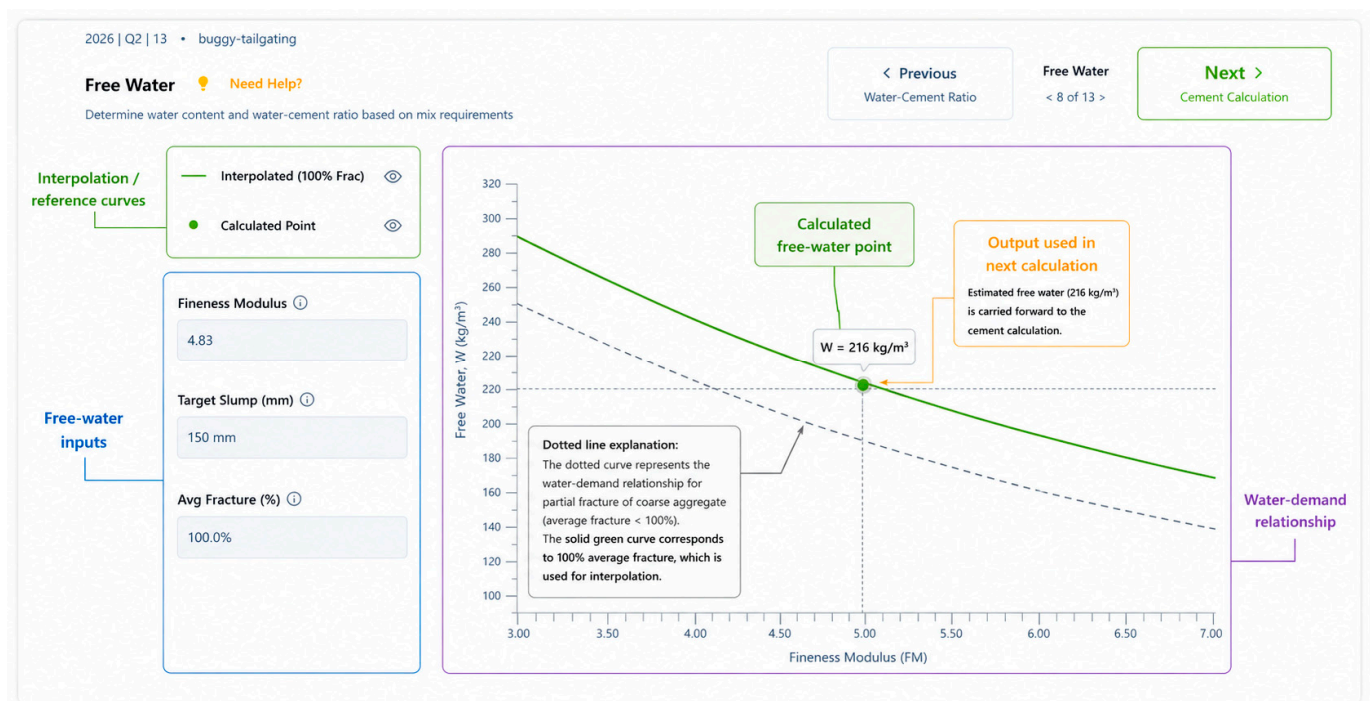


Figure 10. Annotated view of Tab 8: Free Water.

When the aggregate condition lies between rounded and crushed reference curves, the platform can interpolate the water demand as:

$$W_f(\alpha) = (1 - \alpha)W_R + \alpha W_C \quad (21)$$

where W_R and W_C are the water contents associated with rounded and crushed aggregate curves, respectively. A further interpolation may be applied between standard slump curves to match the exact target slump. This approach allows Tab 8 to connect workability,

aggregate packing, particle shape, and admixture effects before the cement content is calculated, ensuring that the subsequent $\frac{w}{c}$ and cement-demand calculations are based on a realistic free-water requirement.

2.9. Tab 9—Cement Calculation

Tab 9 determines the cementitious content based on the previously selected free-water content and the adopted water–cement ratio and then checks the result against the cement-content limits imposed by the durability and exposure requirements. This is consistent with ACI 211.1, in which concrete proportions are selected and adjusted using the absolute-volume method, considering aggregate gradation, workability, strength, and durability requirements [21]. It is also aligned with EN 206 and BS 8500 practice, in which exposure class requirements are commonly expressed as limiting values, such as minimum cement content and maximum free-water/cement ratio; the most onerous exposure requirement governs the final specification [31–33]. In the platform, the initial cement content is therefore calculated as:

$$C_{init} = \frac{W_f}{\left(\frac{w}{c}\right)_d} \quad (22)$$

where C_{init} is the initial cement content, W_f is the selected free-water content, and $\left(\frac{w}{c}\right)_d$ is the finalized design water–cement ratio.

The calculated cement content is then verified against the allowable range defined by the governing exposure condition,

$$C_{min,E} \leq C_d \leq C_{max,E} \quad (23)$$

and where supplementary cementitious materials are included, an equivalent binder expression may be used:

$$C_{eq} = C + \sum_{i=1}^n k_i M_i \quad (24)$$

$C_{eq} M_i S C M k_i$ is derived from the logic of ACI 318 and ACI 301, where limits on water–cementitious material ratios are used to control permeability and improve resistance to aggressive exposure [22,54]. The required water reduction can be expressed as:

$$R_w = \frac{W_{base} - W_{adj}}{W_{base}} \times 100 \quad (25)$$

$$M_{adm} = \frac{d_{adm}}{100} B \quad (26)$$

where R_w is the required water reduction, W_{base} is the unadjusted free-water demand, W_{adj} is the adjusted free-water content, M_{adm} is the admixture mass, d_{adm} is the admixture dosage expressed as a percentage of the total binder mass, and B is the total binder content. Thus, as shown in Figure 11, Tab 9 serves as the platform's cement-content compliance and adjustment module, linking water demand, cementitious content, durability limits, and admixture demand within a single standards-informed calculation.

Precast Tunnel Lining Segments Mix Design Completed Viewing example (read-only) Edit Report Project Summary

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Cement Calculation Need Help? < Previous Free Water Cement Calculation < 9 of 13 > Next > Aggregate Calculation

Calculate cement content based on water-cement ratio

Initial Cement Content Calculation

Free Water	Water–Cement Ratio (W/C)	Initial Cement Content
kg/m ³ 216.00	0.450	kg/m ³ 480.00

Free Water Adjustment

Additional Water per 10 kg cement above 350 kg/m³ – 1.50 + Computed Extra Free Water kg/m³ 19.50

No SCMs selected.

Revised Cement, Free Water, and W/C

Revised Free Water	Water–Cement Ratio (W/C)	Revised Cement (without k)
kg/m ³ 235.50	0.45	kg/m ³ 523.33

Cement Content Compliance Status

Exceeds maximum limit — calculated cementitious content without k-factor exceeds maximum. Reduce cement content or adjust mix parameters.

Minimum Cement Content	Calculated Cement	Maximum Cement Content
kg/m ³ 400	kg/m ³ 523.33	kg/m ³ 450

Water-Reducing Admixture Demand

Calculated cement content exceeds the maximum limit — choose a preferred cement content (Maximum or Max-50).

Preferred cement content	Revised Free Water – 2nd edition
Maximum (450)	kg/m ³ 202.500
Adjusted (400)	kg/m ³ 231.00

Base water + SCM effects + > 350 rule

Required free-water reduction	Superplasticizer dosage	% of binder	Quantity of admixture
kg/m ³ 12.34		0.42	kg/m ³ 1.87

Finalized Values

Cement Content	Free Water Content
kg/m ³ 450.00	kg/m ³ 202.50
Water–Cement Ratio (W/C)	Water-Reducing Admixture
0.450	kg/m ³ 1.87

Figure 11. Annotated view of Tab 9: Cement Calculation.

2.10. Tab 10—Aggregate Calculation

Tab 10 converts the finalized cement, free-water content, air content, and aggregate-blending proportions into aggregate quantities using the absolute-volume method. As shown in Figure 12, this tab calculates the available aggregate volume by subtracting the volumes of cement, water, SCMs/admixtures, and air from 1 cubic meter of concrete. This procedure is consistent with ACI 211.1, which bases normal-density concrete proportioning on the absolute volumes occupied by each constituent [21], and with EN 206/BS 8500 practice, where final mix proportions must be traceable to specified materials, exposure requirements, production control, and conformity criteria [31–33]. ASTM C127 and ASTM C128 further support this step by defining aggregate relative density, absorption, and SSD/OD conditions for coarse and fine aggregates, which are necessary for reliable volumetric batching calculations [29,30]. The available aggregate volume may be expressed as:

$$V_{agg} = 1 - \left(\frac{C}{\rho_c} + \frac{W_f}{\rho_w} + \sum_{j=1}^m \frac{M_{SCM,j}}{\rho_{SCM,j}} + V_{air} \right) \quad (27)$$

where V_{agg} is the total aggregate volume, C is the cement mass, W_f is the free water, ρ_c and ρ_w are the densities of cement and water, $M_{SCM,j}$ is the mass of SCM, j , and V_{air} is the total air volume.

The platform then distributes V_{agg} among the aggregate fractions according to the optimized gradation shares obtained in Tab 6. For each aggregate fraction i , the SSD volume and mass are calculated as:

$$V_i = x_i V_{agg} \quad (28)$$

$$M_{SSD,i} = V_i \rho_{SSD,i} \quad (29)$$

where x_i is the selected aggregate share and $\rho_{SSD,i}$ is the SSD density. Moisture and absorption corrections are then applied to convert SSD quantities into practical batching masses:

$$M_{OD,i} = \frac{M_{SSD,i}}{1 + A_i} \quad (30)$$

$$M_{batch,i} = M_{OD,i} (1 + MC_i) \quad (31)$$

$$W_{batch} = W_f + \sum_{i=1}^n M_{OD,i}(A_i - MC_i) \quad (32)$$

where A_i is the absorption and MC_i is the actual moisture content of aggregate i . These calculations are consistent with standard aggregate characterization and moisture-correction practices, in which SSD, oven-dry and wet conditions must be distinguished before batching. Consequently, Tab 10 serves as the platform's volumetric proportioning and batching-conversion layer, ensuring that the final mixture is expressed not only as a theoretical design but also as practical plant quantities with corrected aggregate masses, mixing water, fresh unit weight, and volume distribution.

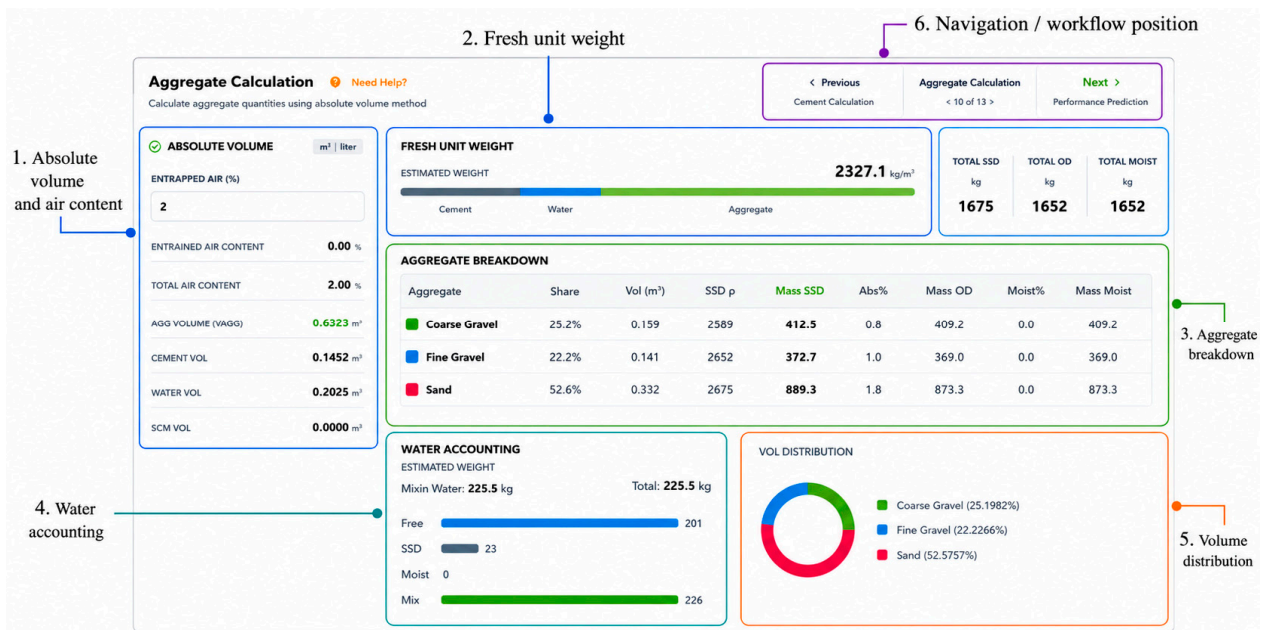


Figure 12. Annotated view of Tab 10: Aggregate Calculation.

2.11. Tab 11—Performance Prediction

Tab 11 extends the conventional mix-design workflow from proportioning to performance, cost, and environmental assessment. As shown in Figure 13, the platform summarizes the finalized concrete constituents and reports the cost and embodied carbon per cubic meter of concrete. This function complements EN 206, which addresses concrete specification, performance, production, and conformity [31], by adding a quantitative decision-support layer for sustainability and economic evaluation. The cost of the mixture is calculated as the mass-weighted sum of constituent unit prices:

$$C_{mix} = \sum_{i=1}^n m_i p_i \quad (33)$$

where C_{mix} is the total cost per 1 m³ of concrete, m_i is the mass of constituent i , and p_i is its unit price. Similarly, embodied carbon is calculated using a life-cycle-based mass-weighted expression:

$$EC_{A1-A3} = \sum_{i=1}^n m_i EF_i \quad (34)$$

where the A1–A3 boundary covers raw material supply, transport, and manufacturing. This calculation structure is consistent with the environmental assessment principles of ISO 14044 [44] and the EPD framework for construction products under ISO 21930 and EN 15804 [41,42]. The embodied-carbon calculation is based on cradle-to-gate A1–A3

emission factors expressed as kg CO₂e/kg of material. The default factors are representative screening values and may be replaced by supplier-specific EPDs, regional LCA databases, or internal project databases.

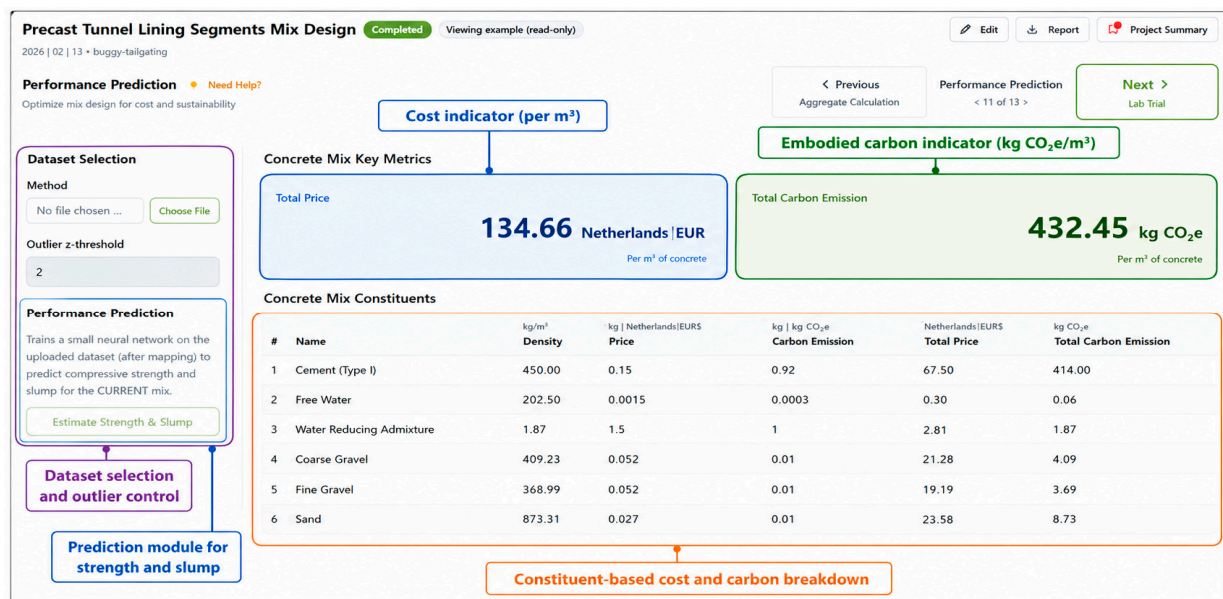


Figure 13. Annotated view of Tab 11: Performance Prediction.

In addition to cost and carbon reporting, Tab 11 provides an optional dataset-based prediction module for compressive strength and slump. The dataset is filtered using an outlier threshold, which may be expressed through the standard z-score:

$$z_i = \frac{x_i - \mu}{\sigma} \quad (35)$$

where x_i is an observed value, μ is the dataset mean, and σ is the standard deviation. After filtering, the platform can train a predictive model to estimate fresh and hardened concrete performance from mixture parameters:

$$\hat{y} = f_{\theta}(C, W, A_{coarse}, SCM, AD, \rho, \dots) \quad (36)$$

This data-driven function does not replace standard conformity testing; rather, it supports rapid screening and optimization before laboratory validation. Therefore, Tab 11 links mix constituents, unit cost, embodied carbon, and predicted performance into a single decision-support environment, while final compliance remains governed by laboratory testing and production-control requirements under standards such as EN 206 [31].

2.12. Tab 12—Laboratory Trial

Tab 12 presents the laboratory validation stage of the platform, which involves converting the finalized mix design into a selected trial-batch volume and recording measured fresh and hardened concrete properties. As shown in Figure 14, each constituent is scaled proportionally according to $m_{i,trial} = m_{i,1m3} V_{trial}$, where $m_{i,trial}$ is the laboratory batch mass of constituent i , $m_{i,1m3}$ is its quantity per cubic metre in the finalized mixture, and V_{trial} is the selected trial-batch volume in cubic metres. This step is consistent with standard concrete quality-control practice, in which trial mixtures are verified by measured slump, air content, fresh density, and compressive strength before implementation. ASTM C143/C143M and EN 12350-2 define slump testing for fresh concrete consistency [55,56], ASTM C138/C138M and EN 12350-6 cover fresh concrete density [57,58], ASTM C231/C231M and EN 12350-7

address air-content determination [59,60], and ASTM C39/C39M and EN 12390-3 define the compressive-strength testing of hardened specimens [61,62].

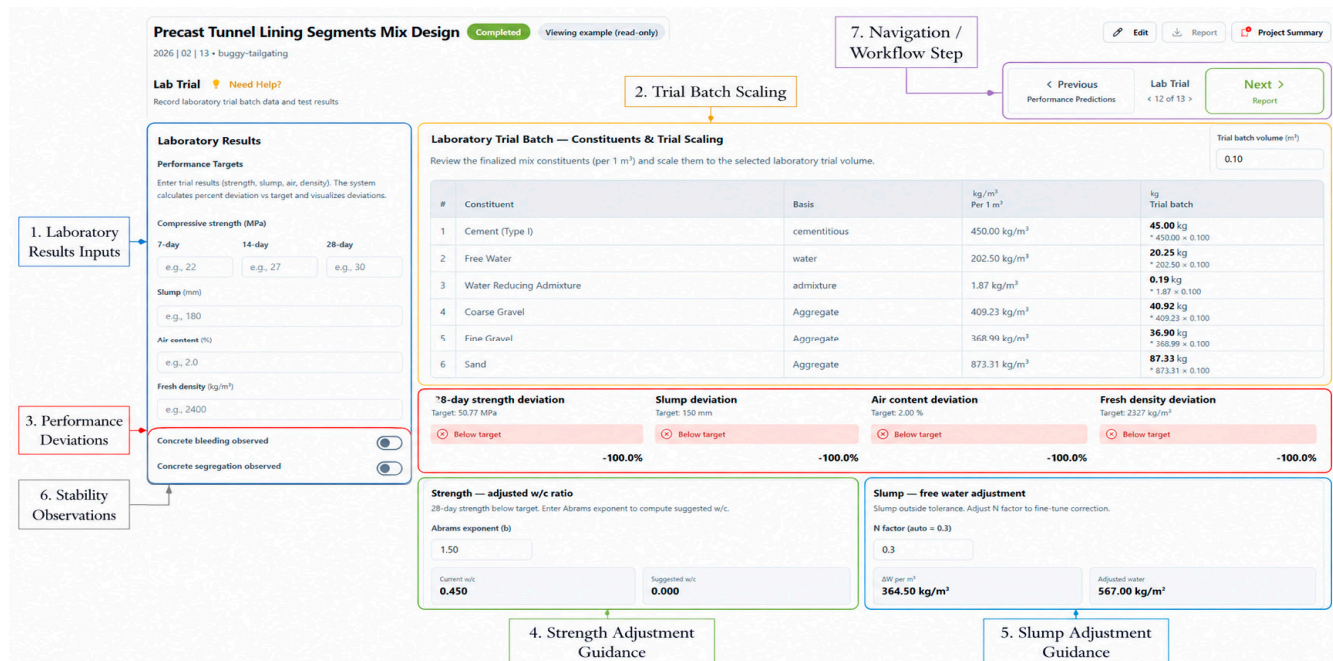


Figure 14. Annotated view of Tab 12: Laboratory Trial Batch.

The tab also establishes a feedback loop between trial results and the design targets required for EN 206 conformity and production-control principles [31]. The deviation of a measured property from its target may be expressed as:

$$\delta_y = (y_{meas} - y_{target}) / y_{target} \times 100\% \quad \Delta w = N(S_t - S_m) S_t S_m N\left(\frac{w}{c}\right)_{new} = \left(\frac{w}{c}\right)_0 + \left(\frac{w}{c}\right)_0 [(f_{c,meas} - f_{cm}) / f_{cm}] \quad (37)$$

The preceding section described the methodological structure and calculation logic of the proposed platform, including project definition, exposure limits, material characterization, mix-design computation, performance prediction, laboratory trial, and reporting modules. The following section shifts from platform methodology to application results by presenting the precast tunnel-lining case study, the input data used in the calculations, and the comparative mix-design outputs obtained with the EcoStruct platform, the BRE method, and SP 23:1982.

3. Results: Case Study and Comparative Mix-Design Outputs

A case study was conducted for a precast tunnel-lining segment concrete mixture to evaluate and compare the mix proportions obtained with two conventional standards-based procedures and the proposed EcoStruct platform. Figure 15 shows the laboratory preparation and characterization of aggregate fractions, fresh-concrete handling and workability assessment, mixing equipment, and compressive-strength testing.

The selected case represented a high-workability precast concrete mixture with a specified compressive strength class of 45 MPa, a target slump of approximately 150 mm, 20 mm maximum aggregate size, crushed aggregate, a durability-controlled maximum water–cement ratio of 0.45, and a cement-content envelope of 400–450 kg/m³. The main case-study specifications, material properties, and aggregate sieve analysis used as platform inputs are summarized in Tables 2 and 3.



Figure 15. Experimental tests of the tunnel-lining concrete case study.

Table 2. Case-study specifications and aggregate properties.

Category	Input Data
Application and production	Precast tunnel-lining segment; automatic batching; bucket transport; mold casting; vibration compaction
Performance requirements	$f_{ck} = 45$ Mpa at 28 days; $S = 3.5$ MPa; slump = 150 mm; required finis: excellent
Mix constrains	$W/C_{max} = 0.45$; cement content = 400–450 kg/m ³
Cement	Portland cement Type I—525; standard mortar strength = 53 MPa, particle density = 3.10 t/m ³
Admixture	Polycarboxylate superplasticizer; density = 1.08, dosage = 0.4–1.5% by cement mass; water reduction = 12–35%
Aggregate properties	Coarse gravel: $G_{SSD} = 2.589$; absorption = 0.8%; fine gravel: $G_{SSD} = 2.652$; absorption = 1.0%; sand: $G_{SSD} = 2.675$; absorption = 1.8%, All aggregates were fully crushed

Table 3. Aggregate sieve analysis used in the case study.

Sieve, mm	19.0	12.5	9.5	6.35	4.75	2.38	1.19	0.60	0.30	0.15
Coarse gravel, passing %	100	40	10	2	0	0	0	0	0	0
Fine gravel, passing %	100	100	70	25	5	0	0	0	0	0
Sand, passing %	100	100	100	100	95	70	50	30	20	10

The calculations were benchmarked against the BRE mix-design method and SP 23:1982, which are documented stepwise procedures for concrete mix proportioning [63,64]. The BRE-based design results are summarized in Table 4. In this method, the durability requirement governed the mixture, and a water–cement ratio of $W/C = 0.45$ was adopted. After applying a 12% water reduction, the free-water content decreased from 225 to 198 kg/m³, producing a cement demand of 440 kg/m³. The aggregate content was then

determined from the estimated fresh density, leading to 805 kg/m³ sand, 300 kg/m³ fine gravel and 605 kg/m³ coarse gravel under SSD conditions [63].

Table 4. BRE-based mix-design calculation.

Stage	BRE Reference	Main Equation/Basis	Calculation	Adopted Value
1. Target strength and W/C	Sections 4.4 and 5.1, Figure 3, Table 2, Figure 4	$M = ks; f_m = f_{ck} + M$	$S = 4.0$ MPa from Figure 3; $M = 1.64(4.0) = 6.56$ MPa; $f_m = 45 + 6.56 = 51.56 \approx 52$ MPa. From Table 2 and Figure 4, strength-based $W/C \approx 0.52$, but specified limit controls	$W/C = 0.45$
2. Free-water content	Section 5.2, Table 3	Water selected from slump, aggregate type, and maximum aggregate size	For 20 mm crushed aggregate and slump 60–180 mm: $W_f = 225$ kg/m ³ With 12% SP water reduction: $W_f = 225(1 - 0.12) = 198$ kg/m ³	$W_f = 198$ kg/m ³
3. Cement content	Section 5.3, Equation (C3)	$C = \frac{W_f}{W/C}$	$C = \frac{198}{0.45} = 440$ kg/m ³ Check: $400 \leq 440 \leq 450$ kg/m ³	$C = 440$ kg/m ³
4. Total aggregate content	Section 5.4, Figure 5, Equation (C4)	$A = D - C - W_f$	For $G_{agg} \approx 2.64$ and $W_f = 198$ kg/m ³ Figure 5 gives $D \approx 2350$ kg/m ³ . Thus, $A = 2350 - 440 - 198 = 1712 \approx 1710$ kg/m ³	$A = 1710$ kg/m ³
5. Fine/coarse aggregate split	Section 5.5, Figure 6, Equation (C5)	$F = A_{pf}, CA = A - F$	For 20 mm aggregate and slump of 60–180 mm: $W/C = 0.45$ and sand with 30% passing, 600 μ m Figure 6 gives: $p_f \approx 47\%$. Thus, $F = 1710(0.47) = 805$ kg/m ³ and $CA = 1710 - 805 = 905$ kg/m ³ Coarse aggregate split of 1:2 gives 300 and 605 kg/m ³	Sand = 805, fine gravel = 300, coarse gravel = 605 kg/m ³
6. Moisture correction	Section 6.1	$M_{dry} = \frac{M_{SSD}}{1 + A_p}; W_t = W_f + W_{abs}$	Sand = $805/1.018 = 791$; fine gravel = $300/1.010 = 297$; coarse gravel = $605/1.008 = 600$ kg/m ³ $W_{abs} = 22$ kg/m ³ ; $W_t = 198 + 22 = 220$ kg/m ³	Dry batching; water = 220, sand = 791, fine gravel = 297, coarse gravel = 600 kg/m ³

The Indian Standard-based design procedure is summarized in Table 5. In accordance with SP 23:1982, the mix was first classified as M45 concrete with 20 mm crushed aggregate and a target slump of 150 mm. The target mean strength was calculated using the plant standard deviation, yielding approximately 51 MPa. The water–cement ratio was then selected from the strength-based relationship and checked against the durability limit; the strength requirement governed the design, resulting in an adopted $W/C = 0.35$, which is lower than the specified maximum value of 0.45 [64]. This indicates that under the SP 23 procedure, the mixture is controlled primarily by strength demand rather than only by the durability limit.

Table 5. SP 23:1982-based mix-design calculation.

Step	SP 23 Reference	Equation/Standard Basis	Calculation	Adopted Result
1. Design data	Section 6.4	Required data: f_{ck} , workability, W/C limit, cement limit, aggregate size/type, and standard deviation	$f_{ck} = 45$ MPa; max aggregate = 20 mm; crushed aggregate; slump = 150 mm; $W/C_{max} = 0.45$ cement = 400–450 kg/m ³	M45 concrete, 20 mm aggregate
2. Target mean strength	Section 6.4, Equation (1), Table 30	$f_t = f_{ck} + KS$; or 5% low results $K = 1.65$	Given plant $S = 3.5$ MPa: $f_t = 45 + 1.65(3.5) = 50.8$ MPa. If no plant data exist, Table 39 gives higher values for M45.	$f_t \approx 51$ MPa
3. Water–cement ratio	Section 6.4, Figure 46/Figure 47	Select W/C from strength curve, and compare with durability limit	For $f_t \approx 51$ MPa and cement strength around 52.5 MPa, Figure 46/47 gives $W/C = 0.35$. This is lower than $W/C_{max} = 0.45$	$W/C = 0.35$
4. Workability conversion	Table 20	Slump of 150–175 mm corresponds approximately to flowing concrete with compacting factor $CF \approx 0.95$	Target slump = 150 mm → $CF \approx 0.95$	$CF \approx 0.95$
5. Entrapped air	Table 41	For 20 mm aggregate, entrapped air = 2%	$V = 1 - 0.02 = 0.98$ m ³	$V = 0.98$ m ³
6. Water and sand content	Table 43 and Table 44	For concrete above M35: at $W/C = 0.35$, $CF = 0.80$, 20 mm aggregate: $W = 180$ kg/m ³ and sand = 25%. Table 44 adjusts for workability and sand grading	Workability adjustment: $W = 180 \left[1 + \frac{0.03(0.95-0.8)}{0.10} \right] = 188.1$ kg/m ³ Sand is zone I, so $p = 25 + 1.5 = 26.5\%$.	Before SP: $W = 188.1$ kg/m ³ $P = 0.265$
7. Cement content and SP correction	Section 6.4	$C = \frac{W}{W/C}$ Check cement limit	Without SP: $C = \frac{188.1}{0.35} = 537$ kg/m ³ > 450. Therefore, using the permitted polycarboxylate SP, water was reduced to satisfy C_{max} : $W = 0.35(450) = 157.5$ kg/m ³ Water reduction = $\frac{188.1-157.5}{188.1} = 16.3\%$, within the 12–35% SP range	$C = 450$ kg/m ³ ; $W = 157.5$ kg/m ³
8. Aggregate volume	Section 6.4, Equations (2) and (3)	$V_{agg} = V - \frac{W}{1000} - \frac{C}{S_c 1000}$	Using $S_c = 3.10$: $V_{agg} = 0.98 - 0.1575 - \frac{450}{3.10 \times 1000} = 0.677$ m ³	$V_{agg} = 0.677$ m ³
9. Fine aggregate mass	Section 6.4, Equations (2) and (3)	$V_{FA} = pV_{agg}$; $M_{FA} = V_{FA} S_{FA} 1000$	$V_{FA} = 0.265(0.677) = 0.1795$ m ³ ; $M_{FA} = 0.1795(2.675)(1000) = 480$ m ³	sand = 480 kg/m ³ SSD
10. Coarse aggregate mass	Section 6.4, Equations (2) and (3)	$V_{CA} = (1-p)V_{agg}$; $M_{CA} = V_{CA} S_{CA} 1000$	$V_{CA} = 0.735(0.677) = 0.498$ m ³ ; Using combined coarse aggregate $S_{CA} \approx 2.614$ $M_{CA} = 0.498(2.614)(1000) = 1301$ kg/m ³ . Split 60: 40 into 20 mm and 10 mm fractions	20 mm gravel = 781; 10 mm gravel = 521 kg/m ³ SSD
11. Moisture correction	Section 6.4 and trial-batching logic	$M_{dry} = \frac{M_{SSD}}{1+A_b}$; $W_t = W + W_{abs}$	Sand: 480/1.018 = 472; 10 mm gravel: 521/1.010 = 515; 20 mm gravel: 781/1.008 = 775 kg/m ³ . $W_{abs} \approx 220$ kg/m ³ , so $W_t = 157.5 + 20 = 177.5$ kg/m ³	Dry batching water ≈ 177 kg/m ³

The EcoStruct platform results are summarized in Table 6. In this approach, the mixture was designed through a sequential digital workflow beginning with performance

constraints, aggregate-blend optimization, and combined grading control. The platform selected a 25/20/55 aggregate blend, yielding a combined fineness modulus (FM) of 4.75, which was suitable for the required high-workability concrete. Subsequent calculations linked the target strength, durability-controlled W/C, free-water demand, cement adjustment, superplasticizer dosage and absolute-volume aggregate calculation. After trial-batch feedback, the final mixture was adjusted to improve workability and strength, resulting in an accepted mix with controlled cement content, reduced water demand and satisfactory fresh and hardened concrete performance.

Figure 16 compares the final mix constituents obtained with the BRE method, the SP 23:1982 method and the EcoStruct platform [63,64]. The SP 23:1982 mix used the highest cement content (450 kg/m^3) and the lowest free-water content (158 kg/m^3 before absorption correction), mainly because the method selected a relatively low W/C of 0.35 to reach the M45 target strength. The BRE and EcoStruct designs both used 440 kg/m^3 of cement, but the EcoStruct platform reduced the free-water content to 190 kg/m^3 compared with 198 kg/m^3 in the BRE mix, owing to the combined effect of aggregate grading selection and water-reducing admixture adjustment. The three methods also produced very different aggregate skeletons. The BRE method generated a more balanced sand/coarse aggregate split, the SP 23:1982 method produced the lowest sand content and the highest coarse aggregate content, while the EcoStruct platform shifted the mixture toward a sand-rich and continuous grading structure suitable for a high-workability tunnel-lining segment.

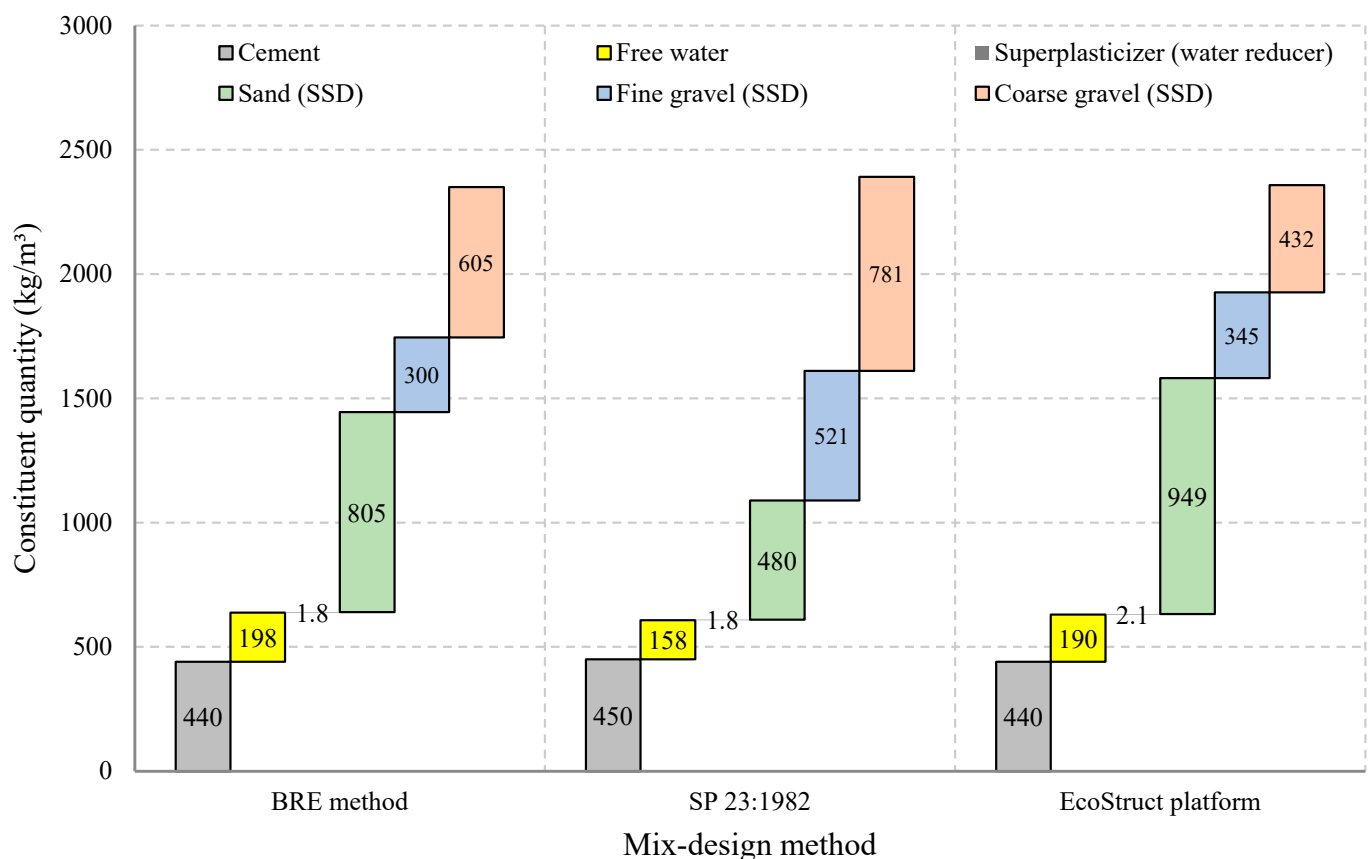


Figure 16. Comparison of final mix constituents obtained with the BRE method, the SP 23:1982 method and the EcoStruct platform.

Table 6. EcoStruct platform mix-design calculation.

Platform Step	Design Basis	Equation/Platform	Calculation	Adopted Result
1. Project definition	Define performance and constrains	Input: $f_{ck} = 45$ MPa; slump = 150 mm; $W/C_{max} = 0.45$ C = 400–450 kg/m ³ ; excellent finish; crushed aggregate	Tunnel lining requires high workability; dense packing, controlled cement content, and low W/C	Performance-based concrete; S3/high workability
2. Aggregate blend optimization	Select aggregate shares to satisfy target combined grading	Platform searches aggregate fractions to approach the target combined grading envelope, close to B ₁₉	Adopted mass shares; coarse gravel = 25%, fine gravel = 20%; sand = 55%	25/20/55 aggregate blend
3. Combined fineness modulus	Check aggregate fineness and grading balance	$FM = \frac{\sum cumulative\ retained\%}{100}$	$FM = (28 + 47 + 61 + 72 + 82 + 89 + 94) / 100 = 4.75$	FM = 4.75 acceptable for high-workability mix
4. Combined SSD density	Estimate average aggregate density for absolute-volume closure	$\rho_{agg} = \left(\frac{0.25}{2.589} + \frac{0.20}{2.652} + \frac{0.55}{2.675} \right)^{-1}$	Platform rounded value used for mix closure: $\rho_{agg} \approx 2.623$ t/m ³	$\rho_{agg} = 2.623$ t/m ³
5. Target mean strength	Reliability-based strength target	$f_{cm} = f_{ck} + 1.34S + 1.5$ Check also $f_{cm} = f_{ck} + 2.33S - 4$	$45 + 1.34(3.5) + 1.5 = 51.2$ MPa; $45 + 2.33(3.5) - 4 = 49.2$ MPa	$f_{cm} \approx 51$ MPa
6. Water–cement ratio	Strength prediction plus durability limit	Strength module suggests $W/C \approx 0.47$; but durability limit controls $W/C \leq 0.45$	Lower value governs	Preliminary $W/C = 0.45$
7. Free-water demand	Workability, crushed aggregate, and grading correction	Base Platform estimate for 150 mm slump: $W_f = 215$ kg/m ³	Initial cement demand: $C = 215/0.45 = 478$ kg/m ³ > 450 kg/m ³	Water reduction required
8. Cement–water optimization	Respect cement-content range and maintain workability using SP	$C = \frac{W_f}{W/C}$	Platform constraint adjustment: reduce cement to 400 kg/m ³ , and reduce free water to 198 kg/m ³	$C = 400$ kg/m ³ $W_f = 198$ kg/m ³
9. Superplasticizer dosage	Maintain slump after water reduction	$SP\% = \frac{SP}{C} \times 100$	$SP = 2.0$ kg/m ³ gives $SP\% = 2.0/440 \times 100 = 0.45\%$ within 0.4–1.5%. Effective $W_f = 196$ kg/m ³ for preliminary volume calculation.	$SP = 2.0$ kg/m ³ , $W_f = 198$ kg/m ³
10. Total aggregate content	Absolute-volume method	$A_{SSD} = \rho_{agg} \left(1 - \frac{C}{\rho_c} - \frac{W_f}{\rho_w} - V_{air} \right)$	$2.623 \left(1 - \frac{440}{3100} - \frac{196}{1000} - 0.01 \right) \times \frac{A_{SSD}}{1000} \approx 1710$	$A_{SSD} = 1710$ kg/m ³
11. Aggregate split	Apply optimized aggregate proportions	$A_i = p_i A_{SSD}$	Coarse gravel = $0.25(1710) = 427.5$; fine gravel = $0.20(1710) = 342$; sand = $0.55(1710) = 940.5$ kg/m ³	Preliminary SSD aggregate: 428, 342, 941 kg/m ³
12. Dry-batching correction	Correct SSD masses for absorption	$M_{dry} = \frac{M_{SSD}}{1 + A_p}$; $W_t = W_f + W_{abs}$	Coarse = $427.5/1.008 = 424$; fine = $342/1.010 = 338.5$; sand = $940.5/1.018 = 924$; $W_{abs} \approx 23$ kg/m ³ ; $W_t = 196 + 23 = 219.5$ kg/m ³	Total mixer water ≈ 220 kg/m ³
13. Trial-mix feedback	Adjust slump and strength after laboratory trial	Trial result: slump = 165 mm, density = 2360 kg/m ³ , 28-day strength = 48.5 MPa. Platform reduces water and adjusts SP.	Adopt $W_f = 190$ kg/m ³ ; Keep C = 440 kg/m ³ , increase SP ≈ 2.2 kg/m ³ New $W/C = \frac{190}{440} = 0.432$	Final adjustment $W/C = 0.432$
14. Final aggregate recalculation	Absolute volume after trial adjustment	$2.623 \left(1 - \frac{440}{3100} - \frac{190}{1000} - 0.01 \right) \times \frac{A_{SSD}^{new}}{1000}$	$A_{SSD}^{new} \approx 1726$ kg/m ³ , Split 25/20/55L coarse = 432, Fine = 345, sand = 949 kg/m ³	Final SSD aggregate = 1726 kg/m ³
15. Final verification	Fresh density and strength confirmation	$p_{fresh} = C + W_f + A_{SSD}$	$p_{fresh} = 440 + 190 + 1726 = 2356 \approx 2359$ kg/m ³ Verification: slump = 145 mm, air = 1.1%, fresh density = 2350 kg/m ³ , 28-day strength = 51.8 MPa	Mix accepted

4. Discussion

The main practical difference among the three approaches lies in the design philosophy used to satisfy workability, strength, and constructability requirements. The BRE and SP 23:1982 methods mainly follow tabulated or chart-based proportioning sequences, whereas the EcoStruct platform links the selected exposure limits, aggregate gradation, water-reducing admixture demand, cement envelope, and batching corrections in a single workflow [63,64]. As a result, the platform does not simply calculate cement and water from a selected W/C; it first determines the aggregate skeleton and free-water demand, then checks whether cement-content limits are violated, and finally adjusts the admixture demand to remain within the allowable cement range.

Figure 17 normalizes the aggregate skeleton, highlighting this shift more clearly. The BRE mixture contains 47.1% sand, 17.5% fine gravel and 35.4% coarse gravel within the aggregate fraction, while the SP 23:1982 mixture contains 36.0% sand and 64.0% coarse aggregate [63,64]. The EcoStruct mixture contains 55.0% sand, 20.0% fine gravel and 25.0% coarse gravel, giving a finer and more continuous aggregate skeleton. For precast tunnel lining, this is technically important because the mixture must pass through congested reinforcement, fill mold edges, produce a good surface finish and maintain cohesion under vibration. The platform output therefore reflects a more placement-oriented aggregate structure than the two conventional comparator methods.

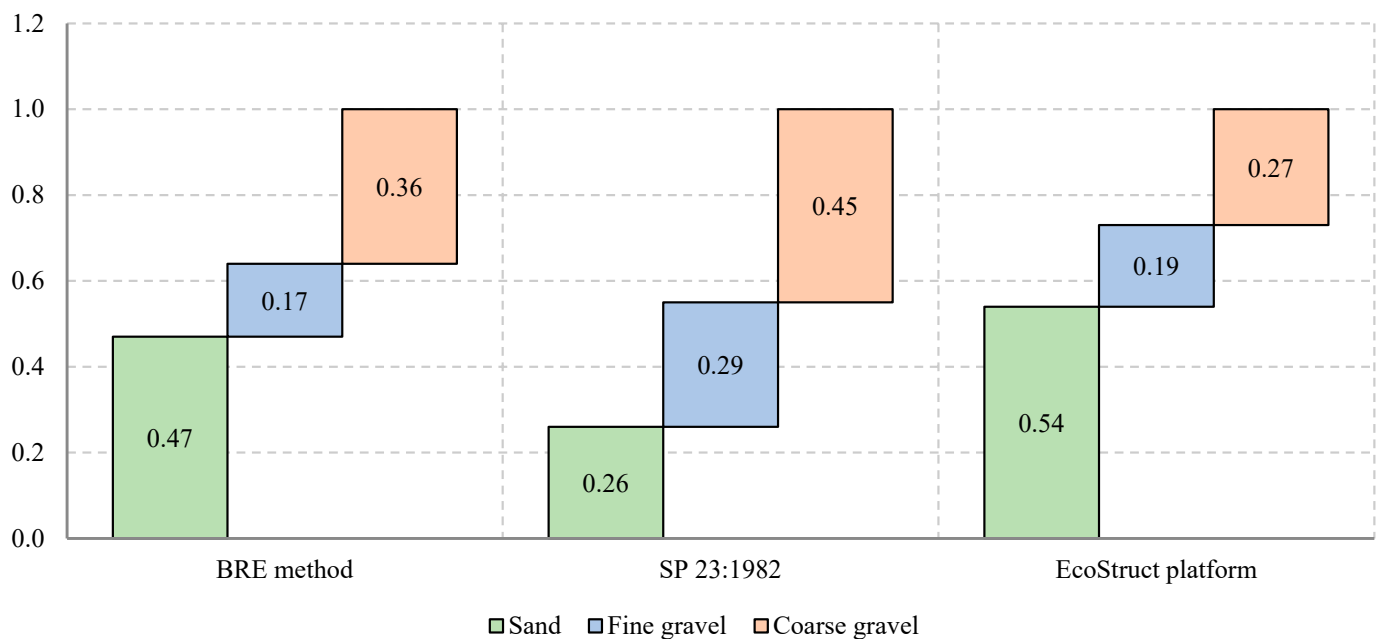


Figure 17. Normalized aggregate-skeleton distribution obtained with the BRE method, the SP 23:1982 method and the EcoStruct platform.

To further clarify the analytical meaning of the comparative results, Table 7 summarizes the main numerical and engineering differences among the BRE, SP 23:1982, and EcoStruct platform outputs. The comparison shows that the platform result is not only a recalculated mix recipe but also an integrated design outcome governed by workability demand, cement-limit control, water reduction, and aggregate-skeleton optimization.

Table 7. Analytical interpretation of comparative mix-design outputs.

Parameter	BRE Method	SP 23:1982	EcoStruct Platform	Analytical Interpretation
Cement content, kg/m ³	440	450	440	SP 23 required the highest cement content because of the low selected W/C. EcoStruct maintained the cement content within the specified envelope.
Free water, kg/m ³	198	158	190	EcoStruct reduced water by about 4% compared with BRE while avoiding the very low water demand obtained with SP 23.
Water–cement ratio	0.45	0.35	0.432	EcoStruct satisfied the durability limit while keeping a less restrictive W/C than SP 23, which improves practical workability.
Superplasticizer, kg/m ³	1.8	1.8	2.1	The slightly higher dosage in EcoStruct supports workability while keeping cement and water within allowable limits.
Sand fraction of total aggregate	47%	26%	55%	EcoStruct produced the highest sand fraction, improving cohesion and mold filling for tunnel-lining concrete.
Fine gravel fraction of total aggregate	17%	29%	20%	EcoStruct kept a moderate intermediate fraction to support a continuous aggregate skeleton.
Coarse gravel fraction of total aggregate	36%	45%	25%	EcoStruct reduced coarse aggregate dominance, which is useful for congested reinforcement and precast surface finish.
Overall design tendency	Balanced aggregate split	Coarse-dominated skeleton	Sand-rich continuous skeleton	EcoStruct gives a placement-oriented mix suitable for high-workability precast tunnel-lining segments.

Overall, the analytical comparison confirms that the main difference between the platform and the two conventional procedures is the treatment of aggregate distribution. While BRE and SP 23:1982 mainly follow tabulated proportioning routes, the EcoStruct platform adjusts the aggregate skeleton together with water, cement, and admixture demand. This explains why the final platform mixture is more suitable for a high-workability precast tunnel-lining application. Meanwhile, recent AI- and machine learning-based studies on concrete mix design have mainly focused on predicting compressive strength, estimating fresh/hardened properties, or optimizing mixtures using data-driven models. These studies are important because they improve prediction accuracy and support multi-objective optimization; however, many of them require large experimental datasets and do not directly translate standard-based exposure limits, cement-content envelopes, aggregate grading constraints, water-demand correction, cost, embodied carbon, and trial-batch reporting into one practical workflow. In contrast, the proposed EcoStruct platform is positioned as a standards-informed decision-support system rather than only a strength-prediction model. Its main contribution is the integration of code-based constraints, material characteriza-

tion, aggregate-skeleton optimization, cost/carbon assessment, and laboratory verification within a single transparent mix-design process.

5. Conclusions

This study developed and demonstrated a standards-informed digital workflow for concrete mix design using the EcoStruct platform. Based on platform development, case-study application, and comparative analysis, the following conclusions can be drawn:

- i. The EcoStruct platform converts fragmented concrete mix-design decisions into a structured thirteen-tab workflow. The workflow links project definition, exposure limits, material characterization, aggregate gradation, water–cement ratio selection, cement adjustment, absolute-volume calculation, performance prediction, cost/carbon assessment, and trial-batch feedback within one traceable design environment.
- ii. From an engineering point of view, the platform provides a practical decision-support route for controlling strength, durability, workability, material constraints, cost, and embodied-carbon indicators simultaneously. This is particularly relevant for precast and infrastructure applications where mixture performance, placement quality, and production repeatability must be considered together.
- iii. The comparison with BRE and SP 23:1982 showed that the main distinction of the platform is not limited to cement or water content but also lies in aggregate-skeleton optimization. For the selected precast tunnel-lining case, the platform used 440 kg/m³ cement and 190 kg/m³ free water, keeping the cement content within the specified 400–450 kg/m³ range while reducing free water relative to the BRE-based design and avoiding the higher cement content required by the SP 23:1982 calculation [63,64].
- iv. The platform output produced a finer and more continuous aggregate structure suitable for high-workability precast tunnel-lining concrete. This is important for passing through congested reinforcement, filling mold edges, improving surface finish, and maintaining cohesion under vibration.
- v. This study contributes to concrete science by showing how standards-based mix-design rules, durability limits, aggregate gradation control, admixture adjustment, cost estimation, embodied-carbon calculation, and laboratory verification can be integrated into a single transparent workflow rather than treated as separate design steps.

Future research should focus on wider experimental validation across different strength classes, exposure conditions, cement types, SCM-rich binder systems, and regional material sources. Further development should also include plant-specific databases, supplier-specific EPD datasets, and extensions to SCC, recycled-aggregate concrete, lightweight concrete, and other low-carbon concrete systems.

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