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Research Article

Multi-Criteria Performance Assessment of Rigid Pavement Concrete with High-Absorption Local Fine Aggregate Using Superplasticizer and Water-Reducing Admixture

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ABSTRACT

Rigid pavement concrete incorporating high-absorption local fine aggregate requires careful control of effective water availability, as aggregate moisture conditions may influence workability, setting behavior, and flexural performance. This study assessed the effects of superplasticizer and water-reducing admixture dosages on pavement concrete designed for a target compressive strength of 30 MPa and a target modulus of rupture of 45 kgf/cm² (4.41 MPa). A laboratory-based performance screening was conducted using a control mixture, superplasticizer mixtures at 0.60–1.50% by cement mass, water-reducing admixture mixtures at 0.15–0.35%, and one combined admixture mixture. Fresh properties were evaluated using slump, visual stability, bleeding and segregation observations, and initial setting time, whereas hardened performance was assessed through 7- and 28-day compressive and flexural strength tests. The control mixture achieved 31.71 MPa compressive strength at 28 days but failed the flexural strength requirement, reaching only 39.70 kgf/cm² (3.89 MPa). The 0.80% superplasticizer mixture achieved balanced performance, with 33.93 MPa compressive strength, 46.43 kgf/cm² (4.55 MPa) modulus of rupture, and an initial setting time of 4 hours. The 0.25% water-reducing admixture produced the highest compressive strength, 37.53 MPa, but did not meet the flexural criterion. The combined admixture mixture showed the best overall laboratory performance, achieving 33.75 MPa compressive strength, 56.90 kgf/cm² (5.58 MPa) modulus of rupture, and an initial setting time of 5 h 15 min. These findings indicate that pavement concrete mixture selection should integrate flexural strength, setting behavior, workability, and fresh-state stability rather than rely solely on compressive strength.

KEYWORDS high-absorption fine aggregate • local aggregate utilization • performance-based mix design • rigid pavement concrete • rigid pavement concrete • resource-efficient construction materials • sustainable pavement infrastructure

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1. INTRODUCTION

Concrete pavement is a critical material system for highways, toll roads, ports, industrial yards, airports, and other heavy-duty transportation infrastructure because it provides high stiffness, load-spreading capacity, and long service potential under repeated traffic loading. In rigid pavement, the concrete slab resists traffic and environmental actions primarily through bending; therefore, pavement concrete performance cannot be judged solely by compressive strength. Flexural strength, commonly expressed as the modulus of rupture (MOR), is a key parameter because it reflects the slab's ability to resist bending-induced cracking [1]. Campos et al. [2] showed a “positive nonlinear correlation” between compressive and flexural strengths, but also demonstrated that fresh field properties, particularly air content, influence both strength parameters. This means that compressive strength can support quality control, but it cannot fully replace MOR for pavement mixture selection. Similarly, studies on concrete pavement performance have shown that elastic modulus, flexural strength, and thermal properties significantly affect predicted rigid pavement behavior [3]–[7]. Thus, pavement concrete mixture design should be treated as a multi-criteria performance problem rather than a conventional compressive-strength-based design exercise.

The use of locally available aggregates is increasingly important in pavement construction because aggregates constitute the largest volume fraction of concrete and strongly influence material costs, transportation requirements, environmental impacts, and construction feasibility. Sustainable pavement research emphasizes that alternative, recycled, and locally sourced aggregates can reduce dependence on conventional quarry materials and support resource-efficient infrastructure. Ramírez-Vargas et al. [8], for example, reviewed sustainable pavement aggregates and emphasized that the use of substitute aggregates must be evaluated based on pavement performance rather than solely on material availability. However, local aggregate utilization is not automatically beneficial from an engineering perspective. Aggregate gradation, particle shape, texture, fines content, density, moisture condition, and absorption capacity can alter paste demand, water requirement, cohesion, bleeding tendency, compaction behavior, interfacial transition zone quality, and hardened mechanical properties [9]–[11]. Therefore, the main issue is not simply whether local aggregates can be used, but rather how their specific characteristics can be controlled to satisfy both structural and constructability requirements in pavement concrete.

Among aggregate properties, water absorption is particularly critical because it controls the difference between total mixing water and effective free water available in the cement paste. Classical concrete theory has long recognized that water availability governs the structure of cement paste, hydration products, capillary porosity, and strength development. Powers and Brownyard’s cement paste model distinguished between unreacted cement, hydration products, gel porosity, and capillary porosity, highlighting the fundamental role of water–cement interaction in the concrete microstructure. Neville also identifies porosity, absorption, moisture content, grading, workability, bleeding, admixture response, and effective water as central topics in concrete behavior and mixture proportioning [12]. In high-absorption aggregate systems, part of the mixing water may be absorbed into aggregate pores during batching and mixing; consequently, the nominal water-to-cement ratio may differ substantially from the effective water-to-cement ratio experienced by the cement paste [12]–[14].

This distinction is especially important when fine aggregate has high absorption, because water exchange between aggregate pores and cement paste can reduce effective water availability, accelerate slump loss, disturb hydration, and affect strength development. Domagała [15] showed that water absorption by lightweight aggregate can reduce the effective water–cement ratio in fresh concrete and influence hardened properties, while Kim et al. [16] reported that highly absorptive lightweight aggregate causes “high slump loss and poor workability.” Sosa et al. [17] further emphasized that the initial moisture condition of porous aggregate strongly affects both fresh and hardened concrete.

Recent studies support this concern by showing that absorption-based water compensation is not always equal to actual water exchange during mixing, particularly because absorption/SSD values, saturation level, and moisture-control method can alter flowability, effective water–cement ratio, and concrete performance [18]–[20]. Therefore, for absorptive fine aggregate, moisture correction should be treated not as a simple batching adjustment but as a critical part of mixture design reliability, requiring control of initial moisture condition, absorption kinetics, surface moisture, and trial-batch verification.

The challenge is more critical in rigid pavement concrete because the mixture must meet both fresh-state constructability and hardened mechanical performance. High-absorption fine aggregate can reduce effective water availability, cause rapid workability loss and make placement, vibration, finishing, and compaction more difficult; poor compaction may increase entrapped air and voids, weaken the paste–aggregate interface, and reduce flexural strength/MOR. Conversely, excessive water correction can raise the effective water–cement ratio, leading to bleeding, segregation, shrinkage, capillary porosity, and reduced surface durability. Current studies confirm that porous or recycled fine aggregates, due to their high absorption and the mortar to which they adhere, require detailed characterization because their effects on concrete performance are difficult to generalize [21]–[23]. Other recent findings also show that moisture condition, saturation level, and correction method significantly influence workability, strength, permeability, and durability [24]–[26]. Therefore, rigid pavement concrete with high-absorption fine aggregate requires integrated evaluation of workability, bleeding resistance, setting time, compaction quality, compressive strength, MOR, and durability.

Chemical admixtures provide a practical approach to address the water-demand and workability problems associated with absorptive aggregates [27]–[29]. Water-reducing admixtures and superplasticizers can reduce mixing water demand, improve cement particle dispersion, increase workability, and support strength development without simply increasing free water content. Wang et al. [30] reviewed water reducers and superplasticizers and reported that these admixtures are generally used to reduce mixing water and improve hardened concrete performance while maintaining fresh workability, but their effects vary with type and dosage. This dosage sensitivity is highly relevant for pavement concrete: insufficient dosage may fail to compensate for water demand and slump loss, whereas excessive dosage may produce instability, delayed setting, bleeding, segregation, or loss of edge stability during paving. Therefore, admixture dosage should be optimized through performance-based trial mixtures rather than selected solely on supplier recommendations.

Modern polycarboxylate-based superplasticizers have become widely used due to their strong dispersing ability. Yang et al. [31] explained that polycarboxylate superplasticizers adsorb onto cement particles and improve dispersion through electrostatic repulsion, steric hindrance, wetting, lubrication, and related mechanisms. Moeinian et al. [32] also showed that electrostatic and steric hindrance forces can act together to improve cement particle dispersion. However, these mechanisms are strongly system-dependent. Superplasticizer effectiveness can be affected by cement chemistry, sulfate balance, aggregate fines, clay contamination, water availability, mixing sequence, and admixture molecular structure. Recent studies on polymer-based superplasticizers similarly report that steric hindrance and electrostatic repulsion depend on adsorption behavior at cement particle surfaces. Therefore, in a high-absorption aggregate system, superplasticizer performance should be evaluated not only by slump or compressive strength, but also by setting behavior, bleeding tendency, and flexural performance [33]–[35].

Although aggregate absorption has been widely discussed in lightweight and recycled aggregate concrete, its effect on rigid pavement concrete incorporating high-absorption natural local fine aggregate remains less systematically addressed. Most previous studies focus on porous lightweight aggregates or recycled aggregates with adhered mortar. In contrast, this study examines natural local sand with an absorption value of 7.94%, which may reduce effective water availability during mixing and influence workability, bleeding, segregation, setting time, compressive strength, and modulus of rupture. This distinction is important because rigid pavement concrete must meet not only compressive-strength requirements but also flexural-resistance and field-construction criteria.

The novelty of this study lies in its multi-criteria performance assessment of rigid pavement concrete containing high-absorption natural local fine aggregate and chemical admixtures. This study evaluates superplasticizer dosages of 0.60–1.50% and water-reducing admixture dosages of 0.15–0.35% by cement mass, using slump/workability, bleeding tendency, segregation tendency, initial setting time, 7- and 28-day compressive strength, and 7- and 28-day modulus of rupture as response parameters. Mixture selection was conducted using a performance-based framework that integrates a 28-day compressive strength target of 30 MPa, a modulus of rupture target of 45 kgf/cm² (4.41 MPa), adequate setting time, and stable fresh-state behavior.

2. MATERIALS AND METHODS

2.1. Research Framework and Experimental

This study was conducted as a laboratory-based experimental investigation to optimize the use of superplasticizer and water reducer in pavement concrete incorporating local fine aggregate with high absorption characteristics. The experimental framework was developed using a performance-based mixture optimization approach, in which the optimum concrete mixture was selected not solely on compressive strength but on a combined evaluation of workability, initial setting time, compressive strength, and flexural strength. For large-scale concrete paving, a mixture should be sufficiently workable under vibration but stiff enough to maintain shape and edge stability after placement, particularly when used with slipform or concrete paver equipment [36], [37].

The concrete was designed for rigid pavement application with a target compressive strength of 30 MPa and a target modulus of rupture of 45 kgf/cm^2 (4.41 MPa). The experimental program consisted of four main stages: aggregate characterization, control mixture evaluation, individual admixture dosage screening, and combined admixture verification. The control mixture was prepared without admixture. Superplasticizer mixtures were prepared using dosages of 0.60%, 0.70%, 0.80%, 0.90%, 1.00%, 1.10%, 1.20%, 1.30%, 1.40%, and 1.50% by cement weight. Water-reducing mixtures were prepared at dosages of 0.15%, 0.20%, 0.25%, 0.30%, and 0.35% by cement weight. The combined superplasticizer–water-reducer mixture was then prepared using the best-performing individual admixture dosages identified in the screening stage.

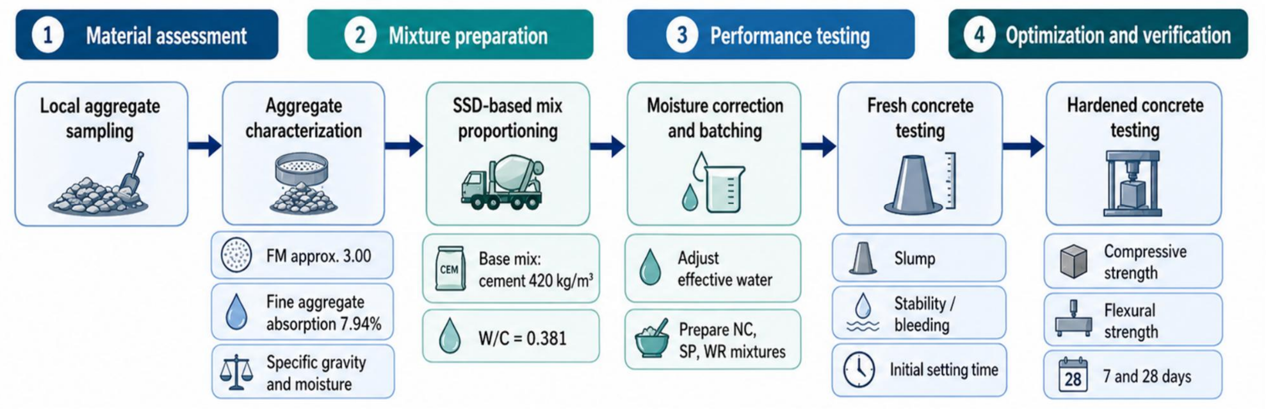

Figure 1. Experimental workflow for mixture optimization.

2.2. Materials and Aggregate Characterization

Materials used in this study included Portland cement, water, local fine aggregate, crushed coarse aggregate with nominal sizes of 10–20 mm and 20–30 mm, superplasticizer, and water reducer. Local aggregate was selected to reflect actual pavement concrete production conditions, as aggregate properties affect water demand, workability, bleeding resistance, strength development, and constructability. Therefore, aggregate grading and quality were evaluated in accordance with ASTM C33/C33M. At the same time, superplasticizer and water-reducing admixture dosages, calculated as percentages of cement weight, were classified according to ASTM C494/C494M, including Type A, Type F, and Type G admixtures [38], [39].

Aggregate characterization was conducted before mixture proportioning to determine the physical properties and grading suitability of the fine and coarse aggregates. The particle-size distribution of fine aggregate, coarse aggregate, and combined aggregate was determined in accordance with ASTM C136/C136M. When required, the amount of material finer than the 75-μm No. 200 sieve was determined by washing in accordance with ASTM C117. The fineness modulus of the fine aggregate was calculated from the sieve analysis results and evaluated in accordance with ASTM C33/C33M. The relative density, specific gravity, and absorption of the coarse aggregates were determined in accordance with ASTM C127.

In contrast, the corresponding properties of the fine aggregate were determined in accordance with ASTM C128. The total evaporable moisture content of each aggregate fraction prior to batching was determined in accordance with ASTM C566 and used to correct the batch water. Organic impurities in the fine aggregate were evaluated in accordance with ASTM C40/C40M. The loose and compacted unit weights of the aggregates were determined in accordance with ASTM C29/C29M. The aggregate properties obtained from these tests were used to adjust the mixture proportions, evaluate compliance with concrete aggregate requirements, and control the effective water availability of the concrete mixture.

Table 1. Materials used in the experimental program.

Material	Source or type	Role in mixture
OPC cement	PT Semen Tonasa	Hydraulic binder
Mixing water	Production-unit water	Hydration and workability
Fine aggregate	Tendeki local sand, Klabat volcanic area	Mortar skeleton and fine fraction
Coarse aggregate 10-20 mm	Crushed aggregate, Kema-Bitung	Coarse skeleton
Coarse aggregate 20-30 mm	Crushed aggregate, Kema-Bitung	Coarse skeleton
Superplasticizer	Consol SG is used as a high-range water-reducing admixture	Dispersion and workability improvement
Water-reducing admixture	Consol N10 MB, used as a water-reducing admixture	Water-demand control and setting adjustment

Table 2. Physical properties of the aggregates.

Property	Fine aggregate	Coarse aggregate 10–20 mm	Coarse aggregate 20–30 mm
Fineness modulus	3.00	–	–
Organic content	No. 3	–	–
Absorption (%)	7.94	1.86	1.41

Property	Fine aggregate	Coarse aggregate 10–20 mm	Coarse aggregate 20–30 mm
Specific gravity	2.43	2.70	2.71
Loose unit weight	1.09	0.59	0.48
Compacted unit weight	1.16	0.59	0.48

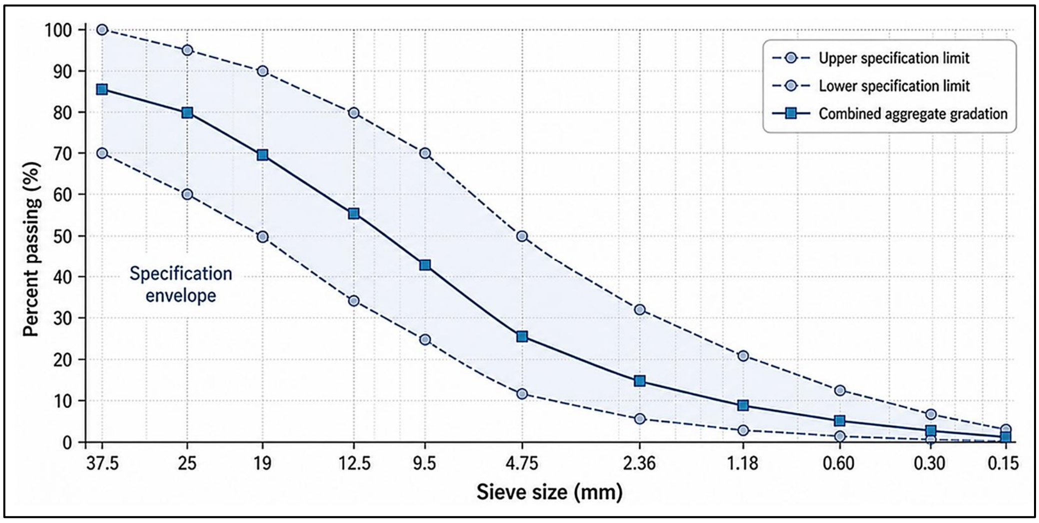

Figure 2. Aggregate gradation envelope and combined aggregate curve.

Based on the aggregate characterization results (Table 2), the fine aggregate had a fineness modulus of approximately 3.00, specific gravity of 2.43, and absorption of 7.94%. In comparison, the coarse aggregates had absorption values of 1.86% for the 10–20 mm fraction and 1.41% for the 20–30 mm fraction. The high absorption of the fine aggregate was therefore considered a critical parameter in the moisture correction and mixture optimization process.

The high absorption of the fine aggregate required careful control of effective water content. If absorbed water is not properly accounted for, the concrete may lose workability rapidly, whereas excessive water compensation may increase bleeding and reduce hardened performance. Therefore, moisture correction was applied before batching.

2.3. Mix Design and Moisture

The base mixture was proportioned on an SSD basis and then corrected according to the measured moisture content of each aggregate fraction (Table 3). To remove ambiguity between nominal and effective water content, this study distinguishes SSD water, batch water added to the mixer, surface moisture contribution, and effective water availability. The SSD mixture contained 420 kg/m3 cement and 160 kg/m3 water, corresponding to a nominal water-to-cement ratio of 0.381. After moisture correction, the batch water added to the mixer was reduced to 106.39 kg/m3 because aggregate surface moisture contributed water to the mixture. The effective water content was calculated using Eq. (1):

$$W_{eff} = W_b + W_{sm} - W_{abs} \tag{1}$$

where W_{eff} is the effective mixing water, W_b is the batch water, W_{sm} aggregates contribute to the surface moisture, and W_{abs} is aggregates absorbed by water during mixing? This distinction is essential because the project records also report an SSD water-to-cement ratio of 0.381 and a moisture-corrected batching condition of approximately 0.253 when only batch water added to the mixer is divided by the cement mass. The latter value should not be interpreted as the final effective water-to-cement ratio unless aggregate surface water and absorption are explicitly included.

Table 3. SSD and moisture-corrected mixture quantities for the control concrete.

Material	SSD quantity (kg/m3)	Absorption (%)	Measured water content (%)	Water correction (kg/m3)	Corrected quantity (kg/m3)
Cement	420.00	-	-	-	420.00
Water	160.00	-	-	-53.35	106.39
Coarse aggregate 10-20 mm	324.37	1.86	3.28	+4.54	328.91
Coarse aggregate 20-30 mm	324.37	1.41	1.80	+1.25	325.62
Fine aggregate	743.47	7.94	14.85	+47.57	791.04

Table 4. Experimental matrix.

Mixture group	Dosage range (% of cement mass)	No. of mixtures	Purposes
Control	0.00	1	Baseline fresh and hardened behavior
Superplasticizer	0.60, 0.70, 0.80, 0.90, 1.00, 1.10, 1.20, 1.30, 1.40, 1.50	10	Single-admixture dosage screening
Water-reducing admixture	0.15, 0.20, 0.25, 0.30, 0.35	5	Single-admixture dosage screening
Combined SP+WR	0.80% SP + 0.25% WR	1	Verification of combined performance

2.4. Experimental Matrix

The experimental matrix consisted of one control mixture, ten superplasticizer mixtures, five water-reducing admixture mixtures, and one combined admixture mixture. Admixture dosages were expressed as percentages of cement mass (Table 4). The combined mixture used 0.80% superplasticizer and 0.25% water-reducing admixture, as these were the best-performing individual dosages during the screening stage. Because only one combined dosage was tested, the combined-mixture result is interpreted as a complementary performance response rather than definitive statistical proof of synergy. The superplasticizer dosage was calculated using Eq. (2):

$$M_{SP} = \frac{D_{SP}}{100} \times M_c \tag{2}$$

where M_{SP} is the superplasticizer mass in kg/m³, D_{SP} is the superplasticizer dosage in percent by cement weight, and M_c is the cement content in kg/m³. The water reducer dosage was calculated using Eq. (3):

$$M_{WR} = \frac{D_{WR}}{100} \times M_c \tag{3}$$

where M_{WR} is the water reducer mass in kg/m³ and D_{WR} is the water-reducer dosage expressed as a percentage by cement weight.

2.5. Batching and Mixing Procedure

Concrete batching was conducted under controlled laboratory conditions. Before batching, the moisture content of each aggregate fraction was determined and the batch water was corrected accordingly. This correction was necessary because the high absorption of the fine aggregate could otherwise alter the effective water-to-cement ratio and affect the fresh concrete response. The following mixing sequence was used for all mixtures to ensure reproducibility:

- The 10–20 mm and 20–30 mm coarse aggregates, and the fine aggregate were introduced into the mixer and dry-mixed for 60 s.
- Portland cement was added and dry-mixed with the aggregates for another 60 s.
- Approximately 70% of the mixing water was added gradually while the mixer was running.
- The admixture was diluted in the remaining 30% of the mixing water before addition.
- For single-admixture mixtures, the diluted superplasticizer or water reducer was added after the initial wet mixing stage.
- For the combined SP+WR mixture, the diluted water reducer was added first, followed by the diluted superplasticizer.
- The concrete was mixed for 3 min after all materials were introduced.
- The mixer was stopped for 2 min to allow the material to stabilize and to scrape unmixed paste from the mixer walls.
- Final mixing was performed for another 2 min before fresh concrete testing and specimen casting.

This consistent mixing protocol was used to minimize variability caused by mixing sequence, admixture dispersion, and batch-to-batch differences. The preparation, mixing, and curing of laboratory concrete specimens should follow ASTM C192/C192M, which provides standardized requirements for preparation of materials, mixing concrete, and making and curing test specimens under laboratory conditions [40].

2.6. Fresh Concrete Testing

Fresh concrete testing was performed immediately after mixing. The fresh-state evaluation consisted of slump measurement, visual stability observation, bleeding tendency, segregation tendency, and initial setting time. Slump testing was used to evaluate the consistency of fresh concrete. ASTM C143/C143M provides a procedure for determining the slump of plastic hydraulic-cement concrete and is commonly used to monitor the consistency of unhardened concrete [41].

Initial setting time was determined using penetration resistance on mortar sieved from the fresh concrete mixture. ASTM C403/C403M covers the determination of the time of setting of concrete mixtures with a slump greater than zero using penetration resistance measurements on mortar sieved from concrete [42].

Table 5. Fresh concrete test parameters.

Parameter	Method	Output	Purpose
Slump	ASTM C143/C143M or equivalent	mm	Workability and consistency
Visual stability	Laboratory observation	Stable/bleeding/segregation	Field suitability
Bleeding tendency	Laboratory observation	None/slight/moderate/severe	Mixture cohesion
Segregation tendency	Laboratory observation	None / visible separation	Stability under handling
Initial setting time	ASTM C403/C403M or equivalent	h: min	Transport and paving window

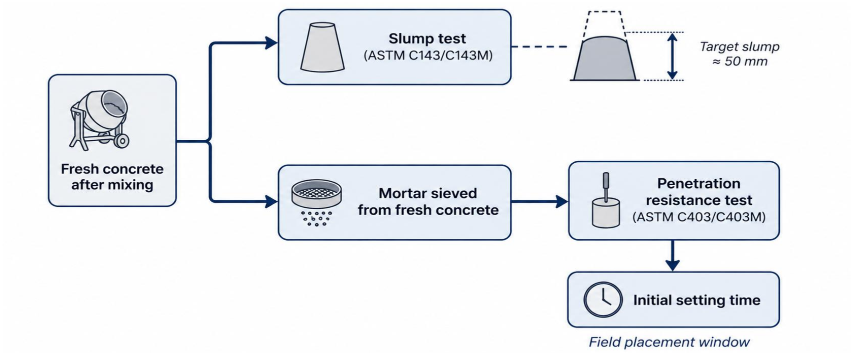

Figure 3. Fresh concrete evaluation scheme for slump and setting time.

The fresh concrete was considered suitable for pavement application when the mixture was workable, cohesive, and stable, with no excessive bleeding or segregation. For concrete paver application, the mixture should maintain sufficient workability for handling and vibration while retaining adequate stiffness after placement.

2.7. Specimen Preparation and Curing

Cylindrical specimens were prepared for compressive strength testing, while beam specimens were prepared for flexural strength testing (Table 6). The cylindrical specimens had a diameter of 150 mm and a height of 300 mm. The compressive strength test records indicate that the cylinder area was 17,671.5 mm², corresponding to a 150 mm diameter specimen.

Table 6. Specimen preparation and curing protocol.

Item	Procedure
Cylinder specimen	150 mm diameter × 300 mm height
Beam specimen	Standard beam specimen for flexural strength testing
Initial storage	24 ± 2 h after casting
Demolding	After 24 ± 2 h
Curing condition	Moist or water curing under controlled laboratory conditions
Test ages	7 and 28 days
Main tests	Compressive strength and flexural strength
Minimum recommended replication	At least three specimens per mixture per test age

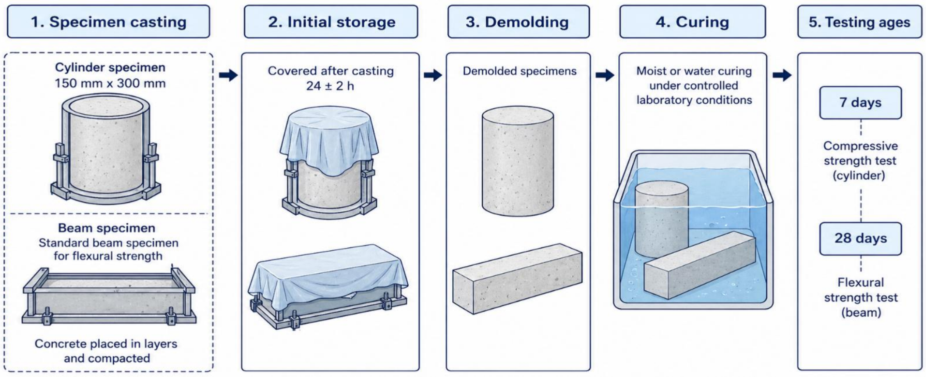

Figure 4. Specimen configuration for compressive and flexural strength testing.

Fresh concrete was placed into molds in layers and compacted using consistent compaction procedures for all mixtures. After casting, the specimens were covered to prevent moisture loss and kept under laboratory conditions for the first 24 ± 2 h. After demolding, the specimens were cured until testing ages of 7 and 28 days. The same curing procedure was applied to all specimens to ensure comparability among mixtures.

2.8. Compressive Strength Testing

Compressive strength testing was performed on cylindrical specimens at 7 and 28 days. ASTM C39/C39M covers the determination of compressive strength of cylindrical concrete specimens, including molded cylinders and drilled cores [43]. The compressive strength was calculated using Eq. (4):

$$f_c' = \frac{P}{A} \tag{4}$$

where f_c' is the compressive strength in MPa, P is the maximum applied load in N, and A is the loaded cross-sectional area in mm². For a 150 mm diameter cylinder, the cross-sectional area was calculated using Eq. (5):

$$A = \frac{\pi d^2}{4} = \frac{\pi (150)^2}{4} = 17{,}671.5 \text{ mm}^2 \tag{5}$$

The average compressive strength was calculated for each mixture and testing age. The 28-day compressive strength was compared with the target value of 30 MPa.

2.9. Flexural Strength Testing

Flexural strength testing was performed using beam specimens at 7 and 28 days (Table 7). The test was conducted using simple beam loading. ASTM C78/C78M covers the determination of concrete flexural strength using a simple beam with third-point loading. The flexural strength, or modulus of rupture, was calculated using Eq. (6):

$$R = \frac{PL}{bd^2} \tag{6}$$

where R is the flexural strength, P is the maximum applied load, L is the span length, b is the average beam width, and $d$is the average beam depth.

The 28-day modulus of rupture was compared with the target value of 45 kgf/cm² (4.41 MPa). A mixture was considered acceptable for pavement concrete only when the 28-day flexural strength reached or exceeded the specified target.

Table 7. Hardened concrete testing matrix.

Test	Specimen	Standard basis	Age	Acceptance criterion
Compressive strength	Cylinder, 150 × 300 mm	ASTM C39/C39M [43]	7 and 28 days	28-day f'c ≥ 30 MPa (305.91 kgf/cm2)
Flexural strength	Beam	ASTM C78/C78M [44]	7 and 28 days	28-day MOR ≥ 45 kgf/cm2 (≥ 4.41 MPa)
Initial setting time	Mortar fraction from fresh concrete	ASTM C403/C403M [42]	Fresh state	Sufficient for placement
Slump	Fresh concrete	ASTM C143/C143M [41]	Fresh state	Suitable for paving

Table 8. Multi-criteria mixture acceptance framework.

Criterion	Acceptance basis	Purpose
Compressive strength	28-day f'c ≥ 30 MPa (305.91 kgf/cm2)	Structural strength requirement
Flexural strength / MOR	28-day MOR ≥ 45 kgf/cm2 (≥ 4.41 MPa)	Pavement bending resistance
Initial setting time	Sufficient for transport and paving	Field placement requirement
Workability	Stable and workable mixture	Concrete paver compatibility
Stability	No excessive bleeding or segregation	Surface quality and edge stability

2.10. Mixture Selection and Optimization Criteria

The optimum mixture was selected using a multi-criteria performance framework (Table 8). A mixture was considered suitable for pavement concrete when it met the requirements for compressive strength, flexural strength, setting time, and fresh concrete stability. This selection strategy was adopted because the highest compressive strength did not necessarily represent the best pavement concrete mixture.

The selection of the combined mixture was directly linked to the results obtained from the individual admixture screening. The 0.80% superplasticizer mixture was selected because it satisfied both compressive and flexural strength requirements. The 0.25% water-reducing mixture was selected because it produced the highest 28-day compressive strength among the water-reducing mixtures. The combined SP+WR mixture was then prepared to evaluate whether the advantages of both admixtures could be integrated into a concrete mixture.

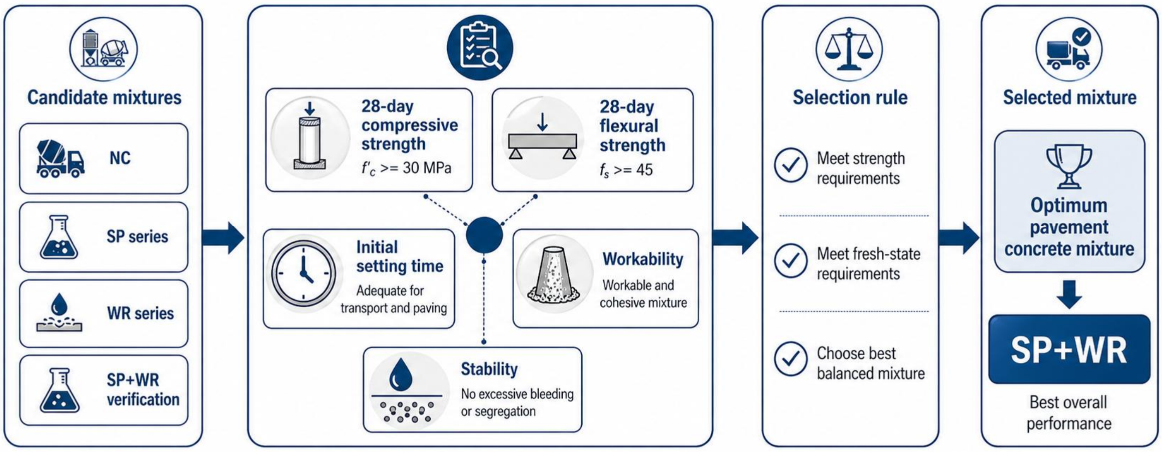

Figure 5. Multi-criteria optimization framework.

2.11. Data Processing and Performance Index

The experimental data were processed by calculating mean values, target achievement ratios, percentage changes relative to the control mixture, and a normalized performance index. The achievement ratio was calculated using Eq. (7):

$$Achievement = \frac{X_{measured}}{X_{target}} \times 100 \tag{7}$$

where $X_{measured}$ is the measured test value and X_{target} is the required design value. For compressive strength, the achievement ratio was calculated using Eq. (8):

$$Achievement_c = \frac{f'_{c,28}}{30} \times 100 \tag{8}$$

For flexural strength, the achievement ratio was calculated using Eq. (9):

$$Achievement_f = \frac{f_{r,28}}{45} \times 100 \tag{9}$$

To compare representative mixtures, a normalized performance index was calculated using Eq. (10):

$$PI = 0.25N_c + 0.35N_f + 0.25N_t - 0.15B \tag{10}$$

where PI is the performance index, N_c is the normalized 28-day compressive strength, N_f is the normalized 28-day flexural strength, N_t is the normalized initial setting time, and $B$is the instability penalty. A penalty value of 1 was assigned to mixtures showing bleeding or instability, while a penalty value of 0 was assigned to stable mixtures. The normalized variables were calculated using Eq. (11-13):

$$N_c = \frac{f'_{c,28}}{30} \tag{11}$$

$$N_f = \frac{f_{r,28}}{45} \tag{12}$$

$$N_t = \frac{t_i}{t_{max}} \tag{13}$$

where t_i is the initial setting time of a mixture and t_{max} is the longest setting time recorded among the representative mixtures.

2.12. Statistical Analysis

The dosage–response relationship between admixture content and concrete performance was evaluated using descriptive and regression-based interpretation. Mean values for compressive and flexural strength were calculated at each testing age. Where replicate-level data are available, standard deviation and coefficient of variation should be reported.

Because replicate-level data were unavailable for all mixtures, the analysis was conducted descriptively. The identified mixture was therefore regarded as the best-performing laboratory candidate within the tested matrix rather than a statistically optimized dosage. Accordingly, the dosage–response trends were used to support comparative interpretation, not to establish statistically significant differences among mixtures.

A quadratic regression model was used to represent the nonlinear relationship between admixture dosage and concrete performance, which was calculated using Eq. (14):

$$Y = \beta_0 + \beta_1 D + \beta_2 D^2 + \varepsilon \tag{14}$$

where Y is the response variable, D is the admixture dosage, β_0, β_1, and β_2 are regression coefficients, and ε is the random error term.

The quadratic model was selected because the experimental results showed that increasing the admixture dosage did not result in a proportional increase in compressive or flexural strength.

3. RESULTS

3.1. Aggregate Characterization & Mixture Adjustment

The aggregate characterization confirmed that the local fine aggregate had a fineness modulus of approximately 3.00 and absorption of 7.94%. Although the aggregate blend could be adjusted to fit within the gradation envelope, the fine aggregate's high absorption created water-demand sensitivity. The control mixture achieved the target slump after water correction, but visual observations showed bleeding and separation of water, cement paste, sand, and aggregate after mixing. This result indicates that gradation compliance alone was insufficient to ensure pavement-concrete constructability.

The combined gradation curve was positioned within the specification envelope, indicating that the aggregate blend was acceptable after adjustment. However, because the fine aggregate had high absorption, gradation compliance alone was not sufficient to ensure concrete performance. Moisture correction and admixture optimization remained necessary.

Table 9. Aggregate-related observations and mixture implications.

Parameter	Observed result	Technical implication
Fine aggregate fineness modulus	≈ 3.00	Relatively coarse fine aggregate; requires optimized blending
Fine aggregate absorption	7.94%	High water demand and potential workability loss
SSD-based water–cement ratio	38.10%	Initial design condition
Adjusted water–cement ratio	25.31%	Corrected according to aggregate moisture
Target slump	50 mm	Fresh-state consistency target
Required action	Mix adjustment and admixture optimization	Needed for pavement concrete applicability

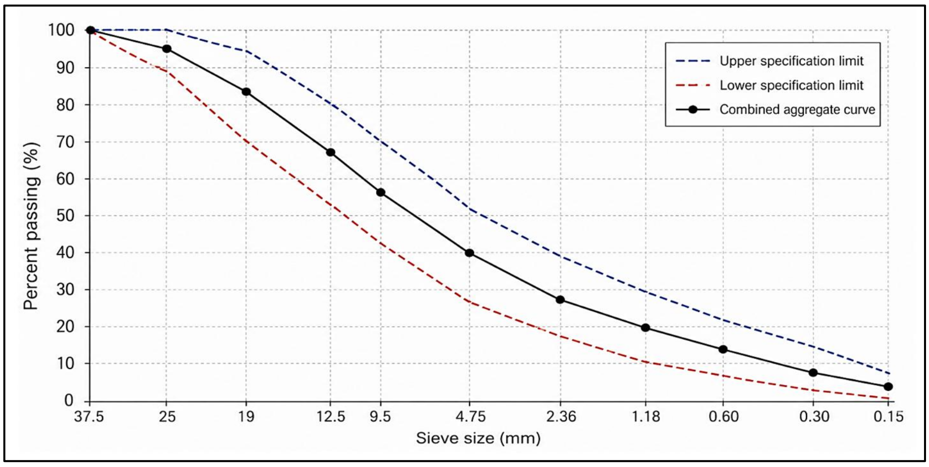

Figure 6. Combined aggregate gradation curve compared with the upper and lower specification limits.

3.2. Fresh Concrete Behavior and Setting Time

Fresh-state behavior varied substantially across representative mixtures. The control mixture had an initial setting time of 2 h 15 min and was judged unsuitable for concrete paver application due to bleeding and separation. The SP0.80 mixture extended the initial setting time to 4 h, the WR0.25 mixture to 4 h 30 min, and the combined SP+WR mixture to 5 h 15 min. These results indicate that the admixtures were particularly important for improving constructability, workability retention, and setting-time window.

The fresh concrete results (Table 10) demonstrate that the normal concrete mixture could not be selected as the final pavement concrete mixture despite achieving the compressive strength target. Field applicability required longer setting time, improved cohesion, and stable fresh-state behavior.

Table 10. Fresh-state performance of representative mixtures.

Mixture	Fresh-state observation	Initial setting time	Field suitability
NC	Bleeding and separation were observed	2 h 15 min	Not suitable
SP 0.80	Improved workability and setting behavior	4 h 00 min	Suitable
WR 0.25	Improved setting time, but the flexural criterion was not met	4 h 30 min	Partially suitable

Mixture	Fresh-state observation	Initial setting time	Field suitability
SP+WR	Best setting time and workability balance	5 h 15 min	Suitable

Table 11. Hardened performance of control concrete.

Parameter	7 days	28 days	Target	28-day achievement	Status
Compressive strength	27.50 MPa	31.71 MPa	≥ 30 MPa	105.70%	Passed
Flexural strength	35.91	39.70	≥ MOR 45	88.22%	Not passed
Initial setting time	—	2 h 15 min	Field-dependent	Insufficient	Not suitable

3.3. Hardened Performance of Control Concrete

The standard concrete mixture was used as the control. The compressive strength of the control concrete reached 27.50 MPa at 7 days and 31.71 MPa at 28 days. Therefore, the control mixture satisfied the 28-day compressive strength target of 30 MPa. However, its flexural strength did not satisfy the pavement concrete requirement. The 7-day flexural strength was 35.91, while the 28-day flexural strength was 39.70, corresponding to only 88.22% of the MOR 45 target.

These results show (Table 11) that compressive strength alone was not an adequate selection criterion for pavement concrete. Although the control mixture met the compressive strength target, it failed to meet the flexural strength requirement. It was not suitable for paving operations because of insufficient setting time and fresh-state instability.

3.4. Effect of Superplasticizer Dosage on Compressive and Flexural Strength

The superplasticizer mixtures were tested at dosages from 0.60% to 1.50% by cement weight (Table 12). The 28-day compressive strength values ranged from 29.952 MPa to 33.928 MPa. Most SP mixtures satisfied the 30 MPa target, except SP1.10, which produced 29.952 MPa. The highest 28-day compressive strength was obtained at SP0.80, reaching 33.928 MPa. This value was 7.00% higher than the control concrete strength of 31.71 MPa.

The compressive strength response was nonlinear. Increasing the SP dosage beyond 0.80% did not increase compressive strength. Instead, the strength decreased or fluctuated at higher dosages. This indicates that SP effectiveness was dosage-dependent and that excessive dosage did not improve the compressive performance of the mixture.

Table 12. Compressive strength of superplasticizer mixtures.

Mixture code	SP dosage (% cement weight)	7-day strength (MPa)	28-day strength (MPa)	28-day achievement vs 30 MPa	Status
SP0.60	0.60	23.117	30.868	102.89%	Passed
SP0.70	0.70	26.736	30.474	101.58%	Passed
SP0.80	**0.80**	**29.569**	**33.928**	**113.09%**	**Passed**
SP0.90	0.90	26.038	30.548	101.83%	Passed
SP1.00	1.00	25.091	30.694	102.31%	Passed
SP1.10	1.10	22.736	29.952	99.84%	Not passed
SP1.20	1.20	27.717	30.312	101.04%	Passed
SP1.30	1.30	26.268	31.308	104.36%	Passed
SP1.40	1.40	27.112	30.878	102.93%	Passed
SP1.50	1.50	28.052	30.172	100.57%	Passed

Table 13. Flexural strength of superplasticizer mixtures.

Mixture code	SP dosage (% cement weight)	7-day flexural strength	28-day flexural strength	28-day achievement vs MOR 45	Status
NC	0.00	35.91	39.70	88.22%	Not passed
SP0.60	0.60	35.98	38.84	86.31%	Not passed
SP0.70	0.70	41.91	39.70	88.22%	Not passed
SP0.80	**0.80**	**46.11**	**46.43**	**103.18%**	**Passed**
SP0.90	0.90	43.55	43.75	97.23%	Not passed
SP1.00	1.00	42.32	45.64	101.43%	Passed
SP1.10	1.10	44.24	45.16	100.35%	Passed

Mixture code	SP dosage (% cement weight)	7-day flexural strength	28-day flexural strength	28-day achievement vs MOR 45	Status
SP1.20	1.20	43.60	43.66	97.02%	Not passed
SP1.30	1.30	41.78	44.74	99.42%	Not passed
SP1.40	1.40	43.07	43.53	96.73%	Not passed
SP1.50	1.50	38.23	39.66	88.12%	Not passed

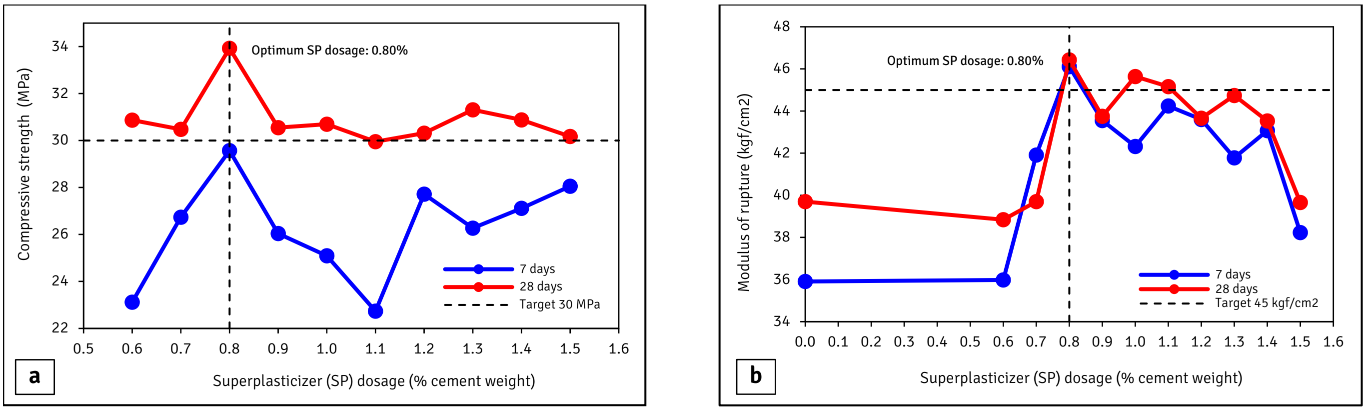

Figure 7. Effect of superplasticizer dosage on 7- and 28-day: (a) compressive strength; (b) modulus of rupture

The flexural strength results showed that only selected SP dosages satisfied the MOR 45 requirement (Table 13). The control mixture reached 39.70 at 28 days. SP0.80 produced the highest 28-day flexural strength among the individual SP mixtures, reaching 46.43, equivalent to 103.18% of the target. SP1.00 and SP1.10 also satisfied the flexural requirement, with 28-day flexural strengths of 45.64 and 45.16, respectively. However, both values were lower than the result obtained at SP0.80. SP0.80 was therefore identified as the best single-superplasticizer mixture, as it satisfied both the 28-day compressive and flexural strength requirements.

At higher dosages, flexural strength decreased below the target. SP1.20, SP1.30, SP1.40, and SP1.50 produced 28-day flexural strengths of 43.66, 44.74, 43.53, and 39.66, respectively. These results confirm that increasing the SP dosage beyond the optimum range did not improve pavement-related flexural performance.

3.5. Effect of Water Reducer Dosage on Compressive and Modulus of Rupture

The WR mixtures were tested at dosages from 0.15% to 0.35% by cement weight (Table 14). All WR mixtures satisfied the 28-day compressive strength target of 30 MPa. The highest compressive strength was obtained at WR0.25, with a 28-day strength of 37.529 MPa. This value corresponds to 125.10% of the target and represents an 18.35% increase relative to the control concrete. Therefore, from the perspective of compressive strength alone, WR0.25 was the best-performing WR mixture.

Although WR0.25 produced the highest compressive strength, this result alone was not sufficient to select it as the optimum pavement concrete mixture. The flexural strength criterion had to be evaluated independently.

Table 14. Compressive strength of water reducer mixtures.

Mixture code	WR dosage (% cement weight)	7-day strength (MPa)	28-day strength (MPa)	28-day achievement vs 30 MPa	Status
NC	0.00	27.50	31.71	105.70%	Passed
WR0.15	0.15	27.499	33.157	110.52%	Passed
WR0.20	0.20	31.704	33.686	112.29%	Passed
WR0.25	0.25	31.912	37.529	125.10%	Passed
WR0.30	0.30	26.931	32.135	107.12%	Passed
WR0.35	0.35	29.397	36.096	120.32%	Passed

Table 15. Flexural strength of water reducer mixtures.

Mixture code	WR dosage (% cement weight)	7-day flexural strength	28-day flexural strength	28-day achievement vs MOR 45	Status
NC	0.00	35.91	39.70	88.22%	Not passed

Mixture code	WR dosage (% cement weight)	7-day flexural strength	28-day flexural strength	28-day achievement vs MOR 45	Status
WR0.15	0.15	39.42	39.77	88.37%	Not passed
WR0.20	0.20	41.45	37.57	83.49%	Not passed
WR0.25	0.25	39.44	39.95	88.77%	Not passed
WR0.30	0.30	36.41	39.42	87.59%	Not passed
WR0.35	0.35	41.66	39.48	87.73%	Not passed

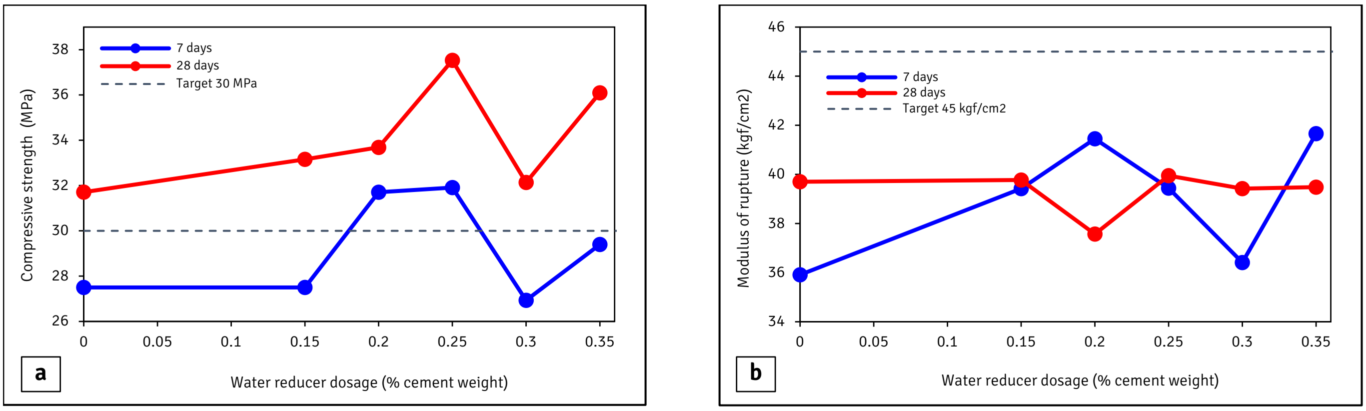

Figure 8. Effect of water reducer dosage on 7- and 28-day: (a) compressive strength; (b) modulus of rupture

The WR mixtures did not satisfy the flexural strength requirement (Table 15). The 28-day flexural strength values ranged from 37.57 to 39.95, all below the MOR 45 target. The highest WR flexural strength was obtained at WR0.25, with a value of 39.95, corresponding to only 88.77% of the target.

These results show that WR improved compressive strength but did not improve flexural strength sufficiently. Therefore, WR0.25 could not be selected as the final optimum mixture despite having the highest compressive strength.

3.6. Combined Superplasticizer and Water Reducer Admixture Mixture

The combined SP+WR mixture was developed based on the best-performing single-admixture results. SP 0.80 was selected because it satisfied both compressive and flexural strength requirements. WR 0.25 was selected because it produced the highest compressive strength among WR mixtures. The combined mixture was then tested to determine whether the mechanical and fresh-state benefits of both admixtures could be integrated into a single pavement concrete mixture.

The combined SP+WR mixture achieved 7-day and 28-day compressive strengths of 30.25 MPa and 33.75 MPa, respectively. Its 28-day MOR reached 56.90 kgf/cm2 (5.58 MPa), corresponding to 126.44% of the target. The initial setting time was 5 h 15 min, the longest among the representative mixtures. The combined SP+WR mixture was therefore classified as Passed for flexural performance because its MOR value of 56.90 kgf/cm² exceeded the required threshold of 45 kgf/cm²

Table 16. Comparative performance of representative mixtures.

Mixture	fc 28 day (MPa)	MOR 28 day (kgf/cm2)	MOR 28 day (MPa)	Initial set	Mandatory criteria decision	Interpretation
NC	31.71	39.70	3.89	2 h 15 min	Rejected	Failed flexural and fresh-state criteria
SP 0.80	33.93	46.43	4.55	4 h 00 min	Acceptable	Best single-SP mixture
WR 0.25	37.53	39.95	3.92	4 h 30 min	Rejected	Highest compressive strength, but failed MOR
SP+WR	33.75	56.90	5.58	5 h 15 min	Selected	Best balanced performance

Note. Target MOR = 45 kgf/cm2 (4.41 MPa)

3.7. Multi-Criteria Optimization Result

A normalized performance index was calculated to compare the selected mixtures using compressive strength, flexural strength, initial setting time, and instability penalty. This index was used only as a comparative tool and did not replace the minimum acceptance criteria.

$$PI = 0.25N_c + 0.35N_f + 0.25N_t - 0.15B \qquad (15)$$

where PI is the performance index, N_c is the normalized 28-day compressive strength, N_f is the normalized 28-day flexural strength, N_t is the normalized initial setting time, and $B$is the instability penalty.

The SP+WR mixture achieved the highest performance index of 0.974, indicating the most balanced performance. WR0.25 had a slightly higher index than SP0.80 due to its higher compressive strength and longer setting time, but it failed the flexural strength requirement. Therefore, WR0.25 could not be selected as the final pavement concrete mixture. The normalized MOR score was calculated using the target MOR of 45 kgf/cm2 (4.41 MPa) as the denominator. The final selected mixture was SP+WR.

Table 17. Threshold-normalized performance scores.

Mixture	Normalized f'c	Normalized MOR (kgf/cm²)	Normalized setting time	Instability penalty	Performance index	Decision
NC	1.057	0.882	0.429	0	0.530	Rejected
SP0.80	1.131	1.032	0.762	1	0.834	Acceptable
WR0.25	1.251	0.888	0.857	1	0.838	Rejected
SP+WR	1.125	1.264	1.000	1	0.974	Selected

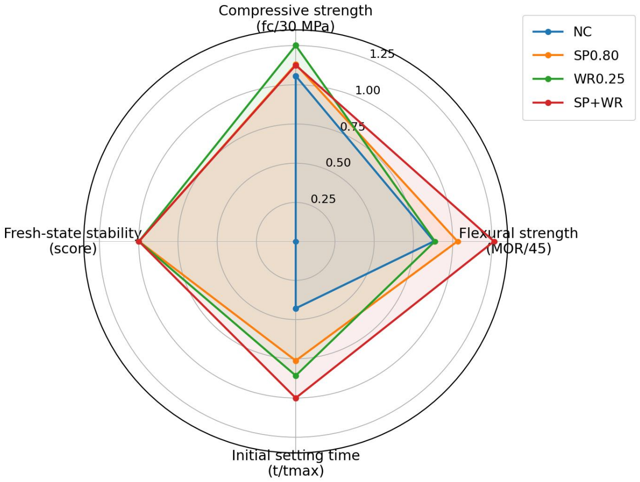

Figure 9. Threshold-normalized multi-criteria performance profile of representative mixtures.

Figure 9 shows that WR0.25 had the highest normalized compressive strength but failed to meet the modulus of rupture requirement, confirming that compressive strength alone is insufficient for selecting pavement concrete. SP0.80 showed a more balanced response than the control mixture, meeting both compressive and flexural strength criteria. The NC mixture had the weakest overall profile due to insufficient MOR and poor fresh-state stability. The combined SP+WR mixture provided the most balanced performance, with the highest normalized MOR, the longest initial setting time, adequate compressive strength, and stable fresh behavior. Therefore, the radar chart indicates that SP+WR is the best-performing laboratory candidate within the tested mixture matrix.

4. DISCUSSION

The results indicate that the main challenge in the mixture design was not aggregate gradation alone, but controlling effective water availability in a high-absorption aggregate system. Although the local fine aggregate had an acceptable fineness modulus and the combined gradation could be adjusted within the specification envelope, its 7.94% absorption created a high risk of workability loss, variability in effective water-to-cement ratio, and instability in fresh concrete behavior. This interpretation is supported by Domagała [15], who showed that aggregate water absorption in fresh concrete can reduce the actual water–cement ratio and that this effect depends on aggregate moisture content, moisture condition, preparation procedure, and concrete composition. In that study, the author emphasized that the actual water–cement ratio is "difficult to determine" when porous aggregate absorbs mixing water from fresh concrete. Similarly, Shin et al. reported that high water absorption in lightweight aggregate leads to "high slump loss and poor workability," confirming that high-absorption aggregate systems require more careful moisture control than conventional aggregate systems [16].

This finding reinforces the need to distinguish between the nominal water-to-cement ratio and effective water availability. In high-absorption aggregate mixtures, SSD water, batch water, surface moisture, and absorbed water may differ substantially; therefore, reporting only nominal mix proportions is insufficient for replication and field transfer. Recent research on recycled aggregate concrete similarly notes that higher aggregate absorption "disrupts the effective water-to-cement ratio," thereby affecting hydration kinetics and concrete performance [17], [18], [45]. Therefore, the revised mixture-design method in this study explicitly reports both SSD-based and moisture-corrected quantities. This improves transparency and reduces the risk of inconsistent field batching, particularly when local aggregates have high absorption capacity.

The most important engineering finding is that the mixture with the highest compressive strength was not the most suitable rigid pavement mixture. WR0.25 achieved the highest 28-day compressive strength of 37.53 MPa (344.15 kgf/cm2), but its MOR was only 39.95 kgf/cm2 (3.92 MPa), which was below the 45 kgf/cm² target. In contrast, the combined SP+WR mixture achieved a lower compressive strength of 33.75 MPa but produced the highest MOR of 56.90 kgf/cm² (5.58 MPa), and the longest initial setting time. This confirms that compressive strength is an incomplete proxy for pavement-quality concrete. Campos et al., based on 1,342 concrete specimens, found only a "positive nonlinear correlation" between compressive and flexural strength, while air content negatively affected both properties [2]. In rigid pavement performance, Sabih and Tarefder [46] also showed that modulus of rupture is one of the key concrete material properties affecting jointed plain concrete pavement performance and should be "carefully considered while designing a rigid pavement."

The superplasticizer response indicates the existence of a practical dosage window. At 0.80%, the SP mixture satisfied both compressive and flexural requirements while improving the initial setting time. However, increasing the dosage beyond this level did not produce proportional strength gains and tended to destabilize the flexural response. This behavior is consistent with research on polycarboxylate-based superplasticizers, which shows that molecular structure, functional groups, adsorption capacity, and dispersion mechanisms strongly influence concrete performance. Ghafari et al. reported that PCE superplasticizers improve concrete performance through electrostatic and steric effects, resulting in lower water demand, enhanced workability, and improved strength [32]. Different water-reducing agents affect fluidity retention, hydration, pore structure, and strength differently; thus, superplasticizer performance should be verified through trial batching with actual materials, dosage, mixing conditions, and field-relevant temperatures, rather than generalized by chemical class alone [47], [48].

The water-reducing admixture produced a different response. WR0.25 improved compressive strength but did not increase MOR to the required level, suggesting that water-demand control alone was not sufficient to improve bending performance in this aggregate system. The low MOR may have been influenced by paste–aggregate bonding, compaction, entrapped air, moisture condition, or specimen-level variability. This interpretation is consistent with research on fine recycled aggregate concrete, where higher aggregate water absorption and a weaker interfacial transition zone were reported to reduce strength and durability performance [23], [49], [50]. Therefore, the WR0.25 result should not be interpreted as a failure of the water reducer in general, but as evidence that compressive strength improvement does not automatically guarantee flexural performance for rigid pavement concrete.

The combined SP+WR mixture provided the most favorable laboratory response among the representative mixtures evaluated in this study. Empirically, this mixture satisfied all mandatory performance criteria, achieving a 28-day compressive strength of 33.75 MPa (382.70 kgf/cm2), a modulus of rupture of 56.90 kgf/cm² (5.58 MPa), and the longest initial setting time of 5 h 15 min. These results indicate that the combined admixture mixture performed better than the control mixture and the single-admixture mixtures when compressive strength, flexural strength, setting time, and fresh-state suitability were considered together. However, this finding should be interpreted as an observed laboratory performance response within the tested mixture matrix, not as definitive evidence of admixture synergy or a statistically optimized formulation.

The increase in MOR observed in the SP+WR mixture may be related to improved cement-particle dispersion, better compactability, enhanced fresh-state stability, or a more favorable paste–aggregate interaction. Previous studies have shown that polycarboxylate-based superplasticizers and related water-reducing systems may influence cement particle dispersion, adsorption behavior, hydration kinetics, pore structure, and cement–admixture compatibility; however, these effects are strongly dependent on cement chemistry, admixture molecular structure, aggregate characteristics, clay or fine-particle contamination, and the method of admixture addition [23], [31], [51]–[53]. Therefore, the mechanisms proposed in this study should be regarded as plausible explanations rather than confirmed causal evidence.

The present study did not directly measure air content, air-void distribution, pore structure, dispersion degree, compaction quality, or interfacial transition zone characteristics. Consequently, the higher MOR of the SP+WR mixture can be reported as an experimental finding, but the mechanisms responsible for this improvement should be discussed cautiously. Future studies should include quantitative fresh-state stability tests, air-content measurements, porosity analysis, microstructural characterization, and factorial SP–WR interaction testing to verify whether the observed improvement is due to dispersion effects, reduced entrapped air, improved paste–aggregate bonding, a modified pore structure, or other mechanisms.

From a practical perspective, the findings support four actions for the production of pavement concrete using local high-absorption fine aggregate. First, aggregate moisture content should be measured before batching, and the batch water should be corrected accordingly. Second, admixture dosage should be verified through trial batching rather than selected solely on supplier recommendations. Third, acceptance criteria should include MOR and setting-time window, not only compressive strength. Fourth, fresh-state stability should be assessed visually and, where possible, quantitatively using bleeding, segregation, air content, unit weight, and slump-retention tests. These controls are necessary because high-absorption aggregate systems are highly sensitive to small changes in effective water availability, which can alter workability, strength development, and pavement constructability.

Several limitations remain. First, replicate-level records were not available for every admixture dosage in the archived dataset; therefore, the current analysis is descriptive and should be strengthened with standard deviation, confidence intervals, ANOVA, or equivalent nonparametric tests. Second, durability properties were not evaluated, although pavement concrete must resist abrasion, drying shrinkage, permeability, fatigue, and long-term surface scaling. Third, the study used one local fine aggregate source, one cement, and two admixtures; therefore, the selected dosage should not be generalized without verification using other materials, temperatures, and batching conditions. Fourth, the combined SP+WR mixture should be confirmed using a factorial experimental design before the term synergy is used definitively.

5. CONCLUSION

This study evaluated the performance of rigid pavement concrete incorporating high-absorption local fine aggregate using a performance-based laboratory mixture selection framework. The conclusions are drawn from the tested mixture matrix and are limited to the evaluated materials, admixture dosages, and laboratory conditions. The fine aggregate absorption of 7.94% made the mixture sensitive to effective water availability. Although the control mixture met the 28-day compressive strength requirement at 31.71 MPa, it failed to meet the modulus of rupture requirement, reaching only 39.70 kgf/cm2 (3.89 MPa), and showed bleeding and an insufficient setting time.

Among the single-admixture mixtures, 0.80% superplasticizer gave the best-balanced response, with 33.93 MPa compressive strength, 46.43 kgf/cm2 (4.55 MPa) modulus of rupture, and a 4 hours initial setting time. The 0.25% water-reducing admixture produced the highest compressive strength, 37.53 MPa, but failed the modulus of rupture criterion. The combined SP+WR mixture provided the most balanced laboratory performance, achieving 33.75 MPa compressive strength, 56.90 kgf/cm2 (5.58 MPa) modulus of rupture, and an initial setting time of 5 h 15 min.

Therefore, within the tested laboratory matrix, the combined SP+WR mixture is the most suitable candidate for rigid pavement concrete with high-absorption local fine aggregate. The findings confirm that compressive strength alone is insufficient for selecting pavement concrete mixtures, and that modulus of rupture, setting time, workability, and fresh-state stability must also be considered. Further validation through replicate-level statistical analysis, factorial SP–WR interaction testing, durability assessment, and field-scale paving trials is recommended before practical implementation.

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CONFLICTS OF INTEREST

The authors declare that no conflicts of interest are associated with this study. All aspects of the research were conducted with the utmost integrity and transparency.

DATA AVAILABILITY

The datasets utilized and analyzed during this research are available from the corresponding author upon reasonable request.

ETHICAL STATEMENTS

Not applicable. This study did not involve any human participants or animals, and no personal or sensitive data were collected, used, or analyzed at any stage of the research.

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REFERENCES

[1] S. S. Pradhan, A. C. Pal, M. Panda, and P. Sarkar, “Predicting Mechanical Strength of Concrete Pavement: A Case Study with IoT-Based Monitoring Systems,” Int. J. Pavement Res. Technol., pp. 1–13, 2025, https://doi.org/10.1007/s42947-025-00616-2

[2] R. Campos, M. M. M. Larrain, M. Zaman, and V. Pozadas, “Relationships between compressive and flexural strengths of concrete based on fresh field properties,” Int. J. Pavement Res. Technol., vol. 14, no. 2, pp. 161–167, 2021, https://doi.org/10.1007/s42947-020-1074-0

[3] G. Sabih and R. A. Tarefder, “Characterizing strength and thermal properties of concrete for implementation of pavement mechanistic-empirical design in New Mexico,” Transp. Geotech., vol. 15, pp. 20–28, 2018, https://doi.org/10.1016/j.trgeo.2018.02.003

[4] G. Sabih, T. Rahman, and R. A. Tarefder, “Quantifying the impact of coefficient of thermal expansion of overlay concrete on unbonded concrete overlay performance,” Heliyon, vol. 4, no. 10, 2018, https://doi.org/10.1016/j.heliyon.2018.e00855

[5] G. Sabih and R. A. Tarefder, “Effects of CTE, MOR, and Elastic Modulus on the Performance of Rigid Pavement by MEPDG Simulation,” in Fourth Geo-China International Conference, 2016, pp. 86–93. https://doi.org/10.1061/9780784480052.011

[6] B. A. L. Fanggi, B. Suswanto, Y. Tajunnisa, J. W. M. Rafael, J. Lassa, and A. B. Habieb, “An Experimental Study on Axial Stress-Strain Behaviour of FRP-Confined Square Lightweight Aggregate Concrete Columns,” Adv. Sustain. Sci. Eng. Technol., vol. 7, no. 1, 2025, https://doi.org/10.26877/asset.v7i1.865

[7] S. Nisumanti, A. Kurniawan, and K. Al Qubroh, "Damage Analysis of Lahat Roads–Fence Natural from Endikat Bridge To Go To Depati H. Duaji Lintas Street Pagaralam–Lahat," J. Appl. Eng. Technol. Sci., vol. 4, no. 1, pp. 251–262, 2022, https://doi.org/10.37385/jaets.v4i1.1066

[8] J. R. Ramírez-Vargas, S. A. Zamora-Castro, A. L. Herrera-May, L. C. Sandoval-Herazo, R. Salgado-Estrada, and M. E. Diaz-Vega, "A Review of Sustainable Pavement Aggregates," Appl. Sci., vol. 14, no. 16, p. 7113, 2024, https://doi.org/10.3390/app14167113

[9] E. O. Fanijo, J. T. Kolawole, A. J. Babafemi, and J. Liu, "A comprehensive review on the use of recycled concrete aggregate for pavement construction: Properties, performance, and sustainability," Clean. Mater., vol. 9, p. 100199, 2023, https://doi.org/10.1016/j.clema.2023.100199

[10] C. M. Nwakaire, S. P. Yap, C. C. Onn, C. W. Yuen, and S. M. H. Moosavi, "Utilisation of Recycled Concrete Aggregates for Sustainable Porous Asphalt Pavements," Balt. J. Road Bridg. Eng., vol. 17, no. 1, pp. 117–142, 2022, https://doi.org/10.7250/bjrbe.2022-17.554

[11] A. J. Zulfikar, M. Y. Yaakob, and R. Syah, "Application of E-Glass Jute Hybrid Laminate Composite with Curved Shape on Compressive Strength of Cylindrical Column Concrete," J. Appl. Eng. Technol. Sci., vol. 5, no. 1, pp. 184–196, 2023, https://doi.org/10.37385/jaets.v5i1.2072

[12] A. Neville, Concrete: Neville's insights and issues. Thomas Telford, 2006.

[13] H. J. H. Brouwers, "The work of Powers and Brownyard revisited: Part 1," Cem. Concr. Res., vol. 34, no. 9, pp. 1697–1716, 2004, https://doi.org/10.1016/j.cemconres.2004.05.031

[14] P. C. Aïtcin and R. J. Flatt, Science and technology of concrete admixtures. Woodhead publishing, 2015. https://doi.org/10.1016/C2015-0-00150-2

[15] L. Domagała, "The effect of lightweight aggregate water absorption on the reduction of water-cement ratio in fresh concrete," Procedia Eng., vol. 108, pp. 206–213, 2015, https://doi.org/10.1016/j.proeng.2015.06.139

[16] Y. H. Kim, C. B. Park, B. Il Choi, T. Y. Shin, Y. Jun, and J. H. Kim, "Quantitative Measurement of Water Absorption of Coarse Lightweight Aggregates in Freshly-Mixed Concrete," Int. J. Concr. Struct. Mater., vol. 14, no. 1, p. 34, 2020, https://doi.org/10.1186/s40069-020-00408-x

[17] M. E. Sosa, Y. A. Villagrán Zaccardi, and C. J. Zega, "A critical review of the resulting effective water-to-cement ratio of fine recycled aggregate concrete," Constr. Build. Mater., vol. 313, p. 125536, 2021, https://doi.org/10.1016/j.conbuildmat.2021.125536

[18] Z. Duan et al., "Hydration kinetics and modified model for effective water to cement ratio control in recycled aggregate concrete," Case Stud. Constr. Mater., vol. 23, p. e05217, 2025, https://doi.org/10.1016/j.cscm.2025.e05217

[19] Y. Wei, Z. Chen, M. Yio, C. Cheeseman, H. Wang, and C. S. Poon, "Advanced moisture control in porous aggregates for improved lightweight high-performance concrete," Cem. Concr. Compos., vol. 155, p. 105826, 2025, https://doi.org/10.1016/j.cemconcomp.2024.105826

[20] X. Chen, H. Hao, J. de Brito, G. Liu, and J. Wang, "Discussion of the implementation of water compensation methods for recycled aggregate concrete: A critical review," Cem. Concr. Compos., vol. 161, p. 106080, 2025, https://doi.org/10.1016/j.cemconcomp.2025.106080

[21] M. Nedeljković, J. Visser, B. Šavija, S. Valcke, and E. Schlangen, "Use of fine recycled concrete aggregates in concrete: A critical review," J. Build. Eng., vol. 38, p. 102196, 2021, https://doi.org/10.1016/j.jobe.2021.102196

[22] J. Kim, "Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview," Constr. Build. Mater., vol. 328, p. 127071, 2022, https://doi.org/10.1016/j.conbuildmat.2022.127071

[23] Y. Ding, A. She, and W. Yao, "Investigation of Water Absorption Behavior of Recycled Aggregates and its Effect on Concrete Strength," Materials (Basel)., vol. 16, no. 13, p. 4505, 2023, https://doi.org/10.3390/ma16134505

[24] A. Fawzy, A. Elshami, and S. Ahmad, "Investigating the Effects of Recycled Aggregate and Mineral Admixtures on the Mechanical Properties and Performance of Concrete," Materials (Basel)., vol. 16, no. 14, p. 5134, 2023, https://doi.org/10.3390/ma16145134

[25] N. V. Khanapur, S. Pradhan, T. Chandra, and B. Tripathi, "Aggregate presaturation and concrete mixing technique for upscaling the use of fine recycled concrete aggregate," Results Eng., vol. 26, p. 105093, 2025, https://doi.org/10.1016/j.rineng.2025.105093

[26] O. A. Qasim, N. Hilal, M. I. Al Biajawi, N. H. Sor, and T. A. Tawfik, "Studying the usability of recycled aggregate to produce new concrete," J. Eng. Appl. Sci., vol. 71, no. 1, p. 129, 2024, https://doi.org/10.1186/s44147-024-00463-1

[27] J. Cheung, L. Roberts, and J. Liu, "Admixtures and sustainability," Cem. Concr. Res., vol. 114, pp. 79–89, 2018, https://doi.org/10.1016/j.cemconres.2017.04.011

[28] S. Barbhuiya, B. B. Das, and D. Adak, "Effects of chemical admixtures on the properties of concrete," in Binding Materials for Sustainable Construction, Elsevier, 2025, pp. 329–362. https://doi.org/10.1016/B978-0-443-26566-2.00009-X

[29] S. Suyuti and M. Muslimin, "an Empirical Study for Estimating Ultimate Bearing Capacity of Concrete Small-Pile Cluster in Soft Clays," J. Appl. Eng. Technol. Sci., vol. 6, no. 2, pp. 1397–1411, 2025, https://doi.org/10.37385/jaets.v6i2.4789

[30] X. H. Wang, Z. C. Fang, and L. Zheng, "Effect of Dose and Types of the Water Reducing Admixtures and Superplasticizers on Concrete Strength and Durability Behaviour: a Review," J. Civ. Eng. Manag., vol. 30, no. 1, pp. 33–48, 2024, https://doi.org/10.3846/jcem.2024.20145

[31] Y. Yang et al., "Interaction mechanisms between polycarboxylate superplasticizers and cement, and the influence of functional groups on superplasticizer performance: a review," Polym. Bull., vol. 81, no. 12, pp. 10415–10438, 2024, https://doi.org/10.1007/s00289-024-05233-w

[32] M. Moeinian, M. Ardjmand, and F. Nosratinia, "Evaluating the operational properties of concrete admixtures containing molecularly modified polycarboxylate superplasticizers," Sci. Rep., vol. 14, no. 1, p. 20170, 2024, https://doi.org/10.1038/s41598-024-71078-y

[33] Q. Liu et al., "Advancing understanding of polymer-based superplasticizers for diverse concrete applications: Insights from quantum chemistry and nanoscale adsorption behavior," Cem. Concr. Compos., vol. 153, p. 105690, 2024, https://doi.org/10.1016/j.cemconcomp.2024.105690

[34] J. Li, X. Zhang, X. Xu, and H. Wu, "Fully recycled aggregate concrete composite functional additives: Proportioning

tests and verification of engineering adaptability," Results Eng., vol. 27, p. 106910, 2025, https://doi.org/10.1016/j.rineng.2025.106910

[35] A. M. Zeyad and A. Almalki, "Influence of mixing time and superplasticizer dosage on self-consolidating concrete properties," J. Mater. Res. Technol., vol. 9, no. 3, pp. 6101–6115, 2020, https://doi.org/10.1016/j.jmrt.2020.04.013

[36] T. J. Van Dam, "Chemical Admixtures for Concrete Paving Mixtures (FHWA-HIF-18-017)." Federal Highway Administration, Washington, DC, 2019. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/43715/dot_43715_DS1.pdf

[37] T. J. Van Dam, "Specifying, designing, and proportioning paving concrete (FHWA-HIF-18-012)." Federal Highway Administration, Washington, DC, 2019. [Online]. Available: https://www.fhwa.dot.gov/pavement/pubs/hif18012.pdf

[38] ASTM International, "ASTM C33/C33M-24: Standard specification for concrete aggregates." ASTM International, West Conshohocken, PA, USA, 2024. https://doi.org/10.1520/C0033_C0033M-24

[39] ASTM International, "ASTM C494/C494M-24: Standard Specification for Chemical Admixtures for Concrete." ASTM International, West Conshohocken, PA, USA, 2024. https://doi.org/10.1520/C0494_C0494M-24

[40] ASTM International, "ASTM C192/C192M-24: Standard practice for making and curing concrete test specimens in the laboratory." ASTM International, West Conshohocken, PA, USA, 2025. https://doi.org/10.1520/C0192_C0192M-24

[41] ASTM International, "ASTM C143/C143M-20: Standard test method for slump of hydraulic-cement concrete." ASTM International, West Conshohocken, PA, USA, 2026. https://doi.org/10.1520/C0143_C0143M-20

[42] ASTM International, "ASTM C403/C403M-23: Standard test method for time of setting of concrete mixtures by penetration resistance." ASTM International, West Conshohocken, PA, USA, 2023. https://doi.org/10.1520/C0403_C0403M-23

[43] ASTM International, "ASTM C39/C39M-21: Standard test method for compressive strength of cylindrical concrete specimens." ASTM International, West Conshohocken, PA, USA, 2023. https://doi.org/10.1520/C0039_C0039M-21

[44] ASTM International, "ASTM C78/C78M-22: Standard test method for flexural strength of concrete (using simple beam with third-point loading)." ASTM International, West Conshohocken, PA, USA. https://doi.org/10.1520/C0078_C0078M-22

[45] Z. Zhao, S. Remond, D. Damidot, and W. Xu, "Influence of hardened cement paste content on the water absorption of fine recycled concrete aggregates," J. Sustain. Cem. Mater., vol. 2, no. 3–4, pp. 186–203, 2013, https://doi.org/10.1080/21650373.2013.812942

[46] G. Sabih and R. A. Tarefder, "Impact of variability of mechanical and thermal properties of concrete on predicted performance of jointed plain concrete pavements," Int. J. Pavement Res. Technol., vol. 9, no. 6, pp. 436–444, 2016, https://doi.org/10.1016/j.ijprt.2016.09.005

[47] W. Xun, C. Wu, X. Leng, J. Li, D. Xin, and Y. Li, "Effect of functional superplasticizers on concrete strength and pore structure," Appl. Sci., vol. 10, no. 10, p. 3496, 2020, https://doi.org/10.3390/app10103496

[48] J. Chakkamalayath, M. Abdulsalam, and S. Al-Bahar, "Compatibility of superplasticizers with cement paste and concrete mixes containing Type I and Type V cement, and volcanic ash," Innov. Infrastruct. Solut., vol. 7, no. 4, p. 259, 2022, https://doi.org/10.1007/s41062-022-00855-3

[49] J. Sivamani and N. T. Renganathan, "Effect of fine recycled aggregate on the strength and durability properties of concrete modified through two-stage mixing approach," Environ. Sci. Pollut. Res., vol. 29, no. 57, pp. 85869–85882, 2022, https://doi.org/10.1007/s11356-021-14420-5

[50] I. G. Amadi, H. Beushausen, and M. G. Alexander, "Multi-Technique Approach to Enhance the Properties of Fine Recycled Aggregate Concrete," Front. Mater., vol. 9, p. 893852, 2022, https://doi.org/10.3389/fmats.2022.893852

[51] A. Zingg et al., "Interaction of polycarboxylate-based superplasticizers with cements containing different C3A amounts," Cem. Concr. Compos., vol. 31, no. 3, pp. 153–162, 2009, https://doi.org/10.1016/j.cemconcomp.2009.01.005

[52] S. Beldarrain, G. Goracci, J. S. Dolado, A. Barquero, and J. R. Leiza, "Poly(carboxylated ether)s as Cement Additives: The Effect of the Addition Method on Hydration Kinetics," Materials (Basel)., vol. 17, no. 21, p. 5343, 2024, https://doi.org/10.3390/ma17215343

[53] Y. Gao et al., "Interaction Between Polycarboxylate Superplasticizer and Clay in Cement and Its Sensitivity Inhibition Mechanism: A Review," Materials (Basel)., vol. 18, no. 11, p. 2662, 2025, https://doi.org/10.3390/ma18112662