Open Journal of Civil Engineering, 2026, 16(3), 577-587
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Mix Design and Mechanical Behaviour of Structural Concrete in Tropical Coastal Environments

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How to cite this paper: Diouf, B., Ba, M. and Cisse, B. (2026) Mix Design and Mechanical Behaviour of Structural Concrete in Tropical Coastal Environments. *Open Journal of Civil Engineering*, **16**, 577-587.
https://doi.org/10.4236/ojce.2026.163029

Received: July 18, 2026
Accepted: September 1, 2026
Published: September 4, 2026

Abstract

This paper presents a comprehensive experimental investigation into the mix design and mechanical behaviour of five structural concrete grades (C20/25 to C40/50) used in the construction of the 4th Abidjan Bridge, Côte d'Ivoire. Mix proportions were established using the Dreux-Gorisse method and two cement types: CPA-CEM I/52.5N (ordinary Portland cement) and CHF-CEM III/B 42.5 L-LH/SR (blast-furnace slag cement). The influence of three key parameters—cement content, water-to-cement ratio (w/c), and cement type—on fresh-state consistency and 7- and 28-day compressive strength was systematically assessed through standardised slump tests (NF EN 12350-2) and compression tests on cylindrical specimens (NF EN 12390-3). Results demonstrate that increasing cement content from 275 to 400 kg/m^3 is associated with a 55% increase in 28-day compressive strength, while reducing the w/c ratio from 0.62 to 0.44 is associated with a 50% strength gain; because cement type, aggregate proportions and admixture dosage also varied among the mixes compared, these values reflect differences between complete mix formulations rather than isolated effects of cement content or w/c ratio alone. At identical cement dosages (380 kg/m^3), CEM I develops 7-day strengths approximately 21% higher than CEM III/B, whereas 28-day strengths converge within 3%, although the mixes compared also differed in w/c ratio and superplasticiser dosage. The mean compressive strength of each grade, based on at least three specimens, exceeded the corresponding target strength class defined under NF EN 206-1; a mean value alone, however, does not constitute the statistical characteristic-strength or conformity assessment required by the standard. The findings are consistent with recent literature on hydration kinetics, capillary porosity, and admixture performance, and provide actionable quality-control guidelines for ready-mix concrete production in tropical coastal settings.

Keywords

Concrete Mix Design, Compressive Strength, Water-to-Cement Ratio, Cement Dosage, Bridge Construction, Tropical Environment

1. Introduction

Concrete is the most widely used construction material in the world, with annual global production exceeding ten billion tonnes [1]. Its widespread adoption stems from its high compressive strength, versatility, and relative cost-effectiveness compared with alternative structural materials. In sub-Saharan Africa, rapid urbanisation and demographic growth are generating unprecedented demand for road infrastructure and large-scale civil engineering structures, making concrete quality a critical concern for the safety and longevity of new assets [2].

The compressive strength of concrete, measured on cylindrical or cubic specimens at 28 days of age, is the primary benchmark for structural design and quality control under EN 206-1 and EN 12390 [3]. This property is governed by a complex interplay of mix composition variables and curing conditions. Among these, cement content, water-to-cement ratio (w/c), and cement type are universally recognised as the most influential parameters [4] [5].

Recent experimental studies have further quantified these relationships. It has been demonstrated [6], through uniaxial compression tests and ultrasonic velocity measurements, that higher w/c ratios produce greater initial porosity and a more pronounced pore-compaction stage, both detrimental to mechanical performance. At equal dosage, CEM III blast-furnace slag cement has been shown [7] to achieve compressive strengths comparable to CEM I at 28 days, while offering significantly lower permeability—a critical advantage in chloride-rich environments. Regarding admixtures, it has been confirmed [8] that polycarboxylate-based superplasticisers, when dosed correctly, enhance both workability and long-term compressive strength by allowing substantial water reduction without loss of consistency.

The construction site of the 4th Abidjan Bridge (Côte d'Ivoire) offers an ideal field laboratory for investigating these parameters in a tropical coastal context. The project involves five distinct concrete grades, ranging from C20/25 blinding concrete to C40/50 prestressed box-girder concrete, exposed to a range of aggressive environments (XC2-XC4, XS1-XS3, XF1, XA1). The Dreux-Gorisse method—a widely adopted semi-empirical grapho-analytical mix design procedure in Francophone Africa—was used to establish the proportions of each grade from locally characterised aggregates [9].

This paper has three objectives: 1) to present the complete mix design procedure for the five concrete grades; 2) to analyse experimentally the individual effects of cement content, w/c ratio, and cement type on compressive strength at 7 and 28 days; and 3) to derive practical quality-control recommendations for ready-mix concrete production in tropical coastal environments. Experimental results are systematically compared with current international literature to contextualise the findings within the broader state of knowledge.

2. Materials and Methods

2.1. Aggregates

Four aggregate classes were sourced from the batching plant stockpiles: fine sand 0/2, coarse sand 0/5, gravel 5/12.5, and gravel 12.5/25. The maximum aggregate size is D_{max} = 25 mm, as required by the structural specifications of the project.

The particle density of sands 0/2 and 0/5 is 2.65 and 2.68 kg/L, respectively, with fineness moduli of 2.0 and 2.8. The sand equivalent of the 0/2 sand is 90%, well above the minimum threshold of 65% required by the standard. The Los Angeles abrasion values of gravels 5/12.5 and 12.5/25 are 25.1% and 27.7%, respectively, both conforming to the maximum limit of 30% prescribed for structural concrete [10]. Aggregate properties are summarised in **Table 1**.

Table 1. Physical properties of aggregates.

Aggregate class	Particle density (kg/L)	Fineness modulus	Sand equivalent (%)	LA abrasion (%)
Sand 0/2	2.65	2.0	90	–
Sand 0/5	2.68	2.8	–	–
Gravel 5/12.5	–	–	–	25.1
Gravel 12.5/25	–	–	–	27.7

2.2. Cements

Two Portland-based cements manufactured by LafargeHolcim were used, selected according to the structural function and environmental exposure class of each concrete element. The CPA-CEM I/52.5N is a pure Portland cement with a characteristic 28-day compressive strength of 58.7 MPa. The CHF-CEM III/B 42.5 L-LH/SR is a blast-furnace slag cement with low heat of hydration and high sulfate resistance, achieving 49.4 MPa at 28 days. The latter is particularly appropriate for elements exposed to aggressive environments (classes XS and XA), where alkali-silica reaction and sulfate attack are identified risks [11]. Chemical compositions and physical properties are presented in **Table 2** and **Table 3**, respectively.

Table 2. Chemical composition of cements (Source: LafargeHolcim technical data sheets).

Cement type	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Cl (%)
CPA-CEM I/52.5N	20.24	4.91	3.22	61.82	1.57	2.87	≤0.1
CHF-CEM III/B 42.5 L-LH/SR	24.27	6.37	2.27	51.75	4.02	3.15	≤0.1

Table 3. Physical properties of cements (Source: LafargeHolcim technical data sheets).

Cement type	Initial set (min)	Final set (min)	Blaine (m^2/kg)	Rc 2d (MPa)	Rc 7d (MPa)	Rc 28d (MPa)
CPA-CEM I/52.5N	131	204	4162	32.8	46.6	58.7
CHF-CEM III/B 42.5 L-LH/SR	145	230	4085	14.5	28.0	49.4

2.3. Chemical Admixtures

Two admixtures were incorporated in all five mixes. PLASTIRETARD, a set-retarding admixture, was used at a dosage of 0.2% by mass of cement. Its role is to maintain workability during transit from the batching plant to the pour locations, given the severe road-congestion conditions in urban Abidjan. TEMPO-12, a polycarboxylate ether (PCE) superplasticiser, was dosed between 1.3% and 2.2% by mass of cement, depending on the target strength class. It enables a substantial reduction in mixing-water content while preserving the S4 consistency class (slump 160 - 210 mm) required by the project specifications. The positive effect of PCE superplasticisers on both workability and compressive strength through water reduction has been confirmed by multiple recent studies [8] [12].

2.4. Mix Design Procedure - Dreux-Gorisse Method

The Dreux-Gorisse method is a semi-empirical grapho-analytical approach that determines optimum constituent proportions from the reference grading curve and the target compressive strength [13]. Key design inputs include the target strength f_{c28}, the cement-to-water ratio (C/W), the NF EN 206-1 exposure classes, and the desired consistency class. The method systematically accounts for local aggregate grading characteristics and incorporates iterative corrections based on reception testing, making it particularly well suited to African construction sites where aggregate properties can vary significantly from batch to batch [9].

Five formulations were developed in accordance with the exposure and strength classes defined under NF EN 206-1, ranging from blinding concrete (C20/25, class X0) to prestressed box-girder concrete (C40/50, classes XC4-XF1-XS1). All mixes target the S4 consistency class (slump 160 - 210 mm). The resulting mix proportions are presented in Table 4.

2.5. Experimental Programme

2.5.1. Sampling and Specimen Preparation

Fresh concrete samples were collected directly from ready-mix trucks at the pour locations in accordance with NF EN 12350-1. Cylindrical specimens (Ø160 mm × H320 mm) were cast in steel moulds and compacted with a vibrating needle in three equal layers (NF EN 12390-2). After demoulding at a minimum age of 16 hours, specimens were stored in water at 20˚C ± 2˚C until the test date.

Table 4. Mix proportions of the five concrete formulations (Dreux-Gorisse method).

Constituent	Mix 1 C20/25	Mix 2 C30/37	Mix 3 C35/45	Mix 4 C35/45	Mix 5 C40/50
Cement type	CEM III/B 42.5	CEM III/B 42.5	CEM III/B 42.5	CEM I 52.5N	CEM I 52.5N
Cement content (kg/m^3)	275	360	380	380	400
Sand 0/2 (kg/m^3)	403	385	398	394	388
Sand 0/5 (kg/m^3)	425	385	398	394	388
Gravel 5/12.5 (kg/m^3)	425	465	420	454	410
Gravel 12.5/25 (kg/m^3)	696	697	687	643	670
Water (L/m^3)	170	164	168	179	184
w/c ratio	0.62	0.46	0.44	0.47	0.46
Superplasticizer TEMPO-12 (L)	4.95	6.48	6.84	8.36	8.00
Retarder PLASTIRETARD (L)	0.55	0.72	0.76	0.76	0.80

2.5.2. Slump Test

Fresh concrete workability was assessed using the Abrams cone slump test (NF EN 12350-2). The standard cone (base Ø200 mm, top Ø100 mm, height 300 mm) was filled in three layers, each rodded 25 times. The slump was measured immediately after cone removal. The target range of 160 - 210 mm corresponds to consistency class S4.

2.5.3. Compressive Strength Test

Compressive strength was determined at 7 and 28 days of age in accordance with NF EN 12390-3, using a hydraulic press conforming to NF EN 12390-4. Loading faces were capped with molten sulfur to ensure planarity and parallelism. A constant loading rate of 0.5 MPa/s was applied throughout each test (within the permissible range of 0.2 - 1.0 MPa/s).

3. Results and Discussion

3.1. Effect of Cement Content

Figure 1 summarises the average compressive strengths recorded at 7 and 28 days for Mixes 1 (275 kg/m^3), 2 (360 kg/m^3), and 5 (400 kg/m^3), together with the measured slump and w/c ratio.

Mixes 1, 2 and 5 are compared here as three complete mix formulations containing 275, 360 and 400 kg/m^3 of cement, respectively; these formulations also differ in w/c ratio (0.62, 0.46 and 0.46), and, more generally, in aggregate proportions and admixture dosage, so the comparison reflects associations between complete formulations rather than the isolated effect of cement content. A strong positive association is observed between the mix formulations and 28-day compressive strength: the change from 275 to 360 kg/m^3 of cement (accompanied by a reduction in w/c from 0.62 to 0.46) is associated with a strength gain of approximately 33%

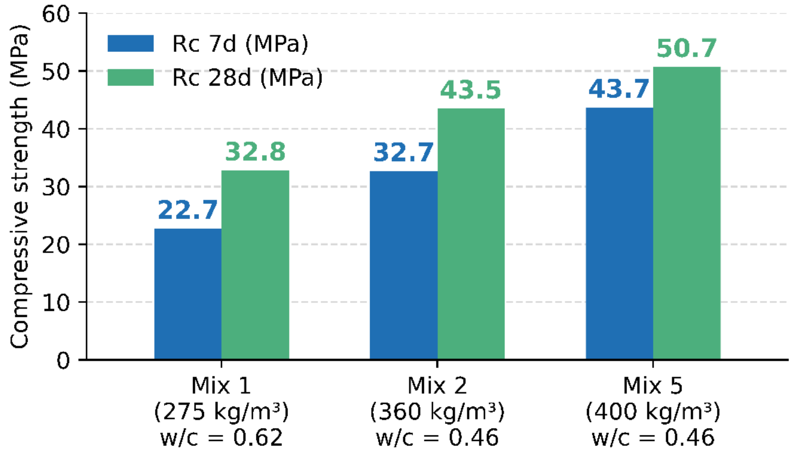

Figure 1. Compressive strength as a function of cement content (mean values).

(32.8 → 43.5 MPa), while the further change from 360 to 400 kg/m^3 of cement (w/c held at approximately 0.46) is associated with an additional 16% gain (43.5 → 50.7 MPa). This behaviour is consistent with the greater quantity of calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H) formed during hydration, which constitute the binding matrix responsible for mechanical resistance [14], although part of the gain between Mixes 1 and 2 may also reflect the concurrent reduction in w/c ratio.

The diminishing marginal return observed at higher dosages (275→360 versus 360→400 kg/m^3) is consistent with findings in the literature [4], indicating that excess unreacted clinker in highly dosed concretes contributes little to ultimate strength. Across all three grades, the measured mean compressive strengths comfortably exceed the target strength values prescribed by NF EN 206-1 for each class, a favourable indication of the Dreux-Gorisse formulations' performance; this observation, however, is based on mean values only and does not by itself constitute the formal conformity assessment defined by the standard, which additionally requires data on the number of batches tested and the associated variability.

3.2. Effect of Water-to-Cement Ratio

To examine the association between the w/c ratio and compressive strength, Mixes 1 (w/c = 0.62), 3 (w/c = 0.44), and 4 (w/c = 0.47) were compared. These mixes also differ in cement content (275, 380 and 380 kg/m^3), cement type (CEM III/B for Mixes 1 and 3, CEM I for Mix 4), aggregate proportions, and admixture dosage, so the comparison should be read as an association between mix formulations rather than an isolated w/c effect. **Figure 2** summarises the results.

A clear inverse association is found between the w/c ratio and compressive strength at both test ages. Reducing the w/c ratio from 0.62 (Mix 1) to 0.44 (Mix 3) is accompanied by an increase in 28-day compressive strength from 32.8 to 49.3 MPa (a 50% gain); however, Mixes 1 and 3 also differ in cement content (275 vs 380 kg/m^3), so this gain cannot be attributed to the w/c ratio alone. Comparing

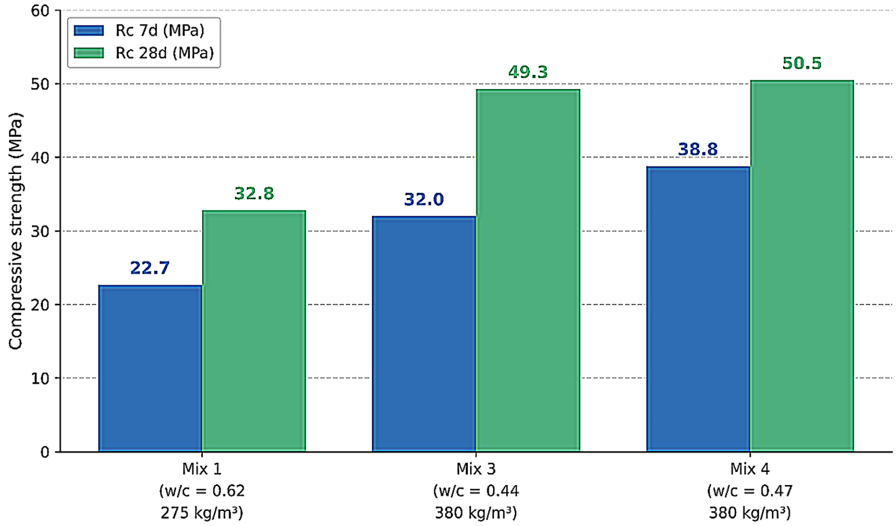

Figure 2. Effect of w/c ratio on compressive strength.

Mix 3 (w/c = 0.44) to Mix 4 (w/c = 0.47) shows only a marginal variation in 28-day strength (49.3 vs 50.5 MPa); differences in cement type, aggregate proportions, and superplasticiser dosage between Mixes 3 and 4 are additional confounding factors, so this comparison likewise does not isolate the effect of the w/c ratio and must be interpreted with care.

These results are consistent with the Féret-Abrams law relating strength to the C/W ratio [5]. Further evidence from ultrasonic pulse velocity measurements [6] shows that concretes with lower w/c ratios exhibit lower initial porosity and a less distinct pore-compaction stage during loading, resulting in superior mechanical performance. Reducing the w/c ratio also diminishes the volume of capillary pores that remain unfilled after hydration, thereby improving durability against the chloride and sulfate ingress characteristic of the marine coastal environment of the Abidjan site [7].

3.3. Effect of Cement Type

The association between cement type and compressive strength was examined by comparing Mixes 3 (CHF-CEM III/B 42.5 L-LH/SR) and 4 (CPA-CEM I/52.5N), which share an identical cement dosage of 380 kg/m^3 but differ in w/c ratio (0.44 vs 0.47), aggregate proportions, and superplasticiser dosage (6.84 vs 8.36 L); consequently, the strength differences reported below cannot be attributed solely to cement type. **Figure 3** presents the results.

At 7 days, CEM I concrete (Mix 4) develops a compressive strength of 38.8 MPa compared with 32.0 MPa for CEM III/B concrete (Mix 3), a differential of approximately 21%; as noted above, this differential reflects an association between two mix formulations that also differ in w/c ratio and superplasticiser dosage, not a controlled cement-type effect. Part of this early-strength difference is nonetheless consistent with the faster hydration kinetics of high-C_3S Portland cement clinker relative to the pozzolanic reaction of ground granulated blast-furnace slag,

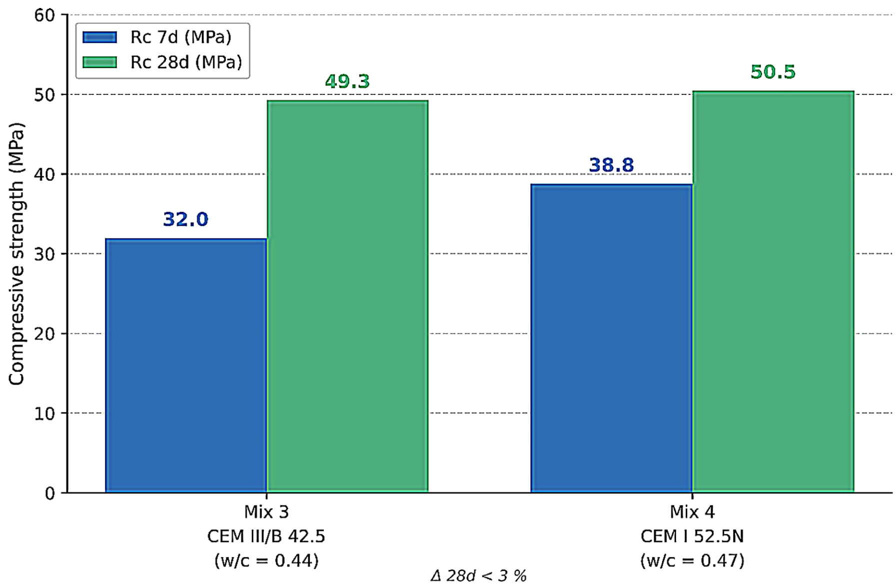

Figure 3. Effect of cement type on compressive strength at equal dosage (380 kg/m³).

which requires the presence of portlandite ($Ca(OH)_2$) released by clinker hydration and proceeds more slowly, particularly at low curing temperatures [11].

By 28 days, however, the strengths converge: 50.5 MPa for CEM I versus 49.3 MPa for CEM III/B, a difference of less than 3%. This pattern aligns closely with findings reported in the literature [7], showing that, at equal dosage and with the same aggregate type, CEM III concrete achieves 28-day compressive strengths comparable to CEM I while providing substantially lower gas permeability and initial water absorption—properties of particular importance for durability in chloride-rich coastal environments. In the context of the Abidjan Bridge, the use of CEM III/B for submerged and buried elements (foundations, piles) where rapid early-strength gain is not required is therefore well justified from a durability standpoint, while CEM I is appropriately deployed for the box-girder elements requiring fast formwork removal.

3.4. Fresh Concrete Workability

All five concrete mixes achieved slump values in the range 160 - 210 mm, conforming to the target S4 consistency class. This confirms the effectiveness of the combined use of TEMPO-12 superplasticiser and PLASTIRETARD set retarder in maintaining workability over the transit duration from plant to site without increasing the w/c ratio. Optimal PCE superplasticiser dosing enables water reductions of 15% - 30% while preserving target slump, with a net positive effect on 28-day compressive strength [12]. The consistency results thus validate the admixture selection strategy adopted for the project.

4. Conclusions

This study investigated the mix design and key factors governing the mechanical behaviour of five structural concretes (C20/25 to C40/50) used in the construction of the 4th Abidjan Bridge, Côte d'Ivoire. Using the Dreux-Gorisse method and two cement types (CEM I/52.5N and CEM III/B 42.5 L-LH/SR) in combination with PCE superplasticiser and set retarder, the following conclusions are drawn:

1) Cement content shows a strong positive association with compressive strength: across the mix formulations compared (which also differ in w/c ratio, cement type, and admixture dosage), increasing the dosage from 275 to 400 kg/m^3 is accompanied by an approximately 55% rise in 28-day strength, with a diminishing marginal return above 360 kg/m^3. All five grades meet or exceed their target strength class under NF EN 206-1 on the basis of mean values from at least three specimens; a full statistical conformity assessment, as defined by the standard, would additionally require the number of batches tested and the associated variability.

2) The w/c ratio shows a strong association with both strength and durability. Reducing the w/c ratio from 0.62 to 0.44 is accompanied by a 50% gain in 28-day compressive strength, consistent with denser C-S-H matrix formation and reduced capillary porosity; as the mixes compared also differ in cement content, cement type, and admixture dosage, this gain should be read as an association across formulations rather than an isolated w/c effect.

3) Cement type is associated with the rate of early-strength development. CEM I/52.5N develops 7-day compressive strengths approximately 21% higher than CEM III/B 42.5 at equal dosage, while 28-day strengths converge within 3%; because the mixes compared also differ in w/c ratio and superplasticiser dosage, this comparison should be interpreted as an association between formulations rather than an isolated cement-type effect. In aggressive coastal environments, CEM III/B is preferred for buried and submerged elements owing to its superior resistance to chloride and sulfate ingress.

4) The combined use of a PCE superplasticiser and a set retarder enables the S4 consistency class to be maintained during transit without increasing the w/c ratio, thereby preserving mechanical performance.

These conclusions have broad applicability to concrete infrastructure projects in tropical coastal settings. Future research directions include long-term durability assessment (accelerated carbonation, chloride migration tests) and the integration of supplementary cementitious materials (fly ash, silica fume, rice husk ash) as partial cement replacements to reduce the carbon footprint of concrete production while maintaining structural performance.

Artificial Intelligence (AI) Declaration

I would like to clarify that AI tools were used only as a language assistance tool, mainly to translate and improve the English presentation of a manuscript that was originally written in French.

The scientific content of the manuscript, including the experimental data, was obtained from laboratory work carried out by my student under my supervision. The analysis, interpretation of the results, and scientific conclusions are based on our own research work and were not generated by AI. AI was therefore not used to generate the experimental data, scientific results, analysis, interpretation, or conclusions presented in the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Adolphe, T. (2026) Drivers and Barriers to Adopting Sustainable Building Materials: Evidence from Construction Professionals in Kigali City, Rwanda. *Smart Construction and Sustainable Cities*, **4**, Article No. 3. https://doi.org/10.1007/s44268-025-00083-5

[2] AFNOR (2019) NF EN 12390-3. Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. Association française de normalisation.

[3] Diouf, B. (2026) Recycled Concrete Aggregates: Review Physical, Mechanical, and Durability Characterisation and Comparison with Natural Aggregates. *Open Journal of Civil Engineering*, **16**, 337-348. https://doi.org/10.4236/ojce.2026.162017

[4] Lin, J., Tian, B., Liang, Z., Hu, E., Liu, Z., Wang, K., *et al.* (2024) Impact of Water-Cement Ratio on Concrete Mechanical Performance: Insights into Energy Evolution and Ultrasonic Wave Velocity. *Materials*, **17**, Article No. 3651. https://doi.org/10.3390/ma17153651

[5] Rudnicki, T. (2022) The Influence of the Type of Cement on the Properties of Surface Cement Concrete. *Materials*, **15**, Article No. 4998. https://doi.org/10.3390/ma15144998

[6] Onyeka, F.C., Igbadumhe, A.O. and Mama, B.O. (2023) Characterization of Concrete Strength, Durability and Workability Impacted by a Super-Plasticizing Additive. *Journal of Materials Engineering, Structures and Computation*, **2**, 14-25.

[7] Diouf, B., Ba, M., Cisse, B. and Fall, A. (2026) Aggregate Testing and Hydraulic Concrete Mix Design for Bridge Construction in an Aggressive Marine Environment: A Case Study of the Émile Badiane and Tobor Bridges, Ziguinchor, Senegal. *Open Journal of Civil Engineering*, **16**, 303-314. https://doi.org/10.4236/ojce.2026.162015

[8] AFNOR (2010) NF EN 1097-2:2010. Essais pour déterminer les caractéristiques mécaniques et physiques de granulats. Partie 2. Association française de normalisation.

[9] Seleem, H.E.H., Rashad, A.M. and El-Sabbagh, B.A. (2010) Durability and Strength Evaluation of High-Performance Concrete in Marine Structures. *Construction and Building Materials*, **24**, 878-884. https://doi.org/10.1016/j.conbuildmat.2010.01.013

[10] Tareque, T., Tousif, F., Billah, M.A., Jabir, A.A.M. and Mirmotalebi, S. (2023) Comprehensive Analysis of the Effects of Superplasticizer Variation on the Workability and Strength of Ready-Mix Concrete. *Open Journal of Civil Engineering*, **13**, 756-770. https://doi.org/10.4236/ojce.2023.134050

[11] Jierula, A., Li, H., Chen, Y., Wu, C., Wu, X. and Yin, H. (2024) Study on the Influence of Density and Water-Cement Ratio on the Cement Utilization, Fluidity, Mechanical Properties, and Water Absorption of Foam Concrete. *Buildings*, **14**, Article No. 3550. https://doi.org/10.3390/buildings14113550

[12] AFNOR (2014) NF EN 206/CN:2014. Béton—Spécification, performance, production et conformité. Association française de normalisation.

[13] Teng, L., Jin, M., Du, J. and Khayat, K.H. (2024) Synergetic Effect of Viscosity Mod-

ifying Admixtures and Polycarboxylate Ether Superplasticizer on Key Characteristics of Thixotropic UHPC for Bonded Bridge Deck Overlay Rehabilitation. *Case Studies in Construction Materials*, **20**, e02739. https://doi.org/10.1016/j.cscm.2023.e02739

[14] Hamza, C., Bouchra, S., Mostapha, B. and Mohamed, B. (2020) Formulation of Ordinary Concrete Using the Dreux-Gorisse Method. *Procedia Structural Integrity*, **28**, 430-439. https://doi.org/10.1016/j.prostr.2020.10.050