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Research Article

Assessment of the Suitability of Aggregates from Southern Benin for Self-Compacting Concrete Production: Characterization, Normative Classification and Multicriteria Comparison

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Abstract

This study assesses the suitability of aggregates from South Benin for self-compacting concrete (SCC) through a five-step approach: a georeferenced inventory of 75 sand and 39 gravel quarries; dimensional classification according to NF EN 12620; physical and mechanical characterization (density, water absorption, cleanliness, Los Angeles and Micro-Deval resistance); evaluation of aggregate behavior in concrete mixes; and a transparent multicriteria ranking. The results show strong heterogeneity. Lagoon sands, although abundant, have a low fineness modulus (2.10) and an insufficient sand equivalent (SE = 62%), and are unsuitable for SCC without treatment. Marine and Oumé alluvial sands (average SE of 72% and 68%) remain below the SE ≥ 80% recommended by EFNARC for SCC and require washing or blending. The chloride content of raw marine sand (0.09% of dry sand mass, i.e. 0.197% of cement mass in a 400 kg/m^3 mix) complies with class Cl 0.40 but leaves almost no margin to class Cl 0.20, so washing is mandatory for prestressed or severely exposed concrete. Crushed basalt and granite show excellent mechanical performance (LA ≤ 22%, MDE ≤ 14%), whereas laterite is unsuitable for structural use. A weighted-sum multicriteria analysis (six criteria, weights of 15–20%) ranks crushed aggregates first (7.62/10), marginally ahead of marine sands (7.51/10), followed by alluvial sands (7.33/10) and lagoon sands (6.89/10); a full sensitivity analysis shows that lagoon sands rank last in all tested scenarios, whereas the order of the first two depends on the weights. A C30/37 SCC can be obtained by combining washed marine or alluvial sand with crushed gravel 5.6/16 or 10/20, a carboxylate superplasticizer, and a mineral addition (fc28 = 33–45 MPa). The originality of this work lies in cross-referencing a georeferenced deposit inventory with SCC-specific normative requirements and in proposing a transparent, reproducible multicriteria ranking tool for SCC mix design.

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Keywords

Self-compacting Concrete (SCC), Tropical Aggregates, Mix Design Optimization, South Benin, Multicriteria Analysis, Chloride Content

1. Introduction

Self-compacting concrete (SCC) is one of the major advances in concrete technology of the last three decades. Developed in Japan in the late 1980s by Okamura and co-workers [1] to address a shortage of skilled labor and improve structural durability, it differs from conventional concrete in its ability to flow under its own weight, fill formwork, pass between closely spaced reinforcing bars, and consolidate without mechanical vibration [2, 3], offering benefits in surface finish quality, casting rate, reduced site noise, and access to difficult-to-reach areas.

The design of SCC relies on a precise rheological balance that requires particular attention to the nature and quality of the aggregates. As the inert skeleton of concrete, aggregates account for 60 to 75% of the total volume and strongly influence properties in both the fresh and hardened states [2, 4]. EFNARC issued precise recommendations in 2002 and 2005 on aggregate shape, particle size distribution, fines content, and cleanliness for SCC [2, 5], which are noticeably stricter than for ordinary concrete.

The influence of aggregates on SCC rheology is well documented: Khayat (1999) showed that particle shape and surface texture affect plastic viscosity and segregation resistance [6]; Domone (2006), based on 68 mix designs, confirmed that more regular calcareous aggregates promote workability, unlike siliceous or crystalline aggregates whose content must be controlled [7]; De Schutter et al. (2008) established that the mechanical strength and durability of SCC strongly depend on the intrinsic quality of the aggregates (resistance to fragmentation, absorption, volumetric stability) [8]; Mehta and Monteiro (2006) noted that aggregate-paste interfaces, which are zones of structural weakness, become even more critical given the higher fluidity of SCC [9].

From a sustainable construction perspective, the valorization of local materials represents a major strategic issue, particularly in developing countries. Substituting imported materials with locally available resources helps reduce construction costs, lower the carbon footprint associated with transportation, and stimulate the local economy [4, 10].

In Benin, and more specifically in the South Benin region, the aggregates used in construction come from several sources: local deposits of fluvial, lagoon, and marine sands exploited along waterways and the coastline, as well as lateritic gravels extracted in several southern communes. Since the coastal sedimentary basin of South Benin has no hard-rock outcrops, the crushed coarse aggregates (granite, basalt, gneiss) used locally for SCC come from quarries located in the central and northern parts of the country [11], or are imported from neighboring Togo and then regularly transported to markets in the south. These materials have specific mineralogical, physical, and mechanical characteristics, linked to the geological conditions of their local or regional basin of origin, which deserve a rigorous assessment with respect to SCC requirements. To date, few studies have addressed the systematic qualification of these aggregates from the perspective of high-performance concrete mix design, which constitutes a notable scientific gap. The scientific novelty of the present work lies in three elements: (i) relating, at this geographic scale, a comprehensive georeferenced inventory of South Benin deposits to the specific normative requirements of SCC; (ii) building an explicit multicriteria decision-making framework, transferable to other West African contexts presenting comparable heterogeneity in aggregate resources; and (iii) the quantified identification of corrective treatments (washing, particle-size blending) needed to bring local aggregates into compliance with SCC requirements.

To position the present study, Table 1 summarizes the main experimental programs that have examined the influence of aggregate type, shape, grading, and origin on the fresh and hardened properties of SCC. Most of them concern temperate or arid regions, a single aggregate family (generally sand), or mortars rather than concretes. To the authors' knowledge, none combines a georeferenced inventory of deposits, a classification according to NF EN 12620, and a transparent multicriteria ranking for the aggregates of a tropical coastal sedimentary basin.

Table 1. *Summary of major previous studies on the influence of aggregates on SCC performance.*

Reference	Region / materials	Aggregate parameter studied	Main findings
Khayat (1999) [6]	SCC, general	Particle shape and surface texture	Shape and texture affect plastic viscosity and segregation resistance.
Domone (2006) [7]	68 SCC mix designs from case studies	Aggregate mineralogy and Dmax	Regular calcareous aggregates favor workability; Dmax > 20 mm increases blocking risk.
De Schutter et al. (2008) [8]	SCC, state of the art	Fragmentation resistance, absorption, volumetric stability	Strength and durability of SCC depend on the intrinsic quality of aggregates.
Westerholm et al. (2008) [30]	Mortars, Sweden	Fine aggregate shape and fines	Particle shape and fines content influence mortar rheology.
Benabed et al. (2012) [29]	Self-compacting mortars	Various sand types	Sand type affects the fresh and hardened properties of self-compacting mortars.
Nanthagopalan and Santhanam (2011) [28]	SCC, India	Manufactured vs natural sand	Fresh and hardened behavior of SCC made with manufactured sand compared with natural sand.
Bouziani (2013) [31]; Bouziani et al. (2014) [23]	SCC, Algeria	River, crushed and dune sand blends	Crushed and dune sands raise sand packing density and J-ring flowability; T500 passing ability decreases with the proportion of crushed sand.
Laoufi et al. (2020) [25]	Self-compacting mortars, Mascara (Algeria)	Three natural and three crushed sands	Crushed sands give a more compact skeleton and higher mechanical performance.
Sooriyaarachchi and Lasintha (2016) [26]	SCC, Sri Lanka	River sand, quarry dust, offshore sand	Minimum fine-aggregate share of 50, 55 and 60% (offshore, river, quarry dust); offshore sand had the lowest water demand, quarry dust the highest 28-day strength.
Sahraoui and Bouziani (2021) [24]	ANN on Algerian literature data	Sand and gravel types and contents	Higher gravel content lowers passing ability but raises viscosity, stability and strength.
Khaoya et al. (2024) [27]	SCC, Kenya	Volcanic tuff replacing river sand (0–10%)	Flowability, passing ability and strength decrease as tuff content increases.
Oluwasola et al. (2020) [18]	Review	Rounded vs crushed aggregates	Crushed aggregates raise compressive strength by 8–15% at equal cement content (as reported).
Houehanou et al. (2026) [20]	SCC, southern Benin	3 sands ×2 gravels (18 mixes)	Natural aggregates improve flowability; crushed aggregates improve strength; crushed sand + crushed gravel reduces passing ability.
This study	South Benin; 75 sand and 39 gravel quarries inventoried	All aggregate families; NF EN 12620 classification; physical, mechanical and chloride tests	Georeferenced inventory, compliance with SCC requirements, transparent multicriteria ranking, and corrective treatments.

2. Materials and Methods

2.1. Experimental Program

The study is structured into five complementary and progressive stages, whose overall coherence ensures the scientific rigor of the approach and the relevance of the results with respect to the stated objectives. The five stages of the study are as follows:

1) Identification, location, and mapping of quarries
2) Dimensional characterization and classification of aggregates
3) Determination of physical and mechanical properties
4) Analysis of aggregate behavior in concrete
5) Multicriteria comparative analysis of aggregates

2.2. Identification, Location, and Mapping of Quarries

This first stage establishes a comprehensive, georeferenced inventory of aggregate production sites in South Benin, through field surveys, interviews with industry stakeholders, and the use of cartographic data (geological maps, satellite imagery), including the identification of active quarries, extraction methods, rock type, and production volumes, resulting in a georeferenced GIS mapping of the sites recorded.

2.3. Dimensional Characterization and Classification of Aggregates

The second stage focuses on the particle size characterization of the materials and their classification according to the standards in force (NF EN 12620, NF P 18-540): sieving and sedimentation analyses, particle size distribution curves, fineness modulus, aggregate size class, coefficients of uniformity and curvature, fines content (< 0.063 mm), grain shape, and compliance with the grading envelopes recommended for SCC.

2.4. Determination of Physical and Mechanical Properties

In the third stage, the main intrinsic properties of the aggregates are determined in accordance with standards NF EN 1097 and NF EN 933: bulk and particle density, water absorption, moisture content, cleanliness (sand equivalent, methylene blue value), resistance to fragmentation (Los Angeles, Micro-Deval) [12], shape and flakiness coefficients, wear resistance, and surface condition. The water-soluble chloride content of the raw marine sand was determined according to NF EN 1744-1 [33].

2.5. Analysis of Aggregate Behavior in Concrete

The fourth stage analyzes the behavior of the selected aggregates in self-compacting concrete mixes, through experimental batches varying the nature and proportion of aggregates according to a structured experimental design. Fresh-state tests (slump flow, L-box, sieve stability, T500) follow the EFNARC (2005) recommendations [2]; in the hardened state, the 28-day compressive strength, the modulus of elasticity, and the splitting tensile strength are measured.

The concretes were produced using a CEM II/B-L 42.5 N cement (NF EN 197-1, density 3.05 g/cm^3, Blaine surface area 3400 cm^2/g), a fine limestone filler (< 63 µm, density 2.65 g/cm^3), and a polycarboxylate superplasticizer (30% dry extract); the exact dosages of cement, filler, effective water, and superplasticizer, as well as the W/C ratio, vary according to the mix design and the type of aggregate considered, and are given in Table 12. Demolding took place at 24 h, followed by curing by immersion in a lime-saturated water bath at 20 ± 2 °C (RH > 95%) until the testing ages. Tests were carried out on fresh and hardened concrete in accordance with the relevant standards (NF EN 12350-8 for slump flow and T500, NF EN 12350-10 for the L-box test, NF EN 12390-3 for compressive strength, NF EN 12390-13 for the modulus of elasticity, and NF EN 12390-6 for splitting tensile strength).

2.6. Multicriteria Comparative Analysis of Aggregates

The fifth stage synthesizes the data through a multicriteria comparative analysis. A performance matrix integrates dimensional, physical, mechanical, and behavioral criteria, weighted according to their importance for SCC, using a weighted sum model whose criteria, weights, scoring relations, and aggregation equations are fully specified in Section 4 (Tables 16-20); more formalized methods (AHP, TOPSIS) were not implemented and are discussed as future perspectives. The results make it possible to identify the best-performing aggregate combinations in South Benin and to formulate recommendations for concrete mix designers and producers.

A subset of sites was selected for laboratory testing, using sampling stratified by commune and by material type (lagoon, marine, alluvial, lateritic, supplemented by samples of crushed aggregates) and by accessibility. Several independent composite samples brought the total to more than 30 samples per aggregate type for the routine tests, and to a minimum of ten samples per rock type for the Los Angeles and Micro-Deval tests. The choice of n > 30 for the routine physical tests aims to ensure asymptotic normality of the distributions and sufficient statistical power for a possible subsequent analysis of variance, whereas the reduced number (10 to 15) used for the Los Angeles and Micro-Deval tests is explained by their destructive nature and the amount of material required per measurement (about 5 kg), which limits the number of feasible repetitions; this number was increased (up to 15) for crushed aggregates exhibiting more pronounced inter-quarry lithological variability. The field campaign was spread over four hydrological seasons (two dry, two rainy), in order to capture the

seasonal variability of alluvial and lagoon deposits. The tests were carried out in accordance with standards NF EN 12620, NF EN 1097, NF EN 933, and the EFNARC (2002, 2005) recommendations.

The seasonal variability of the sampling followed a protocol tailored to each type of test. Instantaneous physical tests (sand equivalent, methylene blue value, fines content) were measured separately in the dry and rainy seasons and analyzed independently. For concrete mixing, however, the aggregates were brought to the saturated surface-dry (SSD) condition.

3. Results and Discussion

Unless otherwise stated, the values presented in the following sections (mapping, particle size distribution, physical and mechanical properties, fresh- and hardened-state behavior) come from the experimental campaign of this study. The chloride content of the raw marine sand was measured in this study (NF EN 1744-1). The chloride diffusion coefficients and the effect of fineness modulus on water demand are, on the other hand, taken from earlier work on comparable materials from South Benin [13-15], and are indicated as such to distinguish original results from comparative data.

3.1. Identification, Location, and Mapping of Quarries and Deposits in South Benin

Seventy-five (75) sand quarries and deposits are recorded in South Benin, distributed as follows: five (05) sand quarries in the commune of Seme-Kpodji, six (06) in the commune of Porto-Novo, seven (07) in the commune of Cotonou, eleven (11) in the commune of Ouidah, three (03) in the commune of Grand-Popo, two (02) in the commune of Come, eleven (11) in the commune of Lokossa, fourteen (14) in the commune of Abomey-Calavi, six (06) in the commune of Sô-Ava, and ten (10) quarries in the commune of Dangbo.

Thirty-nine (39) gravel quarries and deposits are recorded in South Benin, distributed as follows: one (01) gravel quarry in the commune of Kpomasse, one (01) in the commune of Toffo, two (02) in the commune of Tori-Bossito, one (01) in the commune of Athieme, five (05) in the commune of Bopa, three (03) in the commune of Come, sixteen (16) in the commune of Houeyogbe, seven (07) in the commune of Lokossa, and three (03) in the commune of Bonou.

Figures 1 and 2 respectively present the maps of sand and gravel aggregate quarries and deposits in South Benin. Tables 2 and 3 group the aggregate deposits and quarries of South Benin into four broad resource categories and also present the main characteristics of the quarries and deposits.

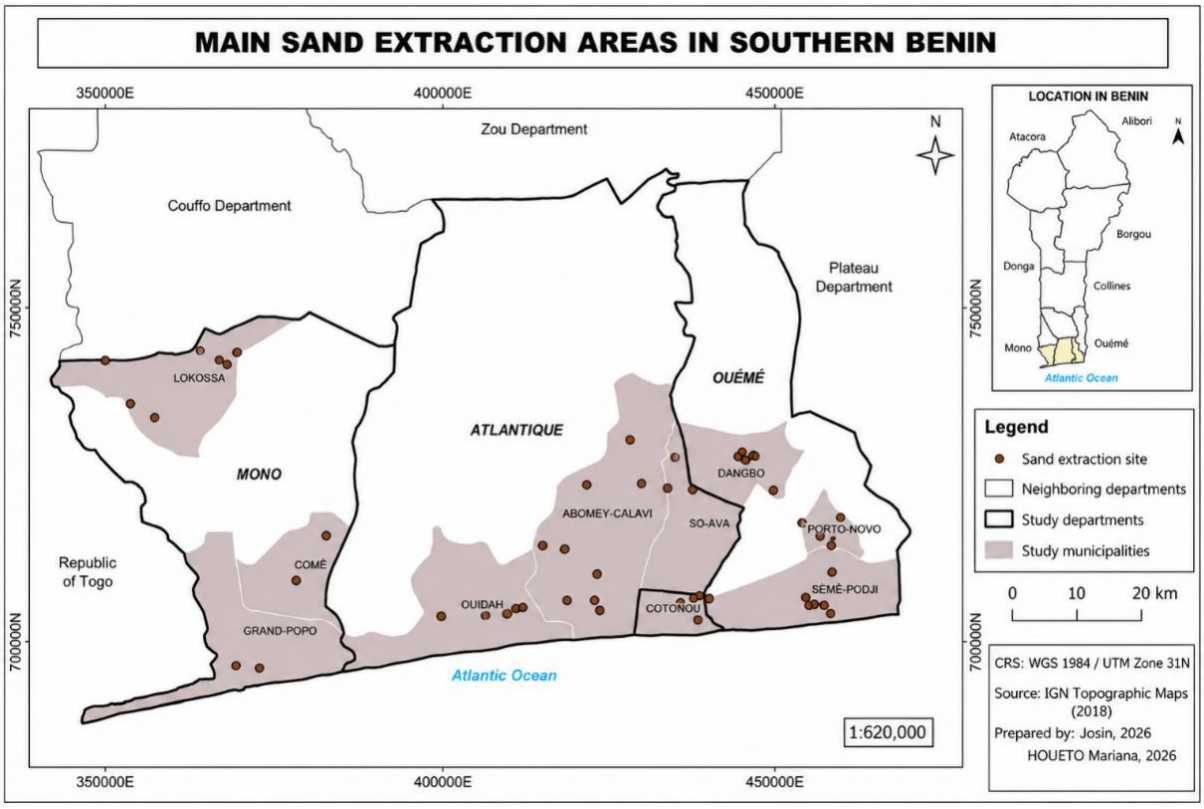


Figure 1. *Graphical representation of sand quarries and deposits in South Benin.*

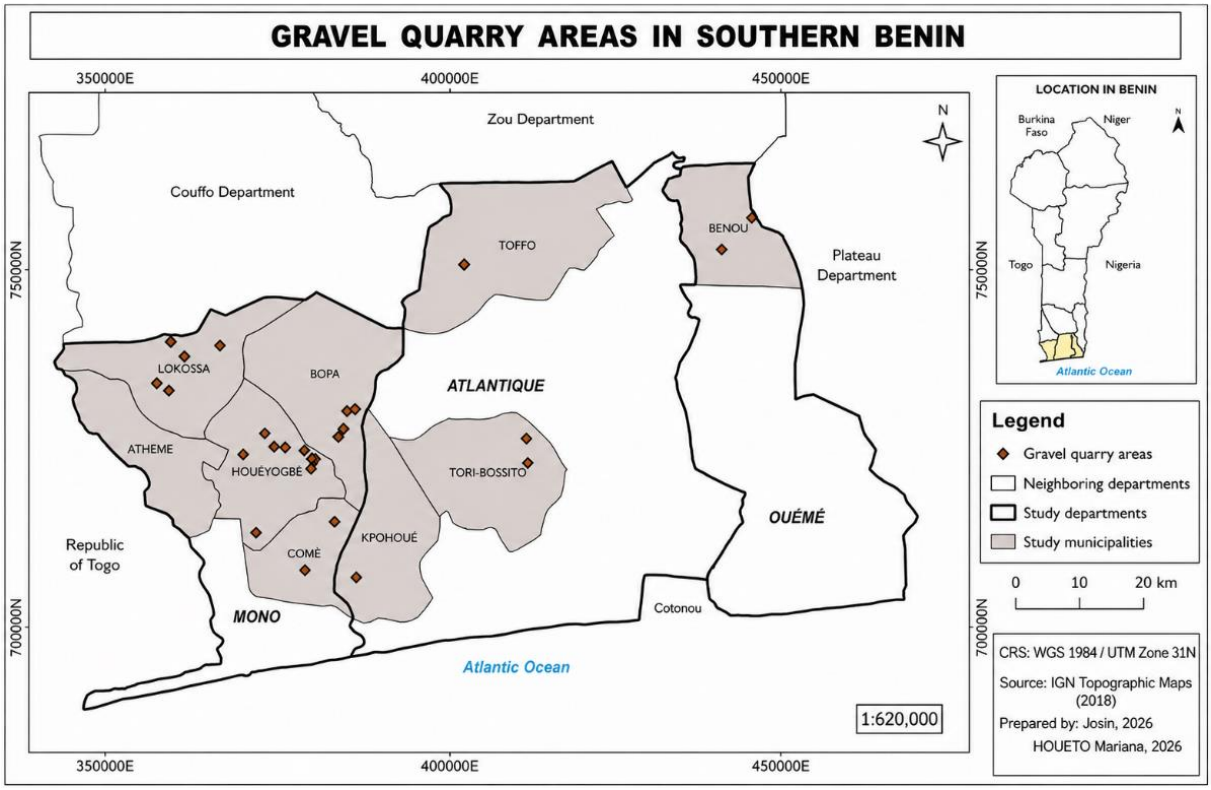


Figure 2. *Graphical representation of gravel quarries and deposits in South Benin.*

Alluvial deposits are the most significant resource in terms of exploitable volume (thicknesses of 2 to 15 m, 60 to 85% usable aggregate). Lagoon deposits (Lake Nokoue, 20-50 Mm^3) supply fine to very fine sands (Mf: 1.8-2.3), exploited by artisanal dredging. Marine and coastal deposits (5-15 Mm^3) yield better-graded sands, but their chloride content requires rigorous monitoring. Continental Terminal formations locally contain quartzose sands that are exploited occasionally (2-8 Mm^3).

Geologically, the sandy deposits of South Benin belong to the coastal sedimentary basin of Benin, made up of unconsolidated Quaternary and Continental Terminal (Mio-Pliocene) formations: lagoon sands and clays deposited under low-energy conditions behind the coastal barriers (Nokoue-Porto-Novo lagoon complex), quartzose fluvial alluvium from the Oueme and Mono basins resulting from the reworking of crystalline and sedimentary formations from the interior of the country, and coastal sands of marine origin reworked by longshore drift along the sandy barrier of the Atlantic coastline. Crushed coarse aggregates (granite, gneiss, basalt), in the absence of hard-rock outcrops within the coastal sedimentary basin, come from the crystalline and crystallophyllian formations of the Precambrian basement outcropping in central and northern Benin (Atacora, Zou, and Collines regions), or from similar deposits in neighboring Togo.

Table 2. *Main sand exploitation zones in South Benin.*

Zone	Department	Sand type	Extraction method	Quality (SE%)	Construction uses
Seme-Kpodji	Oueme	Alluvial / lagoon	Artisanal / dredging	58-74	Masonry, reinforced concrete
Porto-Novo	Oueme	Fine lagoon	Artisanal	55-68	Masonry, mortar
Cotonou (Nokoue)	Littoral	Medium lagoon	Floating dredge	60-75	Concrete, renders
Ouidah	Atlantique	Coastal marine	Dredging / mechanical	65-80	Concrete, marine works
Grand-Popo	Mono	Marine / fluvial	Artisanal	68-83	Ordinary concrete, backfill

Zone	Department	Sand type	Extraction method	Quality (SE%)	Construction uses
Come	Mono	Alluvial	Semi-mechanized	62-76	Concrete, mortar, pavements
Lokossa	Mono	Alluvial (Mono)	Artisanal / mechanical	65-78	Structural concrete
Abomey-Calavi	Atlantique	Lagoon / CT	Artisanal	52-67	Masonry, backfill
Sô-Ava	Atlantique	Very fine lagoon	Artisanal	48-60	Mortar, backfill
Dangbo	Oueme	Oueme alluvial	Semi-mechanized	68-80	Reinforced concrete, pavements

Table 3. *Characteristics of the main aggregate deposits in South Benin.*

Deposit type	Location	Estimated volume (Mm^3)	Dominant particle size	SE average (%)	Exploitation status
Alluvial (Oueme)	Dangbo, Adjohoun, Seme	50-100	0.125-4 mm	68-80	Semi-industrial / artisanal
Alluvial (Mono)	Lokossa, Come, Grand-Popo	15-30	0.25-2 mm	65-78	Predominantly artisanal
Lagoon (Nokoue)	Cotonou, Abomey-Calavi	20-50	0.063-1 mm	55-68	Artisanal (dredging)
Lagoon (Porto-Novo)	Porto-Novo, Seme-Kpodji	10-20	0.063-0.5 mm	52-65	Artisanal
Coastal marine	Grand-Popo, Ouidah, Cotonou	5-15	0.125-0.5 mm	68-83	Semi-mechanized (dredging)
Continental Terminal	Allada, Toffo, Kpomasse	2-8	0.063-0.5 mm	45-75	Occasional artisanal
Crushed aggregates (imported)	Crushing units, Cotonou area	N/A	0-31.5 mm	-	Industrial (imported)

Among all the quarries and deposits inventoried above, a subset of 12 sites was selected for the sampling and characterization campaign (physical and mechanical properties, tests on concretes produced), according to the following sampling plan: river/alluvial sand (3 sites: Dangbo, Adjohoun, Lokossa; 10 samples/site, n = 30; minor riverbed and alluvium, 0.5-1.5 m depth; GPS Dangbo: 6 °35'N, 2 °33'E); lagoon sand (3 sites: Lake Nokoue-Cotonou, Calavi, Sô-Ava; 10 samples/site, n = 30; lagoon dredging, water depth 1.5-3 m, sediment layer 0.2-0.8 m); manufactured sand (2 units: Cotonou, Akassato; 15 samples/unit, n = 30; plant stockpiles 0/4 mm); rounded gravel (2 quarries: Come, Lokossa; 15 samples/quarry, n = 30; ancient alluvial terraces, 1.0-2.5 m depth, 5.6/16 mm fraction); crushed gravel (2 industrial quarries: Bohicon, Zou; 15 samples/quarry, n = 30; hard granite/basalt rock, 5.6/16 and 10/20 mm fractions). Samples are identified by an alphanumeric code of the form [Type]-[Site]-[Season or Batch]-[Number], allowing the origin, preparation procedure, and use of each sample in the physical, mechanical, or concrete tests to be traced.

Logistical Challenges Related to Materials

Availability of aggregates in South Benin depends not only on resource volumes (Tables 2 and 3) but also on logistics. Since the coastal sedimentary basin has no hard-rock outcrops, crushed gravel comes from quarries of central and northern Benin or from Togo [11] and is transported by road to southern markets, whereas sands are abundant locally but extracted artisanally or by dredging under seasonal hydrological control. Table 4 summarizes the main constraints identified during the field campaign, their consequences for SCC production, and the corresponding mitigation measures.

Table 4. Logistical constraints on aggregate supply for SCC in South Benin and mitigation measures.

Logistical constraint	Materials concerned	Consequence for SCC	Mitigation adopted or recommended
No hard-rock outcrop in the coastal sedimentary basin	Crushed gravel 5.6/16 and 10/20 (basalt, granite, gneiss; imports from Togo)	Long road supply chains, higher delivered cost and transport-related CO_2 emissions; dependence on a few industrial quarries	Qualify at least two sources; keep stockpile buffers; use the 5.6/16 fraction, available through import channels or crushing units near Cotonou
Artisanal or semi-mechanized extraction; seasonal hydrology	Alluvial and lagoon sands (Mf 1.80–3.00; SE 52–78%)	Batch-to-batch variability of grading and cleanliness, hence fluctuating water demand and superplasticizer dosage	Grading and SE control at each delivery; dry- and rainy-season sampling; blending of lagoon sand with a coarser sand
Fine and clayey fractions	Lagoon sands (SE 62%, VBs up to 1.2 g/100 g) and manufactured sand 0/4 (fines 12%)	Higher water and superplasticizer demand, loss of flowability, risk of blocking	Washing, dedusting or screening; particle-size blending to reach SE ≥ 80%
Salt contamination of coastal deposits	Marine and coastal sands (0.09% Cl^- of dry sand mass)	Reinforcement corrosion risk; margin to class Cl 0.20 almost nil	Fresh-water washing with settling and drainage areas; chloride test (NF EN 1744-1) on every batch
Variable moisture and limited traceability of stockpiles	All natural sands	Moisture changes alter the effective water content and the rheology of SCC	Saturated surface-dry preparation and moisture correction before batching; sample coding [Type]-[Site]-[Season or Batch]-[Number]

These constraints mean that the technical ranking of Section 4 must be read together with supply considerations: a technically superior material that is supplied irregularly or at high cost may be less suitable in practice than a locally available material that is properly treated. A quantified assessment of transport cost and carbon footprint is outside the scope of this study (see Section 5).

3.2. Dimensional Characteristics and Classification of South Benin Aggregates

Standard NF EN 12620+A1:2008 [34] designates aggregate sizes by the d/D notation, where d and D are the lower and upper sieve sizes of the fraction, selected from the sieve series of the standard (basic set plus set 1 or set 2); fine aggregates have d = 0 and D ≤ 4 mm, and coarse aggregates have D ≥ 4 mm. The nominal fraction labels used in the first version of this paper (5/15, 5/10, 15/25, 16/32) do not belong to this series and are replaced throughout by the nearest standard designation (5.6/16, 4/10, 16/22.4, 16/31.5); the designations 10/20, 20/40, 0/20, and 0/31.5 are already standard. Table 5 presents the dimensional classification of South Benin aggregates according to this standard: fine aggregates (from filler to medium-to-coarse sand) are locally abundant, whereas the coarse aggregates (4/8 to 20/40 mm) essential for SCC come almost exclusively from imports or from quarries located outside the southern region.

Table 5. Dimensional classification of aggregates according to NF EN 12620.

Category	d/D notation	D (mm)	Main use	Local examples
Filler aggregate	0/0.063	0.063	Compacity additive	Crushing fines, lagoon sediments
Very fine sand (fine aggregate)	0/1	1	Mortar, render	Nokoue lagoon sands
Fine sand	0/2	2	Ordinary concrete, mortar	Fine lagoon and marine sands
Medium-to-coarse sand	0/4	4	Reinforced concrete, pavements	Alluvial sands (Oueme, Mono)
Fine gravel (coarse aggregate)	4/8 or 4/10	8–10	SCC, high-performance concrete	Imported crushed gravel
Medium gravel	8/16 or 5.6/16	16	Ordinary reinforced concrete	Crushed gravel (central and northern Benin quarries)

Category	d/D notation	D (mm)	Main use	Local examples
Coarse gravel	16/31.5 or 20/40	31.5–40	Mass concrete, foundations	Imported crushed gravel
All-in aggregate 0/20	0/20	20	Road sub-base, unbound granular material	Crushed graded aggregate (northern Benin quarries)
All-in aggregate 0/31.5	0/31.5	31.5	Road base course	Imported crushed graded aggregate

For SCC, EFNARC recommends in 2005 a Dmax ≤ 20 mm, preferably < 16 mm, to ensure flowability and segregation resistance [2]. Domone (2006), based on 68 mix designs, showed that a Dmax > 20 mm doubles the risk of blocking at the reinforcement (L-box test, H2/H1 < 0.80) [7]. In South Benin, the 5.6/16 mm range (medium gravel) is the most suitable for SCC, available through import channels or crushing units on the outskirts of Cotonou.

3.2.1. Particle Size Distribution Curves

The particle size distribution curves (sieving per NF EN 933-1, Figure 3, Table 6) reveal contrasting behavior depending on sedimentary origin. Lagoon sand is concentrated in the 0.125-2 mm fraction (mode 0.5-1 mm, percentage passing at 1 mm = 82%), indicating moderate lagoon hydrodynamics. Coastal marine sand shows a broader distribution (mode 0.25-0.5 mm, percentage passing at 0.5 mm = 38%) and low fines content (1% at 0.063 mm), shaped by waves and longshore currents. Oueme alluvial sand is the coarsest (percentage passing at 2 mm = 95%, at 4 mm = 99%), reflecting the high transport capacity of this tropical river. Manufactured sand 0/4, with a broader distribution, has a fines content of 8%, which may exceed the 12% recommended by EFNARC (2005) if washing is insufficient [2].

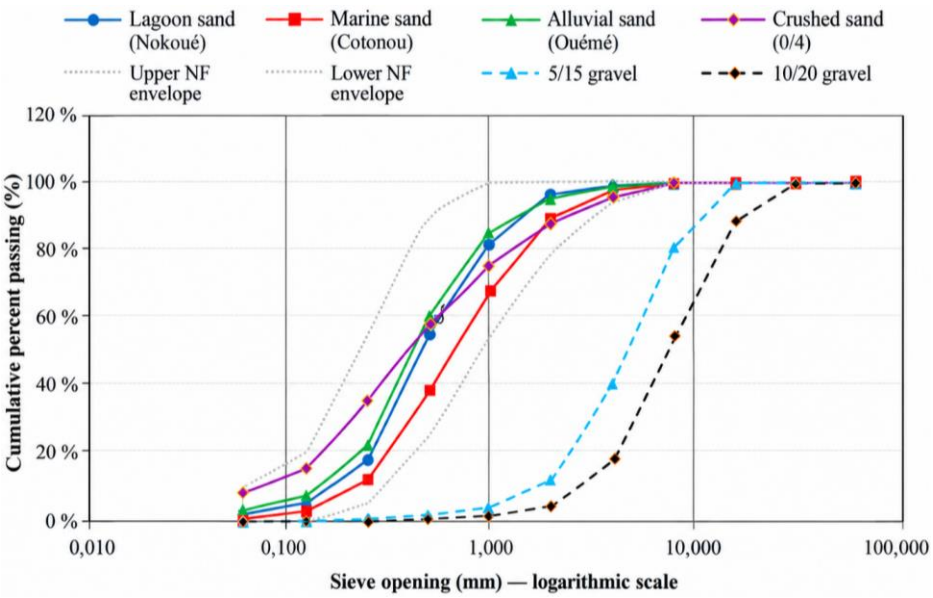


Figure 3. *Comparative particle size distribution curves of South Benin aggregates.*

Table 6. *Cumulative percentage passing (%) of South Benin aggregates according to NF EN 933-1.*

Material / Sieve (mm)	0.063	0.125	0.250	0.500	1.000	2.000	4.000	8.000
Lagoon sand	2%	5%	18%	55%	82%	96%	99%	100%
Marine sand	1%	3%	12%	38%	68%	90%	98%	100%
Alluvial sand	3%	7%	22%	60%	85%	95%	99%	100%

Material / Sieve (mm)	0.063	0.125	0.250	0.500	1.000	2.000	4.000	8.000
Manufactured sand	8%	15%	35%	58%	76%	88%	96%	100%
Gravel 5.6/16	0%	0%	1%	2%	5%	12%	40%	82%
Gravel 10/20	0%	0%	0%	1%	2%	5%	18%	55%
Upper NF envelope	10%	20%	55%	90%	100%	100%	100%	100%
Lower NF envelope	0%	0%	5%	25%	55%	80%	95%	100%

3.2.2. Fineness and Grading Compliance

The fineness modulus (Mf), a synthetic indicator of the average grain size of a sand, is calculated as one-hundredth of the sum of the cumulative percentages retained on the series of standard sieves (0.16 to 5 mm). It governs the water demand and workability of fresh concrete; an Mf between 2.2 and 2.8 is generally recommended for ordinary concrete and SCC [2]. Below 2.2, an overly fine sand increases the specific surface area and water demand, promoting bleeding; above 2.8, it becomes too coarse and impairs the compactness and stability of SCC.

Table 7 and Figure 4 (experimental data, n > 30 samples per type) present the fineness moduli measured for South Benin sands. The results reveal marked inter-type variability.

Table 7. *Fineness moduli of South Benin sands and normative compliance.*

Sand type	Mf min	Average Mf	Mf max	Range	Compliance (2.2-2.8)	Recommendation
Lagoon sand (Nokoue)	1.80	2.10	2.50	0.70	Partial	Blending with coarser sand required
Marine sand (Cotonou)	2.00	2.40	2.80	0.80	Compliant	Anti-chloride washing mandatory
Alluvial sand (Oueme)	2.20	2.60	3.00	0.80	Compliant	Direct use possible
Alluvial sand (Mono)	2.10	2.50	2.90	0.80	Compliant	Direct use possible
Manufactured sand 0/4	2.40	2.80	3.20	0.80	Compliant/marginal	Check fines content (< 12%)
Dune sand (coastal)	1.50	1.80	2.20	0.70	Non-compliant	Not recommended for reinforced concrete

The Nokoue lagoon sand has an average Mf of 2.10, below the minimum threshold of 2.2 recommended by NF P 18-540 and EFNARC (2005) [2], due to low-energy lagoon sedimentation conditions that favor the accumulation of fine fractions. Such an Mf would imply an increase in water demand of 15 to 20 L/m^3 compared with a compliant sand (Mf = 2.50), requiring an adjustment of the superplasticizer dosage [4]. A systematic corrective measure (blending with a coarser sand, or reducing the sand volume compensated by a fine gravel) is therefore necessary for the use of lagoon sands in SCC.

It should be noted that the reported value ranges for the fineness modulus of lagoon sand (1.80-2.50) and marine sand (2.00-2.80) partially overlap around 2.00-2.50. In the absence, at this stage, of a statistical test for comparing means (ANOVA, Student's t-test), the hierarchy proposed between these two sand types should be interpreted as a central tendency consistent with the sedimentary mechanisms described above, rather than as a statistically demonstrated difference between the two sample populations; this point is discussed further in the Limitations and Perspectives section.

Second, Oueme alluvial sands have average Mf values of 2.60, well positioned within the optimal range, although with non-negligible inter-site variability (Mf from 2.20 to 3.00) linked to fluctuations in seasonal hydrological regimes. This variability represents a risk factor for the consistency of SCC mixes and justifies systematic grading control at each delivery. Dune sand, with an average Mf of 1.80, clearly below 2.2, is clearly unsuitable for use in reinforced concrete or SCC under current conditions; its use can only be considered for non-structural masonry mortar or blended with much coarser aggregates. Figure 4 presents the fineness moduli of South Benin sands (min-average-max values, n > 30 samples per sand type).

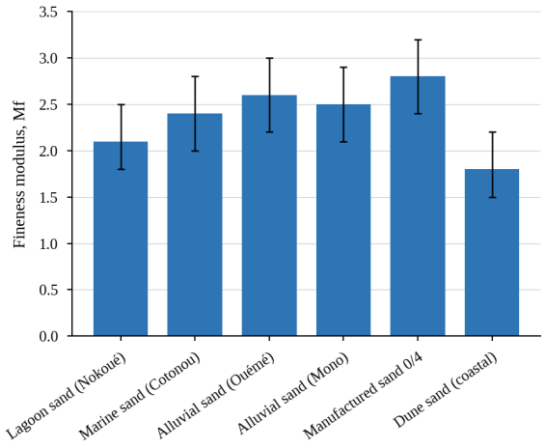


Figure 4. *Fineness moduli of South Benin sands (min-average-max values, n > 30 samples per type; error bars represent the observed min-max range, not a standard deviation).*

3.3. Physical Properties

3.3.1. Particle Density and Bulk Density

The particle density (ρs) is the ratio between the mass of a solid material and the volume of pure solid matter, excluding voids and water-accessible pores. It is determined according to NF EN 1097-6 (pycnometry for sands < 4 mm, hydrostatic weighing for coarse aggregates) and reflects the mineralogical composition: dense minerals (feldspars, iron-rich micas, hornblende) give high values, while porous materials (coal, wood, tiles) give low values. It governs the calculation of absolute volumes (Baron-Lesage or Dreux-Gorisse methods) and the compactness of aggregate mixes [4].

The bulk density (ρap), which accounts for intergranular voids, is used to calculate aggregate masses from storage volumes and the required binder volumes. Lower than the particle density, a high value reflects better aggregate packing, favorable to compactness and to reducing paste demand. According to Tanesi et al. (2017), an increase in ρap from 1.55 to 1.70 t/m^3 can improve concrete strength by 5 to 10% at constant W/C [16].

The measured particle densities range from 2.59 t/m^3 (lagoon sand) to 2.68 t/m^3 (crushed 10/20 gravel), consistent with typical values for quartzose, feldspathic, and crystalline materials (2.55-2.75 t/m^3) [4]. Crushed aggregates show slightly higher values than lagoon sands, owing to their lower porosity and denser mineralogical composition (granite, gneiss, basalt).

The bulk density ranges from 1.42 t/m^3 (lagoon sand) to 1.62 t/m^3 (crushed 10/20 gravel). These values are consistent with the typical values given above. Only the crushed gravels (2.65-2.68 t/m^3) and the marine and alluvial sands (2.61-2.62 t/m^3) fully satisfy the EFNARC (2005) requirement of ρs > 2.60 t/m^3 for SCC [2].

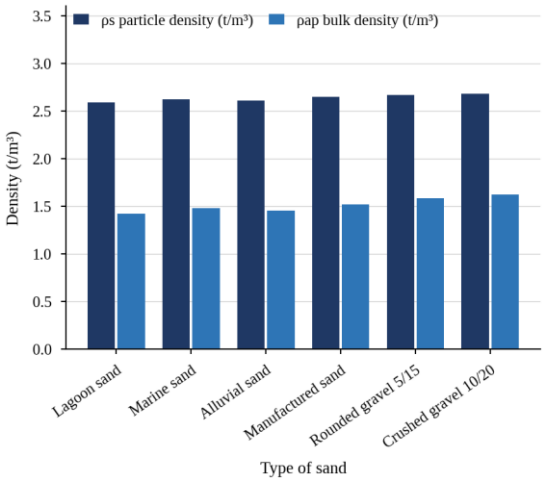


Figure 5. *Particle and bulk density.*

3.3.2. Porosity and Water Absorption

The porosity of aggregates, the ratio of the open void volume to the total apparent volume, is a key parameter for concrete durability: water-accessible voids are preferential pathways for aggressive agents (chlorides, sulfates, CO_2), which can cause reinforcement corrosion or matrix degradation [17]. High porosity also weakens the paste-aggregate interfacial transition zone (ITZ), whose thickness and density largely govern the mechanical performance and durability of concrete [18].

Water absorption (WA24, NF EN 1097-6) reflects the water-accessible porosity and is used to correct the effective water content during mix design. High values (WA > 2%) reduce the water available for hydration and distort the W/C ratio, leading to an underestimation of the expected strength. For SCC, whose rheology is highly sensitive to water content, a highly absorbent aggregate can capture a significant fraction of the mixing water within the first few minutes, causing premature loss of flowability and a risk of blocking in the formwork [2].

Table 8. *Comparative physical properties of South Benin aggregates (NF EN 1097-6, NF EN 933-9).*

Property / Aggregate	Lagoon sand	Marine sand	Alluvial sand	Manufactured sand	Rounded gravel 5.6/16	Crushed gravel 10/20
ρs particle density (t/m^3)	2.59	2.62	2.61	2.65	2.67	2.68

Property / Aggregate	Lagoon sand	Marine sand	Alluvial sand	Manufactured sand	Rounded gravel 5.6/16	Crushed gravel 10/20
ρap (t/m^3)	1.42	1.48	1.45	1.52	1.58	1.62
WA (%)	1.8	1.2	1.5	2.2	0.9	0.7
Porosity (%)	3.5	2.8	3.0	4.2	2.1	1.8
VBs (g/100g)	0.8	0.5	0.7	1.2	0.4	0.3
Fines < 0.063 mm (%)	8	4	6	12	2	1
Conf. WA	OK	OK	OK	Out of threshold	OK	OK
Conf. VBs	OK	OK	OK	Out of threshold	OK	OK

The results in Table 8 call for several important observations. First, manufactured sand shows a water absorption of 2.2%, above the recommended threshold of 2%. This high value is explained by the generation of fines during mechanical crushing (fines content < 0.063 mm: 12%) and by the intrinsic microporosity of crushed particles. In an SCC mix design, this absorption must be carefully taken into account when calculating the effective W/C ratio. It is recommended to saturate the aggregates before mixing (saturated surface-dry condition, SSD) or to correct the water dosage by accounting for the absorbed water using the absolute volume method [2, 17]. Second, crushed gravels show the lowest absorption values (0.7%), reflecting their low porosity and compact surface texture, which makes them particularly well suited to the design of high-performance concrete and low-W/C SCC. Table 8 reports average values without an associated standard deviation, given the number of samples tested (n > 30) per type for the routine tests.

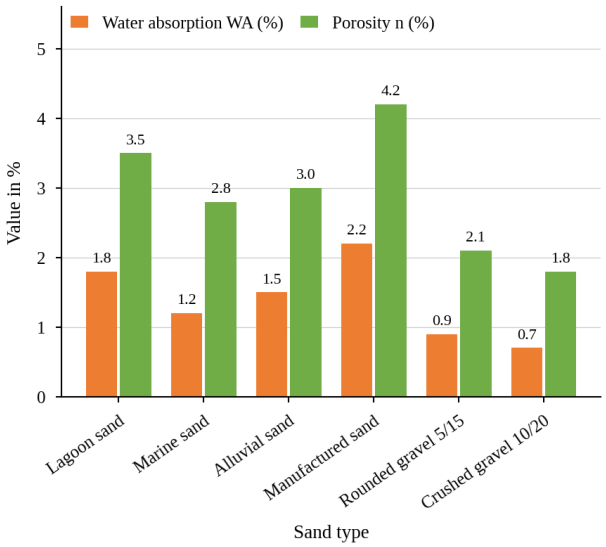


Figure 6. *Absorption and porosity of aggregates.*

3.4. Cleanliness of Aggregates - Sand Equivalent and Methylene Blue Value

Aggregate cleanliness is one of the most important qualification criteria for self-compacting concrete, since the presence of active clay fines can considerably alter the rheology of fresh SCC and compromise the mechanical performance and durability of hardened concrete. Two complementary standardized tests are used to quantify aggregate cleanliness: the sand equivalent (SE) and the methylene blue value (VBs).

3.4.1. Sand Equivalent (NF EN 933-8)

The sand equivalent test (NF EN 933-8) measures, by sedimentation and flocculation, the relative content of fine and clayey elements in a sand: a high SE value indicates a clean sand, while a low SE value indicates significant clay contamination. A high clay content produces several effects: swelling

of clay sheets through water adsorption (smectites, montmorillonite), a clay film reducing paste-aggregate bond, increased water and superplasticizer demand in SCC, and a risk of delayed cracking from shrinkage-swelling.

Normative requirements generally set SE ≥ 70% for sands intended for ordinary reinforced concrete (NF P 18-540), SE ≥ 75% for pavement concrete, and SE ≥ 80% for SCC according to the 2005 EFNARC recommendations [2]. Figure 7 (compiled data, n > 30 samples per type) and Table 9 present the SE values measured for South Benin sands.

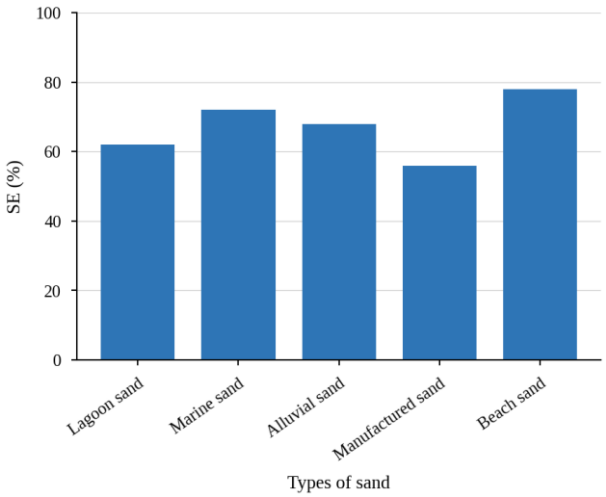


Figure 7. *Sand equivalent values of South Benin aggregates.*

Table 9. *Sand equivalent values of South Benin fine aggregates and normative compliance.*

Property / Aggregate	Lagoon sand	Marine sand	Alluvial sand	Manufactured sand	Beach sand
ES min (%)	52	60	58	45	65
ES moy (%)	62	72	68	56	78
ES max (%)	74	83	78	68	88
Standard deviation	5.5	5.75	5.0	5.75	5.75
RC threshold (70%)	70	70	70	70	70
NRC threshold (60%)	60	60	60	60	60
RC compliance	Washing required	Compliant (avg.)	Washing required	Non-compliant	Compliant

Only marine sands (average SE: 72%) and beach sands (average SE: 78%) satisfy, on average, the SE ≥ 70% requirement for ordinary reinforced concrete; lagoon sands (62%) and alluvial sands (68%) remain below this threshold, although their maximum values reach 74% and 78%. This heterogeneity is explained by spatial and seasonal variations in clay content: hydrodynamically calm areas accumulate more clay than actively flowing channels. Washing with fresh water is therefore essential before use in reinforced concrete, allowing the SE to be raised by 5 to 15 points [15]. Manufactured sand (average SE: 56%), penalized by its high fines content (12% < 0.063 mm), also fails to meet the requirement without treatment; for SCC, where the fines content must remain below 1.5 g/100 g according to EFNARC (2005), prior screening or dedusting is necessary [2].

Within the dataset of this study, lagoon sands (SE = 62%) rank below marine sands (72%) and alluvial sands (68%) but above the manufactured sand (56%): a quality representative of the region, but insufficient for direct use in SCC without treatment.

Table 9 assesses the compliance of the sands against the SE ≥ 70% threshold applicable to ordinary reinforced concrete (NF P 18-540), rather than the specific SE ≥ 80% threshold recommended by EFNARC (2005) for SCC. However, none of the fine aggregates tested meets this stricter requirement in the raw state: marine sand (average SE 72%), alluvial sand (average SE 68%), and beach sand (average SE 78%) all remain below the SCC threshold, despite complying with the

ordinary reinforced-concrete threshold. The condition for acceptability of these sands is washing or particle-size blending to raise their SE above 80%.

3.4.2. Methylene Blue Value (NF EN 933-9)

The methylene blue value (VBs) quantifies, through methylene blue adsorption, the content of active clays (smectites, montmorillonite, swelling illite), which can impair durability through shrinkage-swelling. The limit is generally VBs ≤ 1.0 g/100 g for concrete (NF P 18-540) and ≤ 0.5 g/100 g for pavements. For SCC, EFNARC (2005) recommends VBs ≤ 1.0 g/100 g, above which active clays interfere with superplasticizer action and reduce rheological performance [2].

Most South Benin aggregates satisfy the VBs ≤ 1.0 g/100 g limit, with the exception of manufactured sand (1.2 g/100 g, related to its high fines content) and occasional exceedances observed for the clayey lagoon sands of S ô-Ava and Abomey-Calavi (up to 1.2 g/100 g), associated with the presence of smectites confirmed by X-ray diffraction. Without prior washing, these smectitic clays, with their high adsorption capacity, risk saturating the superplasticizer and reducing the flowability of SCC [17].

3.5. Shape, Texture, and Angularity of Aggregates

3.5.1. Flakiness and Elongation Coefficients

Particle shape is one of the most influential parameters on the fresh-state rheology of SCC. Flat, elongated, or angular aggregates create mechanical interference, increase plastic viscosity, and can block passage through the reinforcement if their size approaches the bar spacing (EFNARC, 2005; Domone, 2006). Conversely, spherical or rounded aggregates promote flowability and deformability, but may slightly reduce mechanical strength by decreasing particle interlocking [2, 7].

The flakiness index (FI, NF EN 933-3) is the percentage by mass of aggregate particles whose thickness is less than 0.6 times the average size of the fraction; the elongation index (EI, NF EN 933-4) is the percentage whose length exceeds 1.8 times this size. Normative requirements are FI ≤ 25 for structural and pavement concrete (FI25), FI ≤ 35 for ordinary concrete (FI35), and EFNARC recommends in 2005 an FI ≤ 20 for SCC [2].

Table 10. *Flakiness and elongation indices of South Benin aggregates (NF EN 933-3).*

Property / Aggregate	Rounded gravel 4/10	Rounded gravel 10/20	Crushed gravel 4/10	Crushed gravel 10/20	Crushed gravel 16/22.4	Crushed graded aggregate 0/20
Origin	Rounded	Rounded	Crushed	Crushed	Crushed	Crushed
IA min (%)	7	9	16	18	20	15
IA moy (%)	10	12	22	25	28	20
IA max (%)	14	16	28	32	35	28
CB moy (%)	12	15	18	22	24	18
FI threshold (35%)	35	35	35	35	35	35
FI compliance	Pavement OK	Pavement OK	Pavement OK	Pavement OK	Concrete only	Pavement OK
Optimal use	Ordinary concrete, SCC	Reinforced concrete, SCC	Reinforced concrete, high-performance concrete	Ordinary reinforced concrete	Ordinary concrete	Base course, unbound granular material

Table 10 shows a significant difference between rounded aggregates (average FI: 10-12%) and crushed aggregates (average FI: 20-28%), consistent with their morphology. Rounded gravels, shaped by the action of currents, have FI values well below the normative thresholds (≤ 25), making them excellent for SCC, although their smooth surface reduces paste-aggregate bond compared with crushed aggregates. The latter remain compliant for most applications but approach the EFNARC limit (FI ≤ 20 for SCC) in the case of the 16/22.4 gravel (average FI: 28%) [2].

These results are consistent with the international literature. Oluwasola et al. showed in 2020, in a systematic review, that replacing rounded aggregates with crushed aggregates can increase the compressive strength of concrete by 8 to 15% for the same cement content, owing to improved mechanical interlocking and chemical paste-aggregate bond [18]. In the specific context of SCC, however, this strength improvement

must be weighed against the increased superplasticizer demand imposed by the higher angularity of crushed aggregates [5].

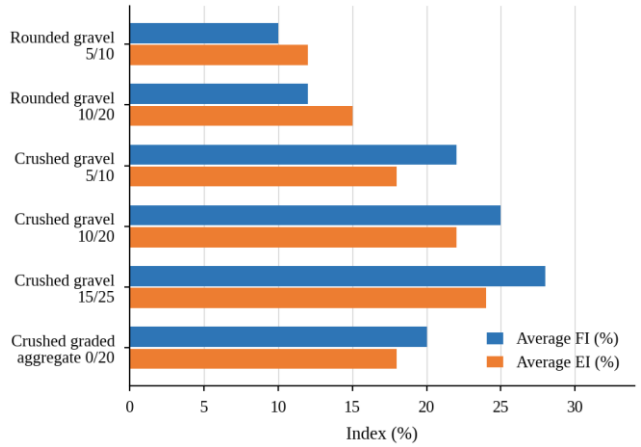


Figure 8. *Flakiness (FI) and elongation (EI) indices.*

3.5.2. Angularity and Surface Texture

Angularity, assessed using the Powers scale or a roughness index, reflects the shaping of particle edges. Rounded lagoon and marine aggregates exhibit very low angularity, which is favorable to workability, whereas crushed aggregates (granite, basalt) are more angular and rough, providing better bonding with the cement paste. Hessouh (2021) points out that this roughness, by promoting the anchoring of hydration products, reduces the thickness and porosity of the interfacial transition zone (ITZ), improving tensile strength and the modulus of elasticity [13]. For SCC, this advantage must be weighed against the increase in water and superplasticizer demand caused by the higher specific surface area of angular aggregates.

3.6. Mechanical Properties

3.6.1. Los Angeles Test - Resistance to Fragmentation (NF EN 1097-2)

The Los Angeles test is the international reference test for the resistance of coarse aggregates to fragmentation under impact and abrasion, simulating the stresses of road compaction or concrete mixing. The LA coefficient is the percentage by mass of fine material (< 1.6 mm) produced after 500 drum rotations (2,500 g sample, 11 steel balls of 47 mm, total mass 4,584 ±25 g): the lower the LA value, the better the resistance to fragmentation.

NF EN 12620 defines the following specifications: LA ≤ 20 (LA20, very high quality); LA ≤ 25 (LA25, pavements, high-strength slabs); LA ≤ 30 (LA30, ordinary structural concrete); LA ≤ 35 (LA35, ordinary concrete); LA ≤ 40 (non-structural uses). For SCC, EFNARC recommends in 2005 an LA ≤ 30 [2].

Table 11. *Los Angeles and Micro-Deval test results for Beninese aggregates and normative compliance.*

Rock type / aggregate	LA (%)	MDE (%)	Mohs hardness (approx.)	NF EN 12620 class	Suitability for structural concrete
Basalt (Atacora)	15-22	10-14	6-7	LA25 / MDE15	Excellent: all uses
Granite compact (Zou)	18-26	14-18	6-7	LA25 / MDE20	Very good: reinforced concrete
Gneiss (periphery)	20-28	16-22	5-7	LA25 / MDE25	Good: ordinary concrete
Limestone (imported)	25-32	18-26	3-4	LA35 / MDE25	Acceptable: unreinforced concrete
Siliceous sandstone	28-38	22-30	5-6	LA40 / MDE30	Marginal: avoid in structural use
Compact laterite	35-45	28-38	4-5	Unclassified	Insufficient: backfill only
Crushed aggregates (imported from Togo)	18-24	12-18	6-7	LA25 / MDE20	Very good: reinforced concrete

Table 11 reveals a clear hierarchy among the rock types. Basalt from the Atacora region and crushed aggregates imported from Togo, with the best performance (average LA: 18-21%, LA20 category), are suitable for all applications, including demanding SCC; consistent with A ŧcin (2016: LA = 15-22% for massive basalts) and Neville (2011), for whom basalt and granite are the best parent rocks for high-quality aggregates [17, 19].

Compact granite from Zou (average LA: 22%) and peripheral gneiss (24%), both in the LA25 category, are well suited

to ordinary reinforced concrete and SCC; their slight difference is explained by the foliated fabric of gneiss, which creates cleavage planes that reduce its resistance to fragmentation compared with massive granite. Imported limestone (average LA: 28%, LA30 category), although compliant for ordinary reinforced concrete, is less resistant owing to its sedimentary nature and lower hardness (Mohs 3, versus 6-7 for granite and basalt); its use in SCC should be limited to classes C25/30 or lower.

Compact laterite, with an average LA of 40%, exceeding the LA40 category limit, and siliceous sandstone (average LA: 33%, at the LA35 category limit) are clearly unsuitable for the production of structural concrete. Despite its local availability and low cost, the use of laterite as an aggregate for structural concrete is strongly discouraged. This reservation applies specifically to use in reinforced structural concrete within the meaning of NF EN 12620, and does not prejudge laterite's suitability for other non-structural uses, in which it remains widely valorized in Benin (stabilized earth blocks, road embankments, subgrade layers). The results confirm the conclusions of previous work on the mechanical strength of Beninese rocks: only basalt and granite offer mechanical performance compatible with all structural construction requirements, which fully justifies importing these materials from quarries in northern Benin and Togo for major construction projects in the Cotonou region [15].

It should be noted that the LA ranges for granite (18-26%) and gneiss (20-28%) partially overlap, around 20-26%. The hierarchy proposed between these two rocks reflects the measured mean values (22% versus 24%) and is supported by a plausible petrographic explanation (foliated fabric of gneiss), but would require, to be fully validated statistically, a test comparing means between the two sample populations (see the Limitations and Perspectives section).

3.6.2. Micro-Deval Test - Resistance to Wear (NF EN 1097-1)

The Micro-Deval test evaluates resistance to wear by abrasion, in a rotating drum with water and steel balls (5,000 ± 5 g, Ø10 mm). The MDE coefficient is the percentage of fines produced (< 1.6 mm) after 12,000 rotations at 100 rpm. It is representative of the stresses encountered in pavement layers and during batching-plant mixing, and governs the durability of surfaces exposed to abrasion and the long-term strength of hardened concrete.

The normative limits (NF EN 12620) are generally: MDE ≤ 10 (excellent, high-traffic wearing courses); MDE ≤ 15 (good, severe road use, high-performance concrete); MDE ≤ 20-25 (acceptable for ordinary concrete); MDE > 30 (insufficient, not recommended for structural use). EFNARC recommends in 2005 an MDE ≤ 20 for aggregates intended for SCC [2].

MDE results (Table 11) are closely correlated with LA values, both tests reflecting the hardness and mineralogical cohesion of the parent rock. Basalt and crushed aggregates from Togo show excellent performance (average MDE: 12-15%), granite (16%) and gneiss (18%) satisfy the MDE20 category suited to reinforced concrete and SCC, whereas compact laterite (average MDE: 33%) is clearly insufficient, owing to its porous microstructure and hydroxylated minerals (goethite, gibbsite) that are poorly resistant to abrasion, consistent with the values above 30% reported for West African compact laterites [9].

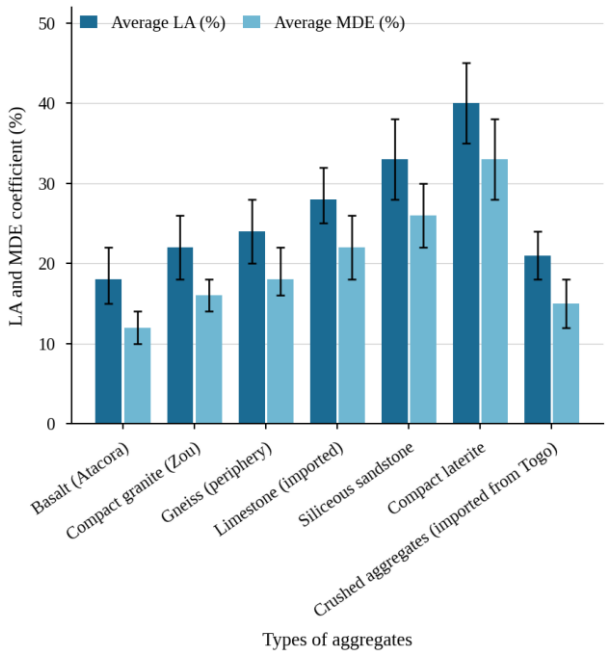


Figure 9. *Los Angeles and Micro-Deval test results for Beninese aggregates (error bars: observed min-max range of measured values per rock type, n ≥ 10 samples).*

3.7. Behavior of South Benin Aggregates in Concrete

3.7.1. Mechanical Performance of Concretes as a Function of Aggregate Type

The six reference concretes compared in this section were proportioned as detailed in Table 12. The W/C ratio decreases from 0.60 (lagoon sand) to 0.35 (high-performance concrete) and the superplasticizer dosage increases from 0.4 to 1.8% of the cement mass as the aggregate quality and the binder content increase. The high-performance concrete contains 50 kg/m^3 of silica fume and the SCC mix 150 kg/m^3 of limestone filler (< 63 µm); the aggregate fractions are those of Section 3.2, with sand-to-gravel proportions adjusted to the consistency required.

Table 12. *Mix proportions of the six reference concretes (per m^3 of concrete).*

Concrete mix	W/C	Cement (kg/m^3)	Effective water (L/m^3)	Additions (kg/m^3)	Superplasticizer (% of cement mass)
Lagoon sand	0.60	320	192	—	0.4
Washed marine sand	0.58	340	197	—	0.5
Alluvial sand	0.55	360	198	—	0.6
Crushed aggregates	0.50	380	190	—	0.8
High-performance concrete (crushed + additions)	0.35*	450	175	Silica fume: 50	1.8
SCC, marine sand + crushed gravel	0.42	400	168	Limestone filler: 150	1.1

* W/C defined on the binder (cement + silica fume): 175/(450 + 50) = 0.35; the water-to-cement ratio alone is 0.39. For the other mixes, effective water = W/C × cement content (e.g. 0.60 × 320 = 192 L/m^3).

Figure 10 (experimental data compiled 2018-2024, Cotonou-Abomey-Porto-Novo) presents the evolution of compressive strength (fc, MPa) at different ages (7, 14, 28, 56, and 90 days) for six types of concrete mixes using South Benin aggregates. Table 13 summarizes the 28-day strength data and the corresponding strength classes according to standard NF EN 206-1.

Table 13. *Evolution of compressive strength (fc, MPa) of concretes according to aggregate type and age.*

Mix / Age (days)	7	14	28	56	90	NF EN 206 class
Lagoon sand (W/C=0.60)	12	18	23	26	27	C20/25
Washed marine sand (W/C=0.58)	15	21	27	30	31	C25/30
Alluvial sand (W/C=0.55)	16	23	29	32	33	C25/30
Crushed aggregates (W/C=0.50)	20	28	35	39	41	C30/37
High-performance concrete, crushed + additions (W/C=0.35)	25	35	45	52	55	C45/55
SCC, marine + crushed (W/C=0.42)	18	24	33	38	40	C30/37

Table 13 confirms the decisive influence of aggregate type on mechanical performance. Concretes made with lagoon sand (fc28 = 23 MPa) are clearly less resistant than those made with alluvial sand (29 MPa) or crushed aggregates (35 MPa), a gap of about 52% explained by two mechanisms: the lower intrinsic strength and higher intragranular porosity of lagoon sands, which weaken the interfacial transition zone; and the higher W/C ratio they require (0.60 versus 0.50 for crushed aggregates) to compensate for their high water demand, which increases the capillary porosity of the matrix [17].

The interpretation of Table 13 should, however, be qualified: the six mix designs compared have substantially different W/C ratios (from 0.35 to 0.60) and also differ in cement content and in the presence or absence of superplasticizer and mineral additions (limestone filler, silica fume). These parameters, known to have a major influence on compressive strength, vary jointly with aggregate type in the experimental plan adopted. Consequently, the strength differences observed between mix designs (for example between lagoon-sand concrete and crushed-aggregate concrete) cannot be attributed exclusively to the nature of the fine or coarse aggregate used; they reflect the combined effect of the aggregate and its associated mix design, each aggregate type having been tested with the W/C ratio and dosage considered appropriate in local practice for that material. A comparison strictly isolating the effect of the aggregate, at constant W/C and binder dosage, would be a useful experimental complement to confirm the proposed hierarchy. The results of this experiment have been published (Houehanou et al., 2026) [20], in which the cement

paste composition (cement, filler, water, and superplasticizer) is kept constant across six SCC mix designs combining sands (river, lagoon, manufactured) and gravels (rounded, crushed), isolating the effect of aggregate type on fresh- and hardened-state performance.

The time evolution of strength is informative: concretes with lagoon sand and with crushed aggregates progress comparably between 28 and 90 days (+17% each), versus +22% for the high-performance concretes, likely related to the continued hydration of the mineral additions. The SCC mix with washed marine sand and crushed gravel (W/C = 0.42) reaches fc28 = 33 MPa (class C30/37), demonstrating the feasibility of high-performance SCC based on local materials, provided the W/C ratio is well controlled and a suitable superplasticizer is used.

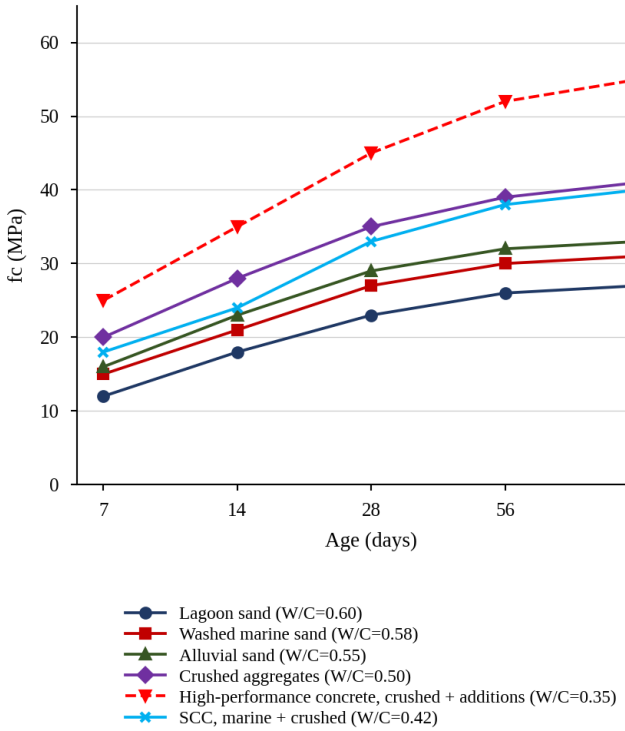


Figure 10. *Evolution of compressive strength fc (MPa).*

3.7.2. Rheological Performance of SCC

Fresh-state tests (Abrams cone slump flow, L-box, sieve stability test, T500) confirm that aggregates with continuous grading, FI < 20, and SE > 70% make it possible to meet the criteria of class SF2 (slump flow 660-750 mm, T500 < 3 s) [2]. Washed marine sands and Oueme alluvial sands, combined with crushed gravels 5.6/16 or 10/20 (LA ≤ 25), constitute the most favorable combinations. The SCC mix of Table 12 (W/C = 0.42, carboxylate superplasticizer at 1.1% of the cement mass, 150 kg/m^3 of limestone filler) reaches fc28 = 33 MPa (Table 13).

3.7.3. Concrete Durability

In the tropical, coastal climate of South Benin, concrete durability is governed by several degradation mechanisms: carbonation, chloride ingress (marine environment), sulfate attack, and the risk of alkali-aggregate reaction. Table 14 summarizes the durability performance measured on the concretes studied, based on the work of Aitcin (2007) and BCG (2022) [15, 21].

Table 14. *Performance of concretes according to aggregate type (fc28, modulus E, durability).*

Aggregate (sand/gravel)	W/C	fc28 (MPa)	E (GPa)	WA concrete (%)	Durability class (NF EN 206)
Lagoon sand + crushed gravel	0.60	21-26	28-32	6.5-9.0	XC2 (carbonation)

Aggregate (sand/gravel)	W/C	fc28 (MPa)	E (GPa)	WA concrete (%)	Durability class (NF EN 206)
Washed marine sand + crushed gravel	0.58	26-31	30-34	5.0-7.0	XC3/XD1 (chlorides)
Alluvial sand + crushed gravel	0.55	29-34	32-36	4.5-6.5	XC3/XS1
Manufactured sand + crushed gravel	0.50	34-41	34-40	3.5-5.0	XC4/XS2
High-performance concrete: crushed gravel + SF + SP	0.35	45	40-48	2.0-3.5	XC4/XS3 — very durable
SCC: marine sand + crushed gravel	0.42	33-45	35-42	3.0-4.5	XC3/XD2

The use of unwashed marine sands represents the most immediate durability risk for reinforced concretes along the Beninese coastline. The water-soluble chloride content of the raw marine reference sand of South Benin, determined according to NF EN 1744-1 [33], averages 0.09% of Cl^- by mass of dry sand. For the SCC mix of Table 12 (875 kg/m^3 of sand and 400 kg/m^3 of cement), the chloride brought by the sand is given by Eq. (1):

$$Cl^- \text{ (\% of cement mass)} = 100 \times (m_{sand} \times c_{Cl}) / m_{cement} = 100 \times (875 \times 0.0009) / 400 = 0.197\% \quad (1)$$

that is 0.7875 kg of Cl^- per m^3 of concrete. This value is below the maximum of chloride content class Cl 0.40 (0.40% of the cement mass, reinforced concrete) of EN 206 [32], but only 0.003 percentage point below the stricter class Cl 0.20 (0.20%), applicable for instance to prestressed concrete. Because the EN 206 limit applies to the total chloride brought by all constituents (cement, mixing water, admixtures, and aggregates), the raw sand alone would use 49% of the Cl 0.40 allowance and 98% of the Cl 0.20 allowance (Table 15). Conversely, for this mix, the maximum chloride content of the sand compatible with the class, if the sand were the only source, is 0.183% (Cl 0.40) and 0.091% (Cl 0.20) of dry sand mass. Washing with fresh water, followed by chloride monitoring on every batch (NF EN 1744-1), is therefore mandatory for prestressed concrete and for structures exposed to a very aggressive marine environment, and strongly recommended for any reinforced SCC made with marine sand. Chloride ion diffusion coefficients (NT Build 492) reach 8 to 25 $\times 10^{-12}$ m^2/s for concrete made with unwashed lagoon sand, compared with 3 to 10 $\times 10^{-12}$ m^2/s for clean crushed aggregates, according to earlier work on comparable materials from the Beninese coastline [15]; these literature values confirm the importance of aggregate cleanliness in a tropical chloride-laden environment but were not measured on the concretes of this study.

Table 15 gathers the durability indicators used in this study, distinguishing the values measured on the aggregates from those taken from the literature.

Table 15. *Durability indicators of South Benin aggregates and concretes: values, benchmarks, and origin.*

Durability indicator	Method / standard	Value	Benchmark	Assessment and origin
Water-soluble chloride content of raw marine sand	NF EN 1744-1	0.09% of dry sand mass (mean)	—	Measured in this study
Chloride brought by the sand in the SCC mix (875 kg/m^3 sand, 400 kg/m^3 cement)	Eq. (1)	0.7875 kg/m^3, i.e. 0.197% of cement mass	Cl 0.40: 0.40%; Cl 0.20: 0.20%	Complies with Cl 0.40 (49% of limit); marginal for Cl 0.20 (98% of limit) — calculated from measured value
Maximum sand chloride content compatible with the class (sand as sole source)	Calculation	0.183% (Cl 0.40); 0.091% (Cl 0.20) of dry sand mass	—	Measured value (0.09%) is at the Cl 0.20 limit

Durability indicator	Method / standard	Value	Benchmark	Assessment and origin
Chloride diffusion coefficient	NT Build 492	8–25 $\times 10^{-12}$ m^2/s (unwashed lagoon sand); 3–10 $\times 10^{-12}$ m^2/s (crushed aggregates)	Lower = better	Literature [15], not measured here
Water absorption of concrete	Table 14	2.0–9.0%	Lower = better	Increases from high-performance to lagoon-sand concrete (Table 14)
Aggregate water absorption and porosity	NF EN 1097-6	WA 0.7–2.2%; porosity 1.8–4.2%	WA ≤ 2%	Manufactured sand out of threshold (2.2%); measured (Table 8)
Aggregate cleanliness (SE; VBs)	NF EN 933-8, 933-9	SE 56–78%; VBs 0.3–1.2 g/100 g	SE ≥ 80% (SCC); VBs ≤ 1.0 g/100 g	Washing or blending required; measured (Tables 8 and 9)
Fragmentation and wear resistance	NF EN 1097-2, 1097-1	LA 15–45%; MDE 10–38%	LA ≤ 30%; MDE ≤ 20%	Basalt, granite comply; laterite does not; measured (Table 11)
Exposure classes of the reference concretes	NF EN 206	XC2 to XS3	—	See Table 14
Alkali–aggregate reactivity; carbonation depth	—	Not assessed	—	Research perspective (Section 5)

3.8. Comparison with Experimental Programs Reported by Other Researchers

The trends observed here can be compared with programs conducted on other tropical or semi-arid aggregates (Table 1). The higher strength of the crushed-aggregate concrete (fc28 = 35 MPa versus 23–29 MPa for natural sands, Table 13) agrees with Laoufi et al. [25], who obtained a more compact skeleton and higher mechanical performance with crushed sands than with natural sands in self-compacting mortars made with six sands from the Mascara region (Algeria). The associated penalty on fresh behavior is consistent with Bouziani et al. [23], who reported that passing ability (T500) deteriorated as the proportion of crushed sand increased in river–crushed–dune sand blends, and with the much higher flakiness of crushed gravels (FI 22–28%) than of rounded gravels (10–12%) in Table 10. In the Sri Lankan program of Sooriyaarachchi and Lasintha [26], offshore (marine) sand required the lowest water content and river sand the highest, while quarry dust gave the highest 28-day strength; likewise, washed marine sand ranks above alluvial sand and crushed aggregates give the highest strength in the present study (Tables 13 and 17). Sahraoui and Bouziani [24], working on Algerian data, found that a higher gravel content lowers passing ability while raising viscosity, stability, and strength, which supports limiting the maximum aggregate size to 16–20 mm (Section 3.2).

Fines deserve a specific comment. Rao and Kumar [35] reported that crushed-rock fines improve fresh characteristics because of their higher fines content, and Nanthagopalan and Santhanam [28] studied SCC made with manufactured sand; in the present campaign, however, the 12% fines of the manufactured sand are associated with the lowest sand equivalent (56%) and require dedusting, which shows that the benefit of fines depends on their cleanliness. Finally, the companion program of the authors [20], in which the paste composition was kept constant, shows the same direction of effects (natural aggregates favor flowability, crushed aggregates favor strength, and the combination of crushed sand and crushed gravel reduces passing ability), and Khaoya et al. [27] showed in Kenya that replacing river sand by a regional alternative material degraded flowability and strength, which illustrates that every regional fine material must be qualified case by case. The directions of the effects therefore agree with these programs, whereas absolute values are not directly comparable because mix designs, paste volumes, and test protocols differ.

4. Multicriteria Comparative Analysis of Aggregates

The multicriteria comparative analysis is the synthesis tool used to integrate all the experimental data gathered in the preceding sections into an operational ranking of the aggregates according to their overall suitability for the production of self-compacting concrete. The performance matrix built here relies on six quality criteria, weighted according to their respective importance for SCC mix design.

4.1. Criteria, Indicators, and Weights

Six criteria were retained because they are measured by standardized tests on every aggregate family and are explicitly addressed by the EFNARC (2005) recommendations for SCC [2]: cleanliness, mechanical strength, grading, particle shape, water absorption, and particle density. Table 16 gives, for each criterion, the indicator and its standard, the preferred direction, the weight, and the normative benchmark. The weights (15 to 20%, summing to 100%) were fixed a priori from the hierarchy of importance documented by EFNARC (2002, 2005) and Domone (2006) [2, 5, 7]: the highest weight (20%) is assigned to mechanical strength (LA) and water absorption (WA) because of their direct influence on the strength and durability of hardened concrete, and 15% to each of the four other criteria.

Table 16. *Criteria, indicators, weights, and normative benchmarks of the multicriteria analysis.*

Criterion j	Indicator and standard	Preferred direction	Weight wj (%)	Normative benchmark	Rationale
1. Cleanliness (SE/VBs)	Sand equivalent SE,% (NF EN 933-8); VBs (NF EN 933-9) used as compliance check	Higher	15	SE ≥ 70% (reinforced concrete); SE ≥ 80% (SCC); VBs ≤ 1.0 g/100 g	Active fines increase water and superplasticizer demand
2. Mechanical strength (LA)	Los Angeles coefficient LA,% (NF EN 1097-2)	Lower	20	LA ≤ 30 (SCC, EFNARC); categories LA20 to LA40 (NF EN 12620)	Governs strength and durability of hardened concrete
3. Optimal grading (Mf)	Fineness modulus Mf (NF EN 933-1)	Within 2.2–2.8	15	2.2 ≤ Mf ≤ 2.8	Governs water demand, packing, and stability
4. Shape (FI)	Flakiness index FI,% (NF EN 933-3)	Lower	15	FI ≤ 20 (SCC, EFNARC); FI25, FI35	Governs viscosity and blocking risk
5. Low absorption (WA)	Water absorption WA24,% (NF EN 1097-6)	Lower	20	WA ≤ 2%	Governs effective water, W/C ratio, and durability
6. Particle density (ρs)	Particle density ρs, t/m^3 (NF EN 1097-6)	Higher	15	ρs ≥ 2.60 t/m^3	Governs absolute volumes, paste demand, and soundness

4.2. Normalization and Aggregation

Each indicator value x_ij of aggregate family i (i = 1 to 4: lagoon sand, marine sand, alluvial sand, crushed aggregates) for criterion j (j = 1 to 6) is converted into a dimensionless score s_ij on a common 0–10 scale, 10 being the best performance (Eq. (2)). The overall score S_i is the weighted sum of the scores (Eq. (3)), with the weights w_j of Table 16:

$$s_{ij} = f_j(x_{ij}), \quad 0 \le s_{ij} \le 10 \tag{2}$$

$$S_i = \Sigma_{j=1\ldots6}\, w_j \cdot s_{ij}, \quad \Sigma\, w_j = 1 \tag{3}$$

The scoring functions f_j are monotonic (increasing for SE, Mf, and ρs; decreasing for LA, FI, and WA) and anchored on the benchmarks of Table 16. Within the range of the data of this study, the scores of Table 17 are reproduced to within 0.1 point by the following linear relations (the deviations are given in Table 18): s(SE) = SE/10 (SE in%); s(Mf) = 2.43 ·Mf + 0.69; s(WA) = 9.38 − 1.21·WA (WA in%); s(ρs) = 14.43·ρs − 29.60 (ρs in t/m^3). These relations are calibrated on the dataset, are valid only within the observed ranges of the indicators (SE 56–72%; Mf 2.10–2.80; WA 0.7–1.8%; ρs 2.59–2.68 t/m^3), and must not be extrapolated.

Two criteria cannot be measured on every family. The Los Angeles and flakiness tests apply to coarse aggregates only; the scores of the three sand columns for LA (6.0, 6.5, 6.8) and FI (8.5, 8.8, 8.0) are therefore conventional proxies reflecting, respectively, the mechanical quality of the parent rock and the rounded morphology of the grains, whereas the crushed-aggregate scores (LA: 8.5; FI: 6.0) derive from the LA (18–22%) and FI (22–25%) values of Tables 10 and 11. Conversely, SE and Mf are measured on sands only: for the crushed-aggregate column they are taken on the manufactured sand 0/4 (SE = 56%; Mf = 2.80), whereas WA and ρs are those of the crushed

gravel 10/20 (Table 8). The matrix is thus an index of general suitability for SCC within each family (sands and gravels) rather than a strictly homogeneous comparison.

4.3. Results and Ranking

Table 17. Comparative multicriteria matrix of South Benin aggregates (normalized scores /10).

Quality criterion	Weight (%)	Lagoon sand	Marine sand	Alluvial sand	Crushed aggregates
Cleanliness (SE/VBs)	15	6.2	7.2	6.8	5.6
Mechanical strength (LA)	20	6.0	6.5	6.8	8.5
Optimal grading (Mf)	15	5.8	6.5	7.0	7.5
Shape (FI index)	15	8.5	8.8	8.0	6.0
Low absorption (WA)	20	7.2	8.0	7.5	8.5
Particle density (ρs)	15	7.8	8.2	8.0	9.0
Weighted score /10	100	6.89	7.51	7.33	7.62
Ranking	-	4th	2nd	3rd	1st

Table 17 and Figure 11 (radar chart) reveal a nuanced ranking of the four aggregate types. Crushed aggregates (granite and basalt imported from Togo or from central-northern quarries) obtain the highest score (7.62/10), owing to their excellent mechanical performance (average LA: 18-22%, score 8.5/10), their low absorption (WA: 0.7%, score 8.5/10), and their high particle density (ρs: 2.67-2.68 t/m^3, score 9.0/10). Their weak point remains shape (average FI: 22-25%, score 6.0/10) and a cleanliness score (5.6/10) set by the manufactured sand fraction (SE = 56%), whereas the coarse crushed gravels themselves are clean (fines: 1-2%, VBs: 0.3-0.4 g/100 g).

Washed marine sands rank second (7.51/10), owing to a favorable shape (rounded FI: 10-12%) and low absorption (WA: 1.2%), provided systematic washing against chlorides is carried out. Oueme alluvial sands follow (7.33/10), with compliant fineness moduli and acceptable cleanliness. Lagoon sands rank last (6.89/10), penalized by their overly fine grading (average Mf: 2.10) and insufficient cleanliness (average SE: 62%). The 0.11-point gap between the first two ranks is smaller than the variation caused by plausible changes of the weights (Section 4.5), so these two families should be regarded as co-leading.

One methodological limitation of this matrix deserves to be highlighted: fine aggregates (sands) and coarse aggregates (crushed gravel) are ranked side by side on a common scale, even though some criteria do not apply to them in a strictly equivalent way. The mechanical strength criterion (LA) can only be measured on gravel; the score attributed to sands on this criterion therefore reflects, by convention of the authors, the mechanical quality of the associated parent rock rather than a direct LA test on the sand itself. Likewise, the fineness modulus (Mf) is only meaningful for fine aggregates and was transposed to coarse aggregates through an optimal-grading indicator of a different nature. The overall ranking (Table 17) should therefore be interpreted as a hierarchy of general suitability for SCC within each aggregate family (sands and gravels), rather than as a direct and strictly homogeneous comparison across all categories on the six criteria.

4.4. Worked Calculation Example

Table 18 lists, for each criterion, the indicator value used and the resulting score, and Table 19 gives the weighted contributions w_j s_ij. For the crushed aggregates, Eq. (3) gives S = 0.15 × 5.6 + 0.20 × 8.5 + 0.15 × 7.5 + 0.15 × 6.0 + 0.20 × 8.5 + 0.15 × 9.0 = 0.840 + 1.700 + 1.125 + 0.900 + 1.700 + 1.350 = 7.615, rounded to 7.62. In the same way, S = 6.885 (6.89) for lagoon sand, 7.505 (7.51) for marine sand, and 7.330 (7.33) for alluvial sand (values rounded half-up to two decimals). As an example of the indicator-to-score conversion, marine sand (SE = 72%; Mf = 2.40; WA = 1.2%; ρs = 2.62 t/m^3) obtains s(SE) = 72/10 = 7.2, s(Mf) = 2.43 × 2.40 + 0.69 = 6.52 (Table 17: 6.5), s(WA) = 9.38 − 1.21 × 1.2 = 7.93 (8.0), and s(ρs) = 14.43 × 2.62 − 29.60 = 8.21 (8.2).

Table 18. *Indicator values x, scores s, and scoring rules (computed values of the linear relations in brackets).*

Indicator	Scoring rule	Lagoon sand: x → s (computed)	Marine sand: x → s (computed)	Alluvial sand: x → s (computed)	Crushed aggregates: x → s (computed)
SE (%)	s = SE/10	62 → 6.2	72 → 7.2	68 → 6.8	56[a] → 5.6
LA (%)	Coarse aggregates only	proxy[b] → 6.0	proxy[b] → 6.5	proxy[b] → 6.8	18–22 → 8.5
Mf	s = 2.43 ·Mf + 0.69	2.10 → 5.8 (5.79)	2.40 → 6.5 (6.52)	2.60 → 7.0 (7.01)	2.80[a] → 7.5 (7.49)
FI (%)	Coarse aggregates only	proxy[b] → 8.5	10–12[b] → 8.8	proxy[b] → 8.0	22–25 → 6.0
WA (%)	s = 9.38 − 1.21·WA	1.8 → 7.2 (7.20)	1.2 → 8.0 (7.93)	1.5 → 7.5 (7.57)	0.7[c] → 8.5 (8.53)
ρs (t/m^3)	s = 14.43·ρs − 29.60	2.59 → 7.8 (7.77)	2.62 → 8.2 (8.21)	2.61 → 8.0 (8.06)	2.68[c] → 9.0 (9.07)

[a] Manufactured sand 0/4 (Tables 7 and 9). [b] Conventional proxy (parent rock for LA; rounded morphology for FI), the indicator being measurable on coarse aggregates only; for marine sand, the FI of rounded gravel (Table 10). [c] Crushed gravel 10/20 (Table 8).

Table 19. *Weighted contributions w_j·s_ij and overall scores.*

Criterion	Weight w_j	Lagoon sand	Marine sand	Alluvial sand	Crushed aggregates
Cleanliness (SE/VBs)	0.15	0.930	1.080	1.020	0.840
Mechanical strength (LA)	0.20	1.200	1.300	1.360	1.700
Optimal grading (Mf)	0.15	0.870	0.975	1.050	1.125
Shape (FI)	0.15	1.275	1.320	1.200	0.900
Low absorption (WA)	0.20	1.440	1.600	1.500	1.700
Particle density (ρs)	0.15	1.170	1.230	1.200	1.350
Sum S_i = Σ w_j·s_ij	1.00	6.885	7.505	7.330	7.615
Overall score /10 (rounded)	—	6.89	7.51	7.33	7.62
Rank	—	4th	2nd	3rd	1st

4.5. Sensitivity and Robustness Analysis

Because the weights are fixed a priori, their influence was tested systematically (Table 20): (i) each weight was in turn set to 10% and to 30%, the five others being rescaled proportionally to their baseline values (12 scenarios); (ii) equal weights were applied; and (iii) 10,000 random weight vectors were drawn from a uniform distribution on the weight simplex. Raising the weight of mechanical strength from 20 to 30% increases the score of crushed aggregates to 7.73 (versus 7.62) and lowers that of marine sands to 7.38 (versus 7.51), without changing the ranking. Over the 14 deterministic scenarios, crushed aggregates rank first in 10 and marine sands in 4 (equal weights, SE = 30%, LA = 10%, FI = 30%), whereas lagoon sands rank last in all 14; alluvial sands rank third, except when the weight of FI is 30% (second). With random weights, crushed aggregates and marine sands rank first in 51 and 48% of the draws, respectively, marine sands outrank alluvial sands in 85% of the draws, and lagoon sands rank last in 83% of the draws (crushed aggregates in 17%, when the weights of cleanliness and shape are high). The first two positions should therefore be regarded as co-leading, and the robust conclusions are that lagoon sands are the least suitable family without treatment, and that the combination of crushed gravel with washed marine or alluvial sand is the best-supported solution.

Table 20. *Sensitivity of the overall scores and ranking to the weighting scheme.*

Weighting scenario	Lagoon sand	Marine sand	Alluvial sand	Crushed aggregates	Ranking (1st > 4th)
Baseline (Table 16)	6.89	7.51	7.33	7.62	Crushed > Marine > Alluvial > Lagoon
Equal weights (16.7% each)	6.92	7.53	7.35	7.52	Marine > Crushed > Alluvial > Lagoon
Cleanliness (SE) weight = 10%	6.93	7.52	7.36	7.73	Crushed > Marine > Alluvial > Lagoon
Cleanliness (SE) weight = 30%	6.76	7.45	7.24	7.26	Marine > Crushed > Alluvial > Lagoon
Strength (LA) weight = 10%	7.00	7.63	7.40	7.50	Marine > Crushed > Alluvial > Lagoon
Strength (LA) weight = 30%	6.77	7.38	7.26	7.73	Crushed > Marine > Alluvial > Lagoon
Grading (Mf) weight = 10%	6.95	7.56	7.35	7.62	Crushed > Marine > Alluvial > Lagoon
Grading (Mf) weight = 30%	6.69	7.33	7.27	7.59	Crushed > Marine > Alluvial > Lagoon
Shape (FI) weight = 10%	6.79	7.43	7.29	7.71	Crushed > Marine > Alluvial > Lagoon
Shape (FI) weight = 30%	7.17	7.73	7.45	7.33	Marine > Alluvial > Crushed > Lagoon
Absorption (WA) weight = 10%	6.85	7.44	7.31	7.50	Crushed > Marine > Alluvial > Lagoon
Absorption (WA) weight = 30%	6.92	7.57	7.35	7.73	Crushed > Marine > Alluvial > Lagoon
Density (ρs) weight = 10%	6.83	7.46	7.29	7.53	Crushed > Marine > Alluvial > Lagoon
Density (ρs) weight = 30%	7.05	7.63	7.45	7.86	Crushed > Marine > Alluvial > Lagoon
Random weights (10,000 draws): mean ± SD	6.92 ± 0.38	7.54 ± 0.33	7.35 ± 0.20	7.52 ± 0.49	1st: crushed 51%, marine 48%; last: lagoon 83%, crushed 17%

These results highlight an essential practical conclusion for SCC mix designers in South Benin: the optimal combination consists of associating crushed gravel 5.6/16 or 10/20 (from basalt or granite) with washed marine sands or Oueme alluvial sands, with a sand-to-gravel ratio adjusted according to the rheological requirements of the targeted SCC class (SF1 to SF3) [2].

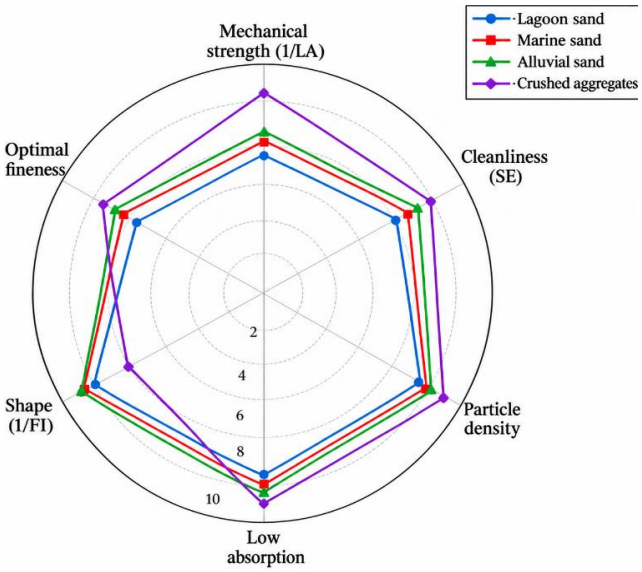


Figure 11. *Radar chart of comparative aggregate quality in South Benin (normalized score /10 across 6 criteria, author compilation 2024).*

5. Limitations of the Study and Research Perspectives

The results presented above provide a solid database for the valorization of South Benin aggregates in SCC. However, several methodological limitations should be pointed out, for the sake of scientific transparency and in accordance with current publication standards in civil engineering.

1) The spatial and temporal representativeness of the sampling could be improved: among the 75 sand quarries and 39 gravel quarries recorded, some were not individually tested; the reported values therefore reflect a representative sample rather than an exhaustive characterization of every site. Extending the campaign to more sites, with multi-year monitoring, would make it possible to better quantify the seasonal variability of alluvial and lagoon sands.
2) The statistical treatment of the data could be strengthened. The min-average-max ranges reported in Tables 7, 9, 10, and 11 are not systematically accompanied by standard deviations or by tests comparing means (ANOVA, Student's t-test), even though some value ranges overlap substantially, particularly between the fineness modulus of lagoon sand and that of marine sand, or between the LA values of granite and gneiss (see corresponding sections). The hierarchies proposed in this study should therefore be interpreted as central tendencies consistent with the regional literature, rather than as statistically demonstrated differences between sample populations; a formal statistical analysis, including the systematic calculation of standard deviations and tests comparing means for all tests, constitutes a priority research perspective. Given the relatively large number of samples tested for most of the routine tests ($n > 30$ per sand type, $n \geq 10$ per rock type), standard deviations should have been systematically calculated and reported for all the results tables (Tables 5, 8, 10, 11, 13, and 14), and not only for Tables 7 and 9; this calculation could not be performed on the raw data of the present campaign within the scope of this preliminary version and is treated here as an explicit limitation rather than as an available result.
3) The multicriteria synthesis method (Tables 16-20) relies on a weighted sum with weights fixed a priori from the normative literature (EFNARC), without recourse to a formalized method (AHP, TOPSIS) or expert consultation (Delphi). The linear scoring relations are calibrated on the observed ranges and conventional proxies are used for LA and FI in the sand columns. The full sensitivity analysis (Section 4.5) shows that the order of the first two ranks depends on the weights, whereas the last position of lagoon sands is robust; validation by AHP (Saaty, 1980 [22]) with a structured expert consultation remains a priority.
4) The environmental and economic assessment of local aggregate valorization, mentioned in the introduction as a major strategic issue, was not quantified in this study, which focused on technical characterization. A comparative life-cycle assessment (ISO 14040:2006) between local and imported aggregates, together with an estimate of the associated economic gains, would be a relevant extension of this work.
5) The chloride content of the raw marine sand was measured in this study (NF EN 1744-1), but as a mean value only: its variability between sites and seasons, the chloride content of the other sand types, and chloride transport in the concretes of this study (NT Build 492) were not measured, and the diffusion coefficients cited

come from earlier work on comparable materials. Alkali–aggregate reactivity and carbonation were not assessed.

6) Far from calling into question the practical conclusions of this study for the valorization of South Benin aggregates, these limitations define a clear complementary research program for future work.

6. Conclusion

The present study carried out a comprehensive quantitative analysis of the aggregates available in South Benin, with a view to their use in the production of self-compacting concrete. The main scientific and practical findings of this research can be summarized as follows.

South Benin aggregates show significant diversity in nature, origin, and quality. Lagoon sands, abundant and inexpensive, have insufficient fineness moduli (average Mf: 2.10) and overly low sand equivalents (average SE: 62%) for direct use in reinforced concrete or SCC. Oueme alluvial sands and washed marine sands better satisfy the dimensional and physical requirements, provided rigorous control is applied. High-quality coarse aggregates (basalt, granite from the Atacora region) show excellent mechanical performance (LA ≤ 22%, MDE ≤ 14%), but their availability depends on distant supply sources.

In terms of SCC performance, the optimal combination identified for the design of class C30/37 SCC in the South Benin context associates washed marine sand (SE ≥ 80% after washing, Mf: 2.2-2.8) or Oueme alluvial sand with crushed gravel 5.6/16 or 10/20 (LA ≤ 25, FI ≤ 20), together with a carboxylate superplasticizer (1.1% of the cement mass in the SCC mix tested, Table 12) and a mineral addition (150 kg/m^3 of limestone filler). This combination makes it possible to achieve fc28 values of 33 to 45 MPa and rheological properties compliant with the EFNARC criteria for class SF2. The SE ≥ 80% requirement corresponds to the specific SCC threshold and is only reached, for the marine and alluvial sands studied, after washing or particle-size correction, since the values measured in the raw state (72% and 68% on average) remain below this threshold.

The multicriteria ranking places crushed aggregates (7.62/10) and marine sands (7.51/10) marginally ahead of alluvial sands (7.33/10) and lagoon sands (6.89/10). The sensitivity analysis shows that lagoon sands rank last in all deterministic scenarios, whereas the order of the first two ranks depends on the weights; these two families should therefore be considered co-leading.

In terms of durability, the use of unwashed marine sands poses the most immediate durability risk and should be avoided in reinforced concrete without prior monitoring of chloride content. The implementation of systematic washing procedures and analytical quality control is therefore an essential practical measure to ensure the durability of reinforced concrete structures along the Beninese coastline. The measured chloride content of the raw marine sand (0.09% of dry sand mass, i.e. 0.197% of the cement mass for 875 kg/m^3 of sand and 400 kg/m^3 of cement) complies with class Cl 0.40 but leaves almost no margin to class Cl 0.20, so washing and per-batch chloride control are mandatory for prestressed concrete or severe marine exposure.

Abbreviations

AHP	Analytic Hierarchy Process
ANOVA	Analysis of Variance
Dmax	Maximum Aggregate Size
EFNARC	European Federation of Producers and Applicators of Specialist Products for Structures
EI	Elongation Index
FI	Flakiness Index
GIS	Geographic Information System
ITZ	Interfacial Transition Zone
LA	Los Angeles Coefficient
MDE	Micro-Deval Coefficient
Mf	Fineness Modulus
SCC	Self-compacting Concrete
SE	Sand Equivalent
SSD	Saturated Surface-dry
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VBs	Methylene Blue Value
WA	Water Absorption
W/C	Water-to-cement Ratio

Author Contributions

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Ernesto Cabral Houehanou: Conceptualization, Writing – original draft
Judicael Koffi Agbellele: Visualization
Ramdane Tchao: Data curation, Investigation
Mohamed Gibigaye: Supervision

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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Mohamed Gibigaye is a distinguished Beninese academic and Full Professor (Professeur Titulaire, CAMES) in Technological and Engineering Sciences (Civil Engineering). He holds an engineering degree in civil and industrial design and a PhD in Mechanics of Deformable Solids, both obtained at the Zaporozhye Machine-Building Institute in Ukraine. He is currently Director of the Doctoral School of Engineering Sciences at the University of Abomey-Calavi, while remaining a permanent teacher-researcher at the Abomey-Calavi Polytechnic School. Specializing in the valorization of local materials and reinforced concrete, he also serves as an international quality expert for CAMES, as well as for courts and banks.

Research Field

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Judicael Koffi Agbellele: Civil engineering, Geotechnical engineering, Soil mechanics, Construction materials, Self-compacting

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Ramdane Tchao: Sustainable construction materials from local resources, Self-compacting concrete with tropical aggregates, Characterization of local aggregates by image analysis, Physicomechanical testing of construction materials, Optimization of concrete mix performance, Fresh and hardened properties of concrete

Mohamed Gibigaye: Civil engineering, Mechanics of deformable solids, Reinforced concrete, Local materials valorization, Construction materials, Self-compacting concrete, Structural durability, Construction quality expertise