

# Influence of Local Aggregate Type and Morphology on the Rheological and Mechanical Properties of Self-Compacting Concrete in Tropical Conditions

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## Abstract

This study experimentally investigates the influence of locally sourced aggregates from southern Benin on the fresh and hardened properties of self-compacting concrete (SCC). A comparative experimental program was conducted using three sand types (river, lagoon, and crushed) and two gravel types (natural and crushed), resulting in 18 concrete mixtures classified as ordinary vibrated concrete (OVC), S4-class concrete (S4C), and SCC. Fresh-state performance was evaluated using standardized tests (slump-flow, J-ring, V-funnel, and L-box) in accordance with EN and EFNARC guidelines, while compressive and flexural strengths were measured at 14, 28, and 90 days. Results indicate that SCC mixtures incorporating natural aggregates exhibited improved flowability and satisfactory passing ability, with slump-flow diameters ranging from 670 to 780 mm and L-box ratios exceeding 0.80. In contrast, crushed aggregates enhanced mechanical performance, increasing 28-day compressive strength by up to 15%, with maximum values reaching 52 MPa. However, the combined use of crushed sand and crushed gravel significantly reduced passing ability, as evidenced by lower L-box ratios and increased V-funnel flow times. Overall, most SCC formulations satisfied EFNARC performance criteria, demonstrating the feasibility of producing structurally reliable SCC using

indigenous tropical aggregates when appropriate mix proportioning and admixture dosage are applied. The findings confirm a trade-off between fresh-state deformability and hardened-state strength governed by aggregate type and grading balance, and provide experimentally validated guidance for optimizing SCC mix design in Sub-Saharan construction contexts.

### Keywords

Self-Compacting Concrete (SCC), Aggregate Morphology, Rheological Behavior, Compressive Strength, Tropical Materials

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## 1. Introduction

Self-compacting concrete (SCC) is one of the most significant advances in concrete technology over the last three decades. Defined by its ability to flow and consolidate under its own weight without external vibration, SCC ensures excellent filling ability, passing ability, and surface finish, particularly in heavily reinforced or complex structural elements. Since its introduction in Japan, SCC has been widely adopted in modern construction due to its improved constructability and structural uniformity compared to conventional vibrated concrete [1].

From a rheological standpoint, SCC behaves as a viscoplastic material whose flow initiation and deformation are governed by yield stress ( $\tau_0$ ) and plastic viscosity ( $\mu_p$ ). In practice, these parameters are commonly assessed through standardized fresh-state tests—such as slump-flow, V-funnel, L-box, and J-ring—which provide reliable macroscopic indicators of flowability, viscosity, and passing ability in the absence of direct rheometer measurements [2].

The performance of SCC is strongly influenced by the characteristics of its constituent materials, particularly aggregates. Aggregate type, production method, surface texture, and grading affect inter-particle friction, paste demand, particle packing, and the quality of the interfacial transition zone (ITZ), thereby influencing both fresh and hardened properties of concrete [3]. In general, rounded natural aggregates tend to enhance flowability and passing ability due to reduced mechanical interlock, whereas crushed aggregates often increase internal friction, leading to reduced workability but improved mechanical strength through better aggregate–paste bonding [4].

Most existing SCC guidelines and experimental studies are based on aggregates commonly available in temperate regions of Europe, North America, or East Asia [2]. However, in tropical and Sub-Saharan regions, concrete production relies on locally available materials such as river sands, lagoon sands, and crushed granitic aggregates, whose geological origin and physical characteristics may differ significantly from those typically reported in international literature. In West Africa, and particularly in Benin, lagoonal sands and natural river aggregates are widely used but remain insufficiently documented in SCC applications, despite their potential relevance for sustainable construction [5].

From a sustainability and resource-efficiency perspective, the valorization of local aggregates in SCC presents a strategic opportunity to reduce dependence on imported materials, limit transportation-related environmental impacts, and promote context-adapted construction practices. Several authors have highlighted the importance of adapting SCC mix design methodologies to local materials in order to achieve both technical performance and environmental efficiency, particularly in developing regions [6].

Within this context, the present study aims to experimentally investigate the influence of locally sourced aggregates from southern Benin—natural versus crushed gravels, and river versus lagoon sands—on the fresh and hardened properties of self-compacting concrete. The analysis is based on a comparative experimental program using standardized SCC fresh-state tests (slump-flow, V-funnel, L-box, J-ring) and mechanical strength measurements (compressive and flexural strengths).

In this work, the effects of aggregate morphology are approached indirectly, through the observed macroscopic behavior of SCC mixtures formulated with different aggregate types, rather than through direct quantitative measurement of morphological indices. This approach is consistent with many experimental SCC studies where aggregate effects are interpreted based on standardized performance indicators and comparative mix behavior.

The objective of this study is therefore to establish a robust experimental database that supports the practical formulation of SCC using indigenous tropical aggregates, while ensuring compliance with international performance criteria. The results are intended to provide guidance for engineers and practitioners in Sub-Saharan Africa, contributing to the development of sustainable, locally optimized, and technically reliable SCC applications.

## 2. Hypothesis and Theoretical Framework

### 2.1. Research Question and Central Hypothesis

The present study addresses the following research question:

How does aggregate type (natural versus crushed; river versus lagoon sand) influence the fresh rheological behavior and mechanical performance of self-compacting concrete (SCC) produced with locally available materials in southern Benin?

The working hypothesis is that the macroscopic behavior of SCC is significantly affected by aggregate origin and production method. In particular:

- Natural, rounded aggregates and finer lagoon sands are expected to enhance flowability and passing ability by reducing inter-particle friction and facilitating particle rearrangement.
- Crushed aggregates, characterized by more angular geometry and rougher surface texture, are expected to increase internal friction, leading to reduced flowability but improved mechanical strength due to enhanced aggregate–paste interlock and improved stress transfer across the interfacial transition zone

(ITZ).

This leads to a trade-off hypothesis:

The optimization of SCC formulated with local tropical aggregates requires balancing fresh-state deformability and hardened-state strength through appropriate aggregate selection and mix proportioning.

This hypothesis is tested experimentally through standardized fresh-state performance indicators and mechanical strength measurements.

## 2.2. Theoretical Framework

The theoretical foundation of this research combines rheological modeling, particle packing theory, and aggregate–paste interaction mechanisms.

### 1) *Rheological Models of SCC*

SCC behaves as a viscoplastic material commonly described by the Bingham model [2] [7], in which shear stress ( $\tau$ ) is expressed as:

$$\tau = \tau_0 + \mu_p \dot{\gamma}$$

where  $\tau$  is the shear stress,  $\tau_0$  the yield stress,  $\mu_p$  the plastic viscosity, and  $\dot{\gamma}$  the shear rate.

In practical applications, direct rheometer measurements are not always performed. Instead, standardized SCC tests (slump-flow, V-funnel, L-box, J-ring) are widely used as macroscopic indicators of yield stress and plastic viscosity.

Lower yield stress is generally associated with larger slump-flow diameters, while higher plastic viscosity is reflected in longer V-funnel flow times. Aggregate type and surface characteristics influence these parameters by modifying frictional resistance and particle mobility within the mix.

### 2) *Particle Packing and Granular Optimization*

Efficient SCC design relies on optimized particle packing to minimize voids and reduce excessive paste demand. The Modified Andreasen and Andersen model describes an ideal particle size distribution for maximizing packing density, typically characterized by a distribution modulus  $q$  between 0.22 and 0.25 for SCC applications [7].

Improved packing density:

- reduces internal voids,
- enhances mix stability,
- limits segregation risk,
- and contributes to improved mechanical strength.

Although the present study does not directly measure packing density parameters, differences in grading between river, lagoon, and crushed sands are expected to influence particle arrangement and fresh-state performance.

### 3) *Aggregate–Paste Interaction*

The mechanical performance of concrete is strongly influenced by the interfacial transition zone (ITZ) between aggregate particles and cement paste. Surface texture and geometry affect the quality of this interface.

- Rounded natural aggregates generally promote smoother flow but may reduce

mechanical interlock.

- Angular crushed aggregates tend to increase mechanical anchorage and frictional resistance, potentially enhancing compressive and flexural strength.

These mechanisms are well documented in SCC literature and form the conceptual basis for interpreting the experimental results of this study [3].

### 2.3. Alternative Hypotheses and Conceptual Model

Alternative hypotheses are also considered to refine interpretation:

In this work, the influence of aggregate morphology is interpreted indirectly through a macroscopic performance framework:

In the present study, the influence of aggregate type is interpreted within a macroscopic performance framework in which aggregate origin and grading affect particle packing and inter-particle friction, which in turn modify fresh-state indicators such as slump-flow diameter, V-funnel flow time, and L-box ratio, ultimately influencing compressive and flexural strength development.

This conceptual chain provides a coherent interpretative model linking aggregate characteristics to observed SCC behavior, without relying on direct quantitative measurement of geometric shape indices.

### 2.4. Scope and Theoretical Contribution

This study does not aim to develop a new rheological model or to quantify geometric shape parameters at the microscopic scale. Instead, it seeks to provide experimentally validated insights into how locally available tropical aggregates influence SCC performance under standardized laboratory conditions.

By integrating established rheological and packing theories with region-specific experimental data, the study contributes to adapting SCC mix design principles to Sub-Saharan construction contexts and supports the development of technically reliable and resource-efficient concrete formulations.

## 3. Methodological Parameters

### 3.1. Experimental Design

The experimental program was designed to evaluate the combined influence of sand type and gravel type on the rheological and mechanical behavior of self-compacting concrete (SCC).

A full factorial design was adopted, consisting of:

- Three sand types: river sand ( $S_1$ ), lagoon sand ( $S_2$ ), and crushed sand ( $S_3$ );
- Two gravel types: natural rounded gravel ( $G_1$ ) and crushed gravel ( $G_2$ ).

This resulted in six aggregate combinations. Each combination was produced under three consistency classes:

- Ordinary Vibrated Concrete (OVC),
- S4-class plastic concrete (S4C),
- Self-Compacting Concrete (SCC).

In total, 18 concrete mixtures were prepared.

The water-to-cement ratio (w/c) and gravel-to-sand ratio (G/S) were maintained constant within each consistency class to allow meaningful comparison of aggregate effects. For SCC mixtures, paste volume was maintained between 33% and 35%, in accordance with EFNARC recommendations [1] [2].

A Portland limestone cement (CEM II/B-L 42.5 N) was used. A polycarboxylate-based high-range water-reducing admixture (HRWRA) was incorporated at dosages between 0.6% and 1.2% by mass of cement, depending on the required consistency.

The physico-chemical properties of the cement are summarized in **Table 1**.

**Table 1.** Physico-chemical properties of the CEM II/B-L 42.5 N cement used in this research.

<b>Physical properties</b>	
<b>Finesse</b>	
- Passerby 45 $\mu\text{m}$ , (%)	8.01
- Specific surface, Blaine, ( $\text{m}^2/\text{kg}$ )	340
<b>Chemical analysis (%)</b>	
- Silica ( $\text{SiO}_2$ )	18.58
- Alumina ( $\text{Al}_2\text{O}_3$ )	4.26
- Iron ( $\text{Fe}_2\text{O}_3$ )	3.06
- Lime ( $\text{CaO}$ )	61.06
- Magnesia ( $\text{MgO}$ )	2.79
- Sodium ( $\text{Na}_2\text{O}$ )	0.15
- Potassium ( $\text{K}_2\text{O}$ )	0.35
- Alkali equivalent en ( $\text{Na}_2\text{O} + 0.658\text{K}_2\text{O}$ )	0.39
- Phosphate ( $\text{P}_2\text{O}_5$ )	0.23
- Titanium ( $\text{TiO}_2$ )	0.32
- Sulfur ( $\text{SO}_3$ )	3.28
- Loss in fire (%)	6.95
<b>Composition (%)</b>	
- Tricalcium silicate (C3S)	60.02
- Dicalcium silicate (C2S)	17.97
- Tricalcium aluminate (C3A)	6.11
- Aluminoferrite tetracalcique (C4AF)	9.30

The mass composition of the 18 concrete mixtures is detailed in **Table 2**.

**Table 2.** Mass composition of concrete mixes ( $\text{kg per m}^3$ ).

<b>Concrete mixes</b>	<b>Sand</b>			<b>Gravel</b>	
	L-04a	L-04b.	C-04	Roulé	Concassé
OVC-RLa	885.42	-	-	885.42	-

**Continued**

OVC-RLb	-	878.9	-	878.9	-
OVC-RC	-	-	935.02	935.02	-
OVC-CLa	895.03	-	-	-	895.03
OVC-CLb	-	888.45	-	-	888.45
OVC-CC	-	-	922.82	-	922.82
CS4-RLa	880.42	-	-	880.42	-
S4C-RLb	-	874.10	--	874.10	-
S4C-RC	-	-	930.02	930.02	-
S4C-CLa	890.16	-	-	-	890.16
S4C-CLb	-	883.61	-	-	883.61
S4C-CC	-	-	917.79	-	917.79
SCC-RLa	856.57	-	-	852.95	-
SCC-RLb	-	850.33	-	846.74	-
SCC-RC	-	-	900.83	900.83	-
SCC-CLa	862.30	-	-	-	862.30
SCC-CLb	-	855.95	-	-	855.95
SCC-CC	-	-	889.08	-	889.08

**3.2. Materials and Source Locations**

Aggregates were collected from five representative sites in southern Benin (Dekoungbé, Zinvié, Sè, Sètto, and Dèkin), covering both river and quarry origins.

- River sands consisted predominantly of naturally rounded particles.
- Lagoon sands were finer and contained moderate silt fractions (<6%).
- Crushed sands and gravels originated from granitic quarries and exhibited more angular geometry and rougher surface texture.

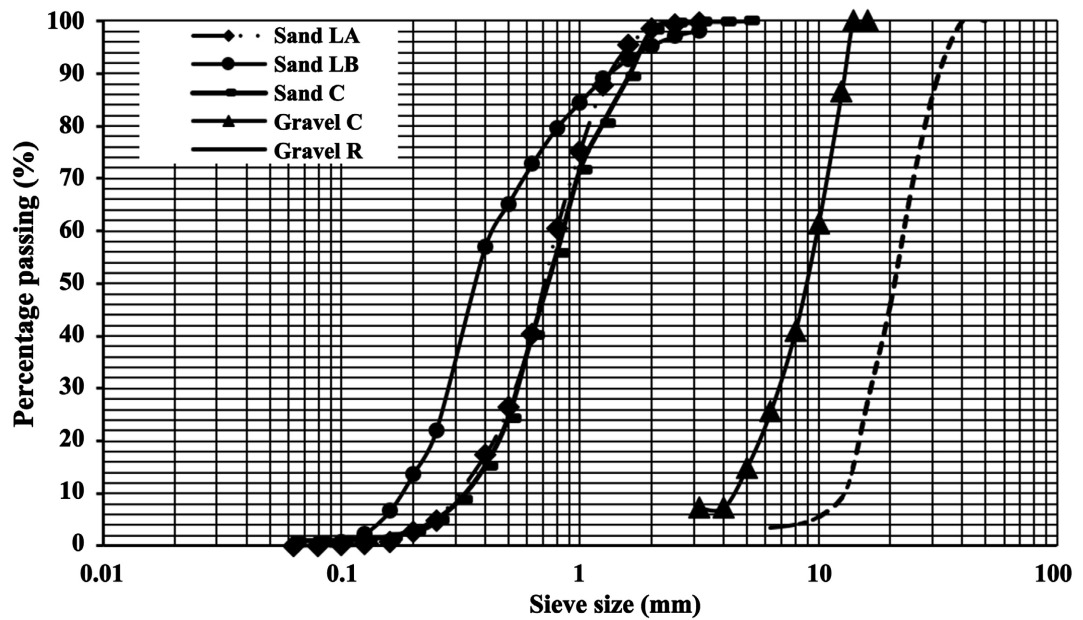
All aggregates were characterized in accordance with EN 933-1 and EN 1097-2 [8] [9] for:

- Particle size distribution,
- Specific gravity,
- Water absorption,
- Los Angeles abrasion resistance.

The influence of aggregate morphology in this study is interpreted indirectly through comparison of aggregate origin (natural versus crushed) and macroscopic performance indicators, rather than through direct quantitative measurement of geometric shape indices.

Particle size distribution curves for the sands and gravels are presented in **Figure 1**.

The measured physical properties of the aggregates are summarized in **Table 3**, including specific gravity, absorption capacity, fines content, and Los Angeles abrasion value.



**Figure 1.** Particle size distribution of local sands and gravels used for SCC formulation.

**Table 3.** Physical properties of sands and gravels used for SCC formulation.

Material	Bulk density $\rho_B$ (g/cm <sup>3</sup> )	Particle density $\rho_s$ (g/cm <sup>3</sup> )	Porosity $n$ (%)	Compacity $(1 - n)$ (%)	Void ratio $e$	Fineness modulus (MF)
Sand LA	1.63	2.45	33.5	66.5	0.50	1.72
Sand LB	1.61	2.49	35.3	64.7	0.55	1.34
Sand C	1.44	2.64	45.5	54.5	0.87	2.69
Gravel C	1.45	2.69	46.1	53.9	0.86	N.A.
Gravel R	1.65	2.63	37.3	62.7	0.59	N.A.

Note: Densities measured according to EN 1097-6; Fineness modulus per EN 933-1; Values rounded to two decimals per ISO 80000-1 (2013) [8] [9].

### 3.3. Mixing and Casting Procedures

Batching and mixing were performed according to EN 12350-1 and CSA A23.2-09 procedures [10] [11].

Dry materials were first homogenized. Approximately 80% of the mixing water was then added, followed by the diluted superplasticizer. Mixing continued for approximately 3 minutes until uniform consistency was achieved.

Specimens were cast immediately after mixing:

- Cylindrical specimens (100 × 200 mm) for compressive strength testing;
- Prismatic specimens (100 × 100 × 500 mm) for flexural strength testing.

Only OVC and S4C mixtures were vibrated. SCC mixtures were poured without vibration to assess self-consolidation capacity.

All specimens were demolded after  $24 \pm 2$  hours and cured at  $20^\circ\text{C} \pm 2^\circ\text{C}$  under 100% relative humidity until testing.

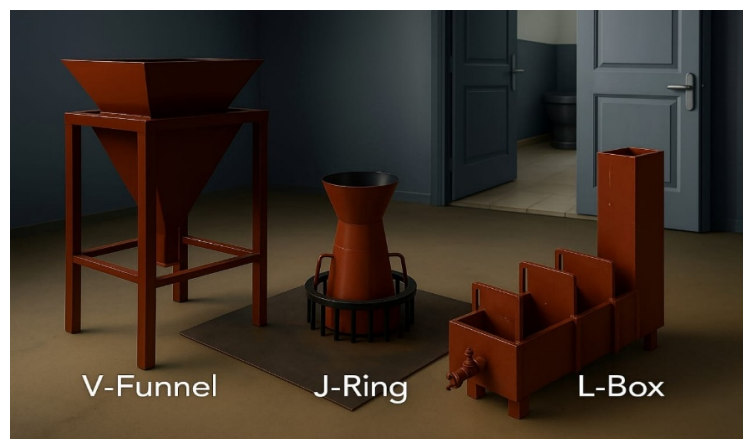
### 3.4. Testing Program

#### 3.4.1. Fresh-State Tests

Fresh properties were measured according to EN 12350-8 to EN 12350-12 and EFNARC (2005):

- Slump-flow test (EN 12350-8): determined deformability ( $D_{50}$ ,  $T_{50}$ ).
- J-ring (EN 12350-12): assessed passing ability through simulated reinforcement.
- V-funnel (EN 12350-9): measured flow time and viscosity.
- L-box (EN 12350-10): evaluated blocking ratio ( $H_2/H_1$ ).

Each test was performed in triplicate. **Figure 2** shows the main testing devices used to assess the fresh-state behavior of SCC, including the slump-flow, V-funnel, and L-box apparatuses.



**Figure 2.** Apparatus used for testing the fresh-state properties of self-compacting concrete: V-Funnel, J-Ring, and L-Box (EN 12350-9, EN 12350-10, EN 12350-12).

#### 3.4.2. Hardened-State Tests

Mechanical properties were evaluated according to EN 12390-3 (compressive) and EN 12390-5 (flexural). Tests were conducted at 14, 28, and 90 days. Compressive strength was measured using a 2000 kN hydraulic press; flexural strength was obtained using third-point loading. Results were expressed as mean  $\pm$  standard deviation ( $\sigma$ ), and the coefficient of variation ( $CV = \sigma/\mu \times 100$ ) was reported.

### 3.5. Statistical and Analytical Methods

Statistical analysis was performed using Minitab 21.

Data normality was verified using the Shapiro–Wilk test. A two-way ANOVA was conducted to evaluate the influence of:

- Sand type,
- Gravel type,
- Consistency class.

Statistical significance was assessed at a 95% confidence level ( $p < 0.05$ ). When significant differences were detected, Tukey’s post-hoc test was applied to identify homogeneous groups.

Correlation analyses were conducted between fresh-state indicators and mechanical properties to examine rheology–strength relationships.

No direct geometric shape indices were included in the statistical evaluation.

### 3.6. Quality Assurance and Safety Protocols

All procedures were conducted under laboratory conditions consistent with ISO/IEC 17025 principles.

- Equipment was regularly calibrated.
- Ambient temperature and humidity were monitored.
- Aggregate moisture content was measured and corrected prior to batching.
- All tests were performed in triplicate.

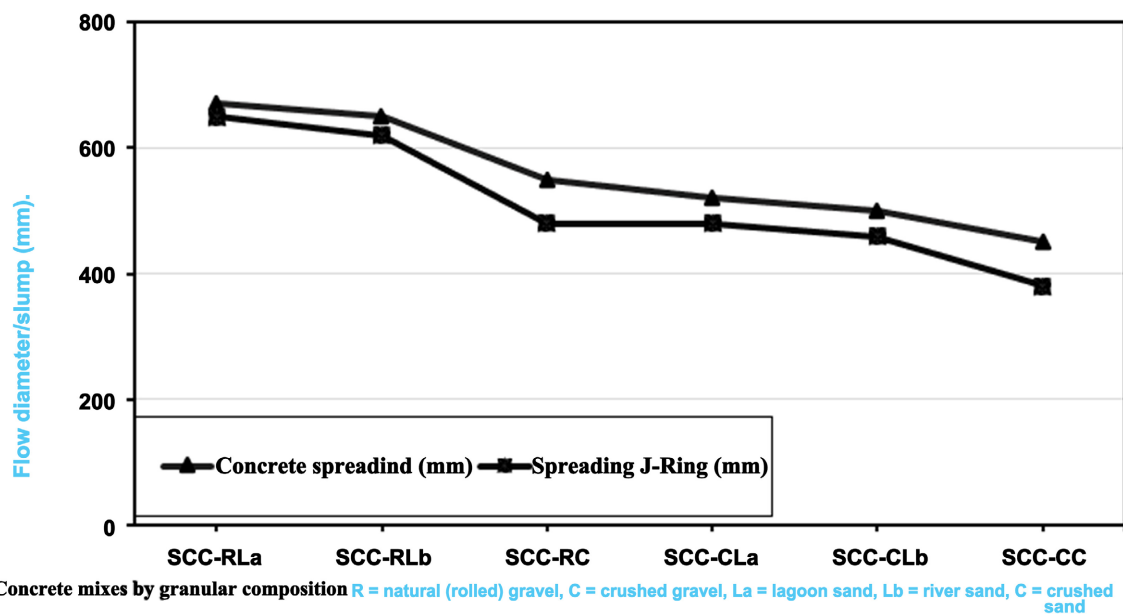
The coefficient of variation remained below 6% for all key parameters, indicating satisfactory experimental repeatability.

## 4. Results and Discussion

### 4.1. Fresh-State Behavior

#### 4.1.1. Slump-Flow and Passing Ability

SCC mixtures exhibited slump-flow diameters ranging from 450 mm to 780 mm, depending on aggregate combination. Two mixtures incorporating crushed sand and crushed gravel fell below the typical EFNARC SF1 threshold ( $\geq 550$  mm), reflecting reduced deformability. Mixtures incorporating natural river or lagoon sands (SCC-RLa and SCC-RLb) showed the highest flowability, with slump-flow diameters between 650 mm and 780 mm. In contrast, mixtures combining crushed sand and crushed gravel (SCC-CLb and SCC-CC) exhibited lower flowability, with slump values decreasing to approximately 450 - 500 mm.



**Figure 3.** Slump-flow diameter (D) and  $T_{50}$  time as a function of sand and gravel types, including J-Ring flow spread comparison.

J-ring results followed a similar trend. For mixtures incorporating natural aggregates, the difference between slump-flow and J-ring spread remained limited, indicating satisfactory passing ability. However, the SCC-CLb and SCC-CC mixtures showed a marked reduction in J-ring spread compared to slump-flow diameter, suggesting increased blocking tendency under simulated reinforcement conditions.

The slump-flow diameter and J-ring performance results for the SCC mixtures are presented in **Figure 3**, while  $T_{50}$  times are discussed in the text.

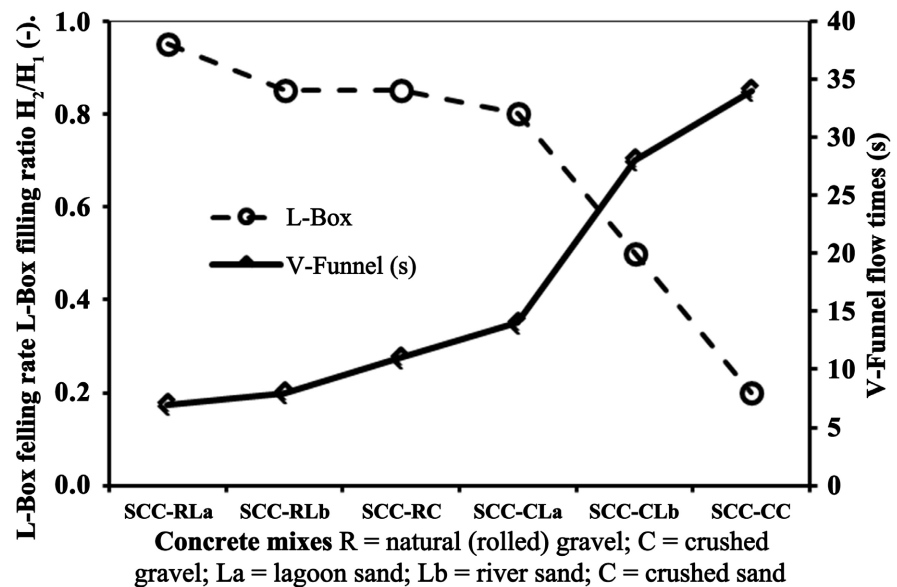
These results indicate that aggregate type strongly influences flow initiation and particle rearrangement. Natural aggregates enhance deformability through reduced inter-particle friction, whereas crushed aggregates increase internal resistance to flow.

#### 4.1.2. V-Funnel and L-Box Results

The V-funnel flow times at  $t_0$  ranged from 6.5 s to 9.8 s, all within EFNARC limits for stable SCC.

Lagoon-sand mixes recorded the shortest times ( $\sim 7$  s), while crushed-sand mixes required up to 9.5 s, confirming higher plastic viscosity ( $\mu_p$ ). After 30 minutes, flow times increased moderately (+1.5 s), indicating mild thixotropy without segregation.

The L-box ratios ( $H_2/H_1$ ) ranged between 0.82 and 0.93, demonstrating adequate passing ability. Mixes with lagoon and river sands achieved the best ratios, while crushed aggregates slightly reduced mobility due to interlock (**Figure 4**).



**Figure 4.** L-Box filling ratio ( $H_2/H_1$ ) and V-Funnel flow time ( $t_0$  and  $t_{50}$ ) for SCC mixtures with different aggregate combinations (EFNARC 2005 criteria).

All SCC formulations thus met EFNARC flowability and stability criteria, proving that local Beninese aggregates can produce high-performance SCC when grad-

ing and admixture dosage are properly optimized.

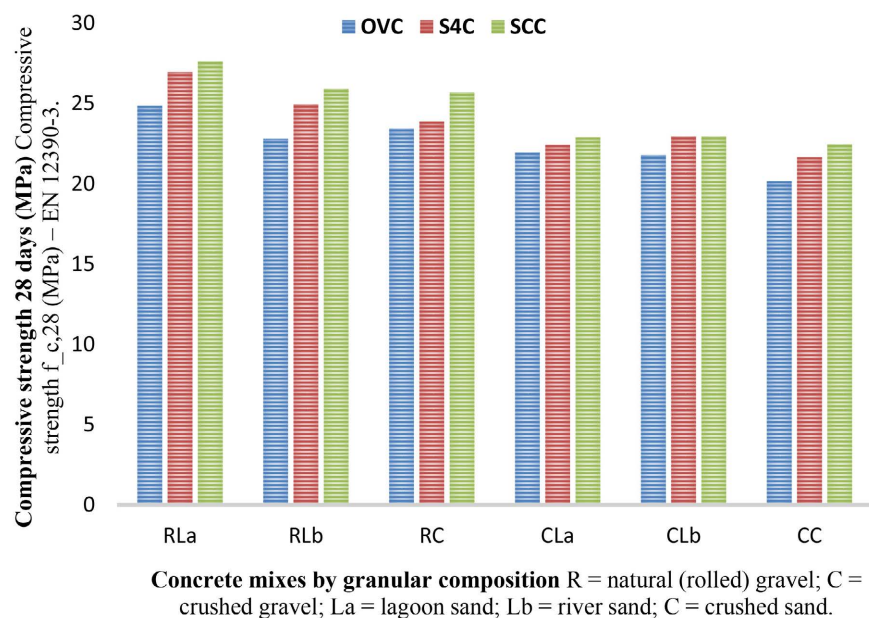
## 4.2. Hardened-State Performance

### 4.2.1. Compressive Strength

At 14 days, compressive strengths ranged from 34 to 41 MPa, and at 28 days from 41 to 52 MPa.

Mixes containing crushed gravel achieved up to 15% higher strength than those with natural gravel, due to improved aggregate–paste interlock and a denser interfacial transition zone (ITZ).

SCC made with crushed sand + crushed gravel reached 52.4 MPa at 28 days, while lagoon sand + natural gravel gave 43.2 MPa, still compliant with structural concrete requirements (Figure 5).



**Figure 5.** Compressive strength at 28 days for different sand-gravel combinations test per EN 12390-3.

At 90 days, selected SCC mixes exceeded 58 MPa, confirming sustained hydration.

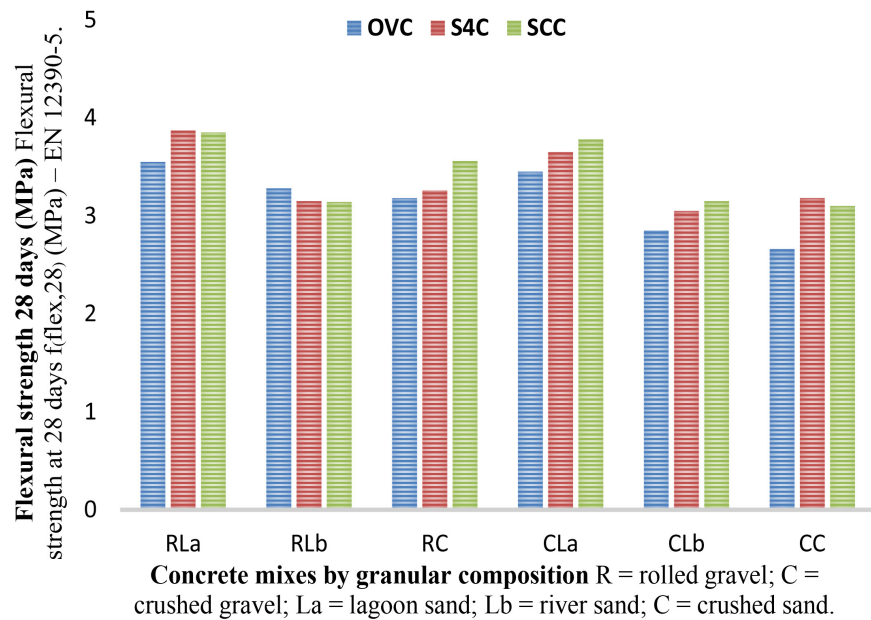
The coefficient of variation (CV) remained below 6%, showing good reproducibility.

### 4.2.2. Flexural Strength

Flexural strengths ranged from 4.5 MPa (lagoon sand) to 6.2 MPa (crushed sand) at 28 days.

The angularity of crushed aggregates improved the mechanical bond with the matrix, enhancing tensile resistance (Figure 6 and Table 4).

Flexural strength values range between 2.8 and 3.9 MPa, with SCC showing slightly higher performance due to improved homogeneity and ITZ bonding. Results comply with EN 12390-5 and confirm the correlation between aggregate morphology and mechanical behavior.



**Figure 6.** Flexural strength at 28 days for ordinary vibrated concrete (OVC), S4-class concrete (S4C), and self-compacting concrete (SCC) with different sand-gravel combinations.

**Table 4.** Summary of fresh-state and mechanical properties of concrete mixes (mean  $\pm$  SD; CV  $\leq$  5%).

	Concrete mixes					
	OVC-RLa	OVC-RLb	OVC-RC	OVC-CLa	OVC-CLb	OVC-CC
Slump (mm)	85	80	65	70	65	55
Density (kg/m <sup>3</sup> )	2350	2338	2450	2370	2357	2426
Compressive strength 14 days (MPa)	19.65	17.46	18.87	18.20	17.34	17.26
Compressive strength 28 days (MPa)	24.85	22.79	23.43	21.96	21.78	20.15
Flexural strengths 28 days (MPa)	3.55	3.28	3.18	3.45	2.85	2.66
	Concrete mixes					
	S4C-RLa	S4C-RLb	S4C-RC	S4C-CLa	S4C-CLb	S4C-CC
Slump (mm)	190	160	150	110	115	120
Density (kg/m <sup>3</sup> )	2345	2332	2444	2364	2351	2419
Compressive strength 14 days (MPa)	20.35	19.96	20.92	18.34	17.82	17.08
Compressive strength 28 days (MPa)	26.95	24.95	23.87	22.43	22.95	21.65
Flexural strengths 28 days (MPa)	3.87	3.15	3.26	3.65	3.05	3.18
	Concrete mixes					
	SCC-RLa	SCC-RLb	SCC-RC	SCC-CLa	SCC-CLb	SCC-CC
Concrete spreading (mm)	670	650	550	520	500	450
J-Ring	650	620	480	480	460	380
L box	0.95	0.85	0.85	0.80	0.50	0.20
V-Funnel flowTVF (s)	7	8	11	14	28	34
Density (kg/m <sup>3</sup> )	2343	2331	2439	2362	2349	2415

**Continued**

Compressive strength 14 days (MPa)	19.81	17.92	16.45	17.85	15.73	16.94
Compressive strength 28 days (MPa)	27.62	25.91	25.69	22.89	22.95	22.46
Flexural strengths 28 days (MPa)	3.85	3.14	3.56	3.78	3.15	3.10

Tests performed per EN 12350 (fresh) and EN 12390 (mechanical);  $CV \leq 5\%$ . The results show consistent improvements from ordinary vibrated concrete (OVC) to self-compacting concrete (SCC) in both workability and mechanical strength. All SCC mixes meet EFNARC (2005) flowability and passing ability requirements (SF1–SF2,  $\Delta D < 25$  mm,  $H_2/H_1 \geq 0.80$ ).

These findings mirror those of [4] [5], confirming the strong influence of aggregate morphology on both rheology and strength development.

### 4.3. Discussion and Interpretation

#### 4.3.1. Rheology-Strength Trade-Off

The experimental results reveal a consistent trade-off between fresh-state deformability and mechanical strength. Mixtures incorporating natural aggregates demonstrated superior flowability and satisfactory passing ability. Conversely, mixtures combining crushed sand and crushed gravel exhibited increased mechanical strength but showed significant reduction in passing ability, as evidenced by elevated V-funnel times and reduced L-box ratios.

This behavior highlights the critical need to balance aggregate angularity and grading in SCC formulation. While crushed aggregates enhance mechanical interlock and compressive strength, their combined use may compromise passing ability if paste volume and admixture dosage are not adequately adjusted.

#### 4.3.2. Interpretation within the Theoretical Framework

The observed behavior is consistent with established rheological and packing theories discussed in Section 2.

Reduced inter-particle friction in mixtures with natural aggregates likely contributes to lower effective yield stress, resulting in larger slump-flow diameters. Conversely, angular crushed aggregates increase internal friction and resistance to flow, but enhance stress transfer within the hardened matrix.

These interpretations are based on macroscopic performance indicators and are consistent with previously reported findings in SCC literature [4].

#### 4.3.3. Regional Relevance

The results demonstrate that locally available tropical aggregates in southern Benin can be successfully incorporated into self-compacting concrete mixtures capable of meeting international performance standards when appropriately proportioned. Four out of six SCC formulations satisfied EFNARC flowability and passing ability criteria, particularly those incorporating natural aggregates or balanced combinations of natural and crushed materials.

However, mixtures combining crushed sand and crushed gravel exhibited significant reductions in passing ability, highlighting the importance of aggregate

grading control and paste optimization in tropical SCC applications. These findings emphasize that while locally sourced materials are technically viable for SCC production, careful mix design adjustments are required to ensure both fresh-state performance and mechanical reliability.

From a regional perspective, this study provides experimentally validated guidance for optimizing SCC formulations using indigenous materials in Sub-Saharan construction contexts, supporting sustainable and resource-efficient concrete production.

## 5. Conclusion

This study experimentally investigated the influence of locally sourced aggregates from southern Benin—natural versus crushed gravels, and river versus lagoon sands—on the fresh and hardened properties of self-compacting concrete (SCC) using standardized laboratory procedures. The results confirm that aggregate origin significantly affects both rheological performance and mechanical strength. Mixtures incorporating natural sands and gravels exhibited improved flowability and satisfactory passing ability, reflected by larger slump-flow diameters and L-box ratios exceeding 0.80. In contrast, mixtures formulated with crushed aggregates showed slightly reduced deformability but enhanced compressive and flexural strength, with improvements of up to approximately 15% at 28 days. However, the combined use of crushed sand and crushed gravel resulted in a marked reduction in passing ability, as evidenced by significantly lower L-box ratios and increased V-funnel flow times, highlighting the sensitivity of SCC fresh-state performance to aggregate angularity and grading balance. Overall, most SCC formulations satisfied EFNARC performance criteria, demonstrating the feasibility of producing structurally reliable SCC using indigenous tropical aggregates when appropriate mix proportioning and admixture dosage are applied. The findings confirm the proposed trade-off between fresh-state deformability and hardened-state strength, governed by the balance between reduced inter-particle friction and increased mechanical interlock. From a practical perspective, the study provides region-specific guidance for optimizing SCC mixtures in Sub-Saharan construction contexts. Future research may focus on quantitative aggregate morphology characterization and long-term durability assessment to further refine SCC mix design adapted to tropical materials.

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## Conflicts of Interest

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

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## Nomenclature

(Symbols marked with ★ indicate parameters or notations used in experimental sections or equations)

### Latin Symbols

Symbol	Definition	Unit
E/C	Water-to-cement ratio	–
G/S	Gravel-to-sand ratio	–
N	Porosity	%
P	Packing density (compactness)	%
e	Void index	–
D★	Slump-flow diameter	mm
$t_0, t_{30}$ ★	V-funnel flow time at 0 and 30 minutes	s
$H_2/H_1$ ★	L-box filling ratio	–
$f_c$ ★	Compressive strength	MPa
$f_{flex}$ ★	Flexural (bending) strength	MPa
CV★	Coefficient of variation	%

### Greek Symbols

Symbol	Definition	Unit
$\rho$	Density (mass per unit volume)	$\text{kg}\cdot\text{m}^{-3}$
$\sigma$	Stress (compressive)	MPa
$\tau_0$ ★	Yield stress (rheological parameter)	Pa
$\mu_p$ ★	Plastic viscosity	Pa·s

### Subscripts and Abbreviations

Abbreviation	Definition
BOV	<i>Béton Ordinaire Vibré</i> (Ordinary vibrated concrete)
BS4	<i>Béton de consistance S4</i> (S4-class plastic concrete)
BAP	<i>Béton Autoplaçant</i> (Self-compacting concrete)
SP★	Superplasticizer (High-range water-reducing admixture)
ITZ★	Interfacial Transition Zone
S <sub>1</sub> , S <sub>2</sub> , S <sub>3</sub> ★	Sand types: river, lagoon, crushed
G <sub>1</sub> , G <sub>2</sub> ★	Gravel types: natural, crushed
NF EN★	French and European standard (Norme Française Européenne)
EFNARC★	European Federation of National Associations Representing Concrete
RILEM★	International Union of Laboratories and Experts in Construction Materials, Systems and Structures

## **Units**

All measurements are expressed in the International System of Units (SI), with rounding in accordance with ISO 80000-1 (2013) and EFNARC (2005) recommendations.