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Aggregate Testing and Hydraulic Concrete Mix Design for Bridge Construction in an Aggressive Marine Environment: A Case Study of the Émile Badiane and Tobor Bridges, Ziguinchor, Senegal

Babacar Diouf*, Mariama Ba, Bator Cisse, Ahmadou Fall

Institut Polytechnique de Saint-Louis (IPSL), Université Gaston Berger, Saint-Louis, Senegal
Email: *babacar2.diouf@ugb.edu.sn

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Abstract

This paper evaluates basalt aggregates from the Diack quarry and develops two concrete mixes for bridge construction in an XS1 saline environment. The study applies the Dreux-Gorisse and Féret-Bolomey mix design methods to a conventional C35/45 concrete and a self-compacting C35/45 concrete using CEM III/B cement. The reported aggregate properties meet the cited compliance limits, and both proposed mixes satisfy the prescriptive binder-content and effective water-to-cement ratio requirements for XS1 exposure. Basalt aggregates from the Diack quarry were characterized for physical properties (particle size distribution, specific gravity, bulk density, water absorption) and mechanical properties (Los Angeles and Micro-Deval coefficients) in accordance with applicable NF EN standards. All reported aggregate test results were within NF EN 12620 compliance limits. Two concrete formulations were derived: a conventional structural concrete B40 (C35/45) using the Dreux-Gorisse method, and a Self-Compacting Concrete (BAP, C35/45) using the Féret and Bolomey approaches, both incorporating slag cement CEM III/B 42.5 N-SR and a polycarboxylate superplasticizer. All granular fractions were used in saturated surface-dry (SSD) conditions, and effective water contents were corrected for aggregate absorption prior to mix proportioning. The resulting mix designs achieved effective water-to-binder ratios of 0.449 (B40) and 0.376 (BAP), satisfying the XS1 class requirements for minimum binder content (≥330 kg/m^3) and maximum w/c ratio (≤0.55). Fresh-state performance targets for the BAP (slump flow ≥ 650 mm, yield stress $\tau_0 < 50$ Pa, plastic viscosity $\eta < 20$ Pa·s) and an estimated service life exceeding 100 years under DuraCrete assumptions represent design objectives that require experimental validation prior to site implementation. The study demonstrates that locally sourced basalt aggregates are suitable for high-performance bridge concrete in estuarine West African environments, provided appropriate cement selection and admixture optimisation are applied.

Keywords

Concrete Mix Design, Bridge Infrastructure, Basalt Aggregates, Self-Compacting Concrete, Saline Environment

1. Introduction

Bridge infrastructure in sub-Saharan Africa faces mounting pressure from increasing traffic loads, limited maintenance budgets, and, particularly in coastal regions, aggressive chemical environments caused by chloride ingress and carbonation [1]. The Casamance region of southern Senegal, traversed by the Route Nationale N4, exemplifies these challenges: tidal estuaries, seasonal flooding, elevated humidity, and brackish water create exposure conditions that can compromise the long-term integrity of reinforced concrete structures [2].

The construction of the Émile Badiane and Tobor bridges in Ziguinchor, financed under the Plan Diomaye pour la Casamance, represents a strategic investment in regional connectivity and economic development. These structures demand concrete formulations that simultaneously achieve high mechanical strength, adequate workability for pumped placement, and durability in marine exposure class XS1 (chloride from seawater, but not in direct contact) as defined in EN 206-1 [3].

In West Africa, the design of structural concrete often relies on empirical European methods, most notably Dreux-Gorisse [4], Féret [5], and Bolomey [6], adapted to locally available materials. While these methods are well established in French engineering practice, their application to tropical and estuarine contexts, where aggregate quality and ambient conditions differ markedly from temperate climates, remains an active area of investigation [7]-[9].

The use of blast-furnace slag cements (CEM III) in aggressive marine environments has been extensively studied and is recommended by EN 197-1 and EN 206-1 for its pozzolanic reactivity, lower heat of hydration, and superior resistance to sulfate and chloride attack compared to ordinary Portland cement [10]-[12]. Similarly, the addition of silica fume (microsilica) to Self-Compacting Concrete (SCC) formulations has been shown to refine the pore structure and enhance resistance to ionic penetration [13] [14].

This study contributes to the literature in two respects: i) it provides a systematic characterization of basalt aggregates sourced from the Diack quarry, a primary supply source for construction projects in Senegal, and ii) it applies two complementary mix design methodologies for bridge concrete under XS1 exposure, offering a reproducible framework for similar projects in the West African sub-region.

2. Materials

2.1. Aggregates

Five fractions of basalt aggregates were sourced from the Diack quarry, located approximately 80 km from Dakar: a fine sand (0/3 mm), and four coarse fractions (3/8, 8/14, 8/16, and 16/25 mm). Basalt was selected for its high density, mechanical resistance, and established use in Senegalese construction practice. The aggregates are angular, crushed, with a dark grey texture indicative of a dense mineralogical matrix.

2.2. Cement

CEM III/B 42.5 N-SR (slag cement with sulfate resistance designation) was selected in accordance with EN 197-1. This cement class is specifically recommended for structures in exposure classes XS1 to XS3 because the high slag content (typically 66% - 80%) reduces the C3A content responsible for ettringite formation and significantly lowers the permeability of the hardened matrix [10]. Its 28-day characteristic compressive strength of 42.5 MPa satisfies the structural requirements of the bridges.

2.3. Mixing Water

Potable water conforming to NF EN 1008 was used. Particular attention was paid to chloride ion content, which must not exceed 1,000 mg/L for reinforced concrete per EN 1008, especially critical in a coastal environment where construction water may be inadvertently contaminated.

2.4. Chemical Admixtures

A third-generation polycarboxylate-based superplasticizer, Sika® ViscoCrete®-2 Tempo 12 Plus, was incorporated to reduce the water demand while maintaining or improving workability. Its solid content is 33%, and it was dosed at 0.75% by cement weight (bwoc). For the BAP formulation, a dosage of 2.3% bwoc was applied to achieve Self-Compacting Concrete (SCC) flow criteria (slump flow ≥ 650 mm per EN 12350-8) while controlling segregation.

2.5. Supplementary Cementitious Materials

For the BAP (SCC) formulation, condensed silica fume (Sikacrete® HD, undensified, amorphous SiO_2 ≥ 85%) was incorporated at 6% by cement weight (23.9 kg/m^3), within the recommended range of one to two 15 kg bags per cubic metre per the technical datasheet. Silica fume reduces the mean capillary pore diameter, densifies the interfacial transition zone (ITZ) between paste and aggregate, and markedly reduces chloride diffusion coefficients [13].

3. Experimental Methods and Aggregate Test Results

3.1. Physical Properties

All physical tests were conducted at an accredited laboratory (CEREEQ SA, Dakar) in accordance with the applicable NF EN standards.

3.1.1. Particle Size Distribution and Physical Properties

Sieve analysis was performed according to NF EN 933-1 using the AFNOR sieve series. The sand 0/3 fraction yielded a fineness modulus (FM) of 3.876, exceeding the upper limit of 2.5 recommended for concrete sand. Accordingly, a 40% corrective fine sand (0/1 mm) was incorporated in the BAP formulation to improve packing density and reduce the risk of segregation. The physical properties of all fractions are presented in **Table 1** and confirm continuous grading conforming to NF EN 12620.

Table 1. Aggregate physical properties.

Fraction (mm)	Specific Gravity (T/m³)	Bulk Density (T/m³)
Sand 0/3	2.865	1.688
Gravel 3/8	2.919	1.562
Gravel 8/14	2.954	1.629
Gravel 8/16	2.998	1.663
Gravel 16/25	2.989	1.650

The basalt aggregates exhibit high specific gravity values (2.865 - 2.998 T/m³), confirming their dense and durable nature, suitable for hydraulic concrete. Bulk density ranges from 1.562 to 1.688 T/m³, with higher values for the fine fraction due to better packing and lower values for coarser fractions due to increased voids. Overall, these properties indicate good potential for optimized aggregate blending, leading to improved compaction, reduced porosity, and enhanced mechanical performance in hydraulic concrete.

Particle size distributions of all fractions are presented in **Figure 1** and confirm continuous grading conforming to NF EN 12620.

The particle size distribution curves obtained from sieve analysis show that the basalt aggregates are well separated into distinct size fractions, with the coarse fractions (3/8, 8/14, 8/16, and 16/25) exhibiting steep and narrow grading typical of uniformly graded materials, while the 0/3 fraction presents a more continuous distribution with higher fines content. For hydraulic concrete applications, this granulometric configuration is particularly relevant, as the fine fraction contributes to filling voids and improving workability, whereas the coarse fractions provide the structural skeleton and mechanical strength. The complementarity of these fractions therefore enables the design of optimized aggregate blends with enhanced packing density, reduced porosity, and improved strength and durability of the resulting concrete.

3.1.2. Specific Gravity, Bulk Density, and Water Absorption

Specific gravity was determined per NF EN 1097-6, yielding values between 2.865 and 2.998 T/m³, consistent with dense baszalt of igneous origin [15]. Bulk densities ranged from 1.562 to 1.688 T/m³, all within the NF EN 1097-3 conformity limits.

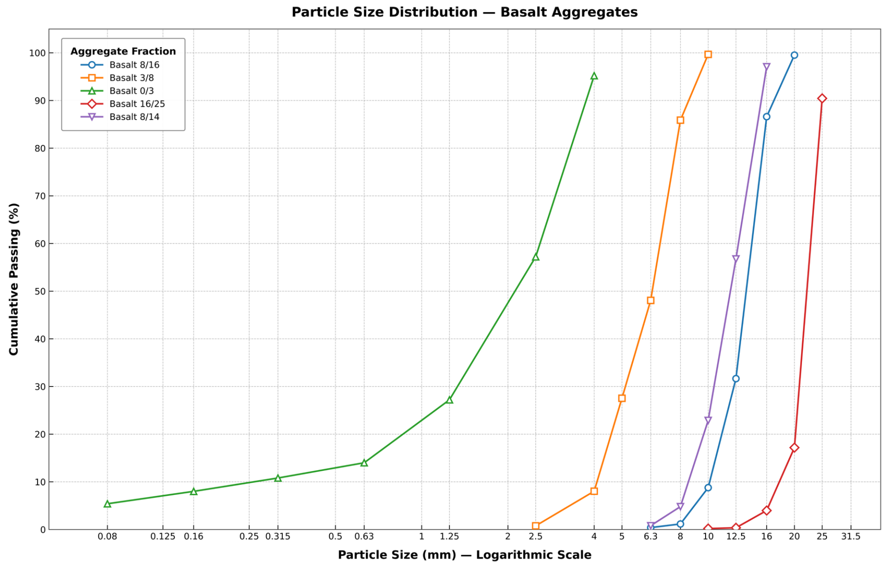

Figure 1. Particle size distribution curves of the five basalt aggregate fractions from the Diack quarry (NF EN 933-1).

Water absorption coefficients, determined per NF EN 1097-6, ranged from 0.44% (16/25 mm) to 1.44% (8/16 mm). All values comply with the maximum 3.5% limit for structural concrete aggregates (NF P 18-545). All granular fractions were used in saturated surface-dry (SSD) conditions; pre-saturation was achieved by soaking for 24 h, followed by surface drying to remove free surface water. Water absorption is directly relevant to the effective water-to-cement ratio calculation; effective water was computed as: $w_{eff} = w_{total} - w_{agg}$, where w_{agg} denotes the quantity of water pre-absorbed by the aggregates prior to mixing. Because fractions were introduced at the SSD state, the absorption correction ($w_{agg} = WA\% * m_{agg}$) was zero for the batching calculation; any residual free moisture on aggregate surfaces was accounted for by reducing the added mix water accordingly, so the effective w/c ratios reported in Table 3 and Table 4 are directly reproducible from the tabulated masses.

3.2. Mechanical Properties

Mechanical resistance of aggregates was evaluated through two standardised impact and wear tests.

3.2.1. Los Angeles (LA) Coefficient

The LA coefficient, measuring resistance to fragmentation (NF EN 1097-2), ranged from LA = 6.6% (16/25 mm) to LA = 15.4% (3/8 mm). All values are well below the LA ≤ 25% (category LA25) threshold specified for concrete aggregates for bridges in French practice [16]. The low LA values of the coarser fractions confirm the high intrinsic hardness of the Diack basalt.

3.2.2. Micro-Deval (MDE) Coefficient

The MDE coefficient, measuring resistance to abrasion in the presence of water

(NF EN 1097-1), ranged from MDE = 7.5% (8/16 mm) to MDE = 14.8% (3/8 mm), all below the MDE ≤ 25% (category MDE25) conformity limit. The combination of LA ≤ 25 and MDE ≤ 25 satisfies the dual-criterion requirement for traffic-bearing structures in Eurocode-aligned French specifications. LA and MDE results for all tested fractions are summarised in Table 2.

Table 2. Summary of mechanical test results for basalt aggregates.

Aggregate Fraction	Los Angeles Coeff. LA (%)	Micro-Deval Coeff. MDE (%)
Basalt 3/8	15.4	14.8
Basalt 8/14	11.1	12.3
Basalt 8/16	9.8	7.5
Basalt 16/25	6.6	—
Limit (EN 12620)	**≤25 (LA25)**	**≤25 (MDE25)**

4. Concrete Mix Design

4.1. Design Criteria

Both concrete grades target a minimum characteristic compressive strength of C35/45 (fck, cyl = 35 MPa, fck, cube = 45 MPa) at 28 days, and must comply with the durability requirements for exposure class XS1 (EN 206-1): effective w/c ratio ≤ 0.55, minimum binder content of 330 kg/m³, and minimum strength class C30/37. The B40 concrete is intended for all above-foundation structural elements. The SCC formulation (BAP) was designed for densely reinforced sections requiring pump-assisted placement without vibration.

The design safety margin Δf was set at 7.5 MPa for a coefficient of variation (CoV) of 15%, typical for supervised site mixing in Senegal (EN 206-1, Table NA.3—production category 2, good statistical control absent an extended record), giving a target mean strength fcm = 42.5 MPa, which aligns with the characteristic strength class of the selected cement. The G/S mass ratio of 1.3 was selected from the Dreux-Gorisse compacity chart for Dmax = 25 mm with crushed aggregates at S3 consistency, following the graphical procedure in Dreux and Festa [4]. The paste volume for the BAP formulation was fixed at 350 L/m³ in accordance with the EFNARC SCC specification guidelines [17], which recommend a paste volume of 300 - 380 L/m³ for gap-graded aggregates with Dmax = 14 mm. The 40% corrective fine sand proportion was determined iteratively to bring the combined grading curve within the Fuller reference envelope and to compensate for the excess coarseness of the 0/3 fraction (FM = 3.876 vs. the recommended maximum of 2.5 for SCC powder-rich mixes, per EN 12620 Annex B guidance).

4.2. B40 Structural Concrete—Dreux-Gorisse Method

The Dreux-Gorisse method [4] [18] is a widely adopted graphical-analytical procedure for proportioning concrete in French-speaking countries. The procedure involves: 1) determining the optimal cement-to-water ratio (C/E) from the Abrams-

Féret strength equation; 2) establishing the granular coefficient G from Dmax and aggregate quality; 3) reading the optimal water content from the W-A chart as a function of consistency (S3 class, slump 100 - 150 mm for pumped concrete); and 4) solving the absolute volume equations for fine and coarse aggregate fractions.

For Dmax = 25 mm, a compactness value of 0.79 was read from the Dreux-Gorisse compactness chart. The granular coefficient G was taken as 0.45 (crushed basalt, well-graded). The water content was set at W = 180 L/m^3 (before correction for aggregate absorption). Iterating on the C/E ratio to achieve fcm ≥ 42.5 MPa while minimizing cement content yielded C = 400 kg/m^3 (w/c = 0.449, corrected effective). Aggregate mass was split with a G/S ratio of 1.3, and granulometric continuity was verified per NF EN 12620. The resulting mix composition is given in Table 3.

Table 3. Theoretical mix composition of B40 structural concrete (per m^3).

Component	Mass (kg/m^3)	Volume (L/m^3)
CEM III/B 42.5 N-SR	400	129.0
Natural Sand 0/3	322.5	124.0
Basalt Gravel 3/8	156.6	53.6
Basalt Gravel 8/16	100.5	33.5
Basalt Gravel 16/25	861.9	288.4
Effective Water	179.7	179.7
Superplasticizer Tempo 12	8.48	7.85
Entrapped Air	—	15.0
TOTAL	**2513.5**	**1000**
w/c Ratio	**0.449**	**—**

4.3. Self-Compacting Concrete (BAP), Féret-Bolomey Approach

SCC mix design followed the Féret [5] and Bolomey [6] volume-based approaches, which are adapted for high-powder content mixes characteristic of SCC [19]. The paste volume was fixed at 350 L/m^3 to provide sufficient matrix for gap-filling without segregation. Silica fume replacement (6% bwoc) was treated as an equivalent binder in the Bolomey fines volume criterion (target: 110 - 140 L/m^3 for Dmax = 14 mm). The corrective sand (0/1 mm, 40% of total sand mass) was introduced to fill the fine end of the gradation curve, partially compensating for the high FM of the 0/3 basalt sand. Superplasticizer dosage was calculated to target a Bingham yield stress of $\tau_0 < 50$ Pa (design target equivalent to slump flow ≥ 650 mm per EN 12350-8) while maintaining a target plastic viscosity $\eta < 20$ Pa·s to prevent dynamic segregation, in accordance with EFNARC guidelines [17]. These rheological values are design targets derived from the superplasticizer manufacturer's dosage-flow relationship; fresh-state testing (slump-flow, L-box, V-funnel per EN 12350-8/10/11) has not yet been conducted and is required prior to any site implementation of the BAP formulation. Similarly, the target compressive strength fcm ≥ 42.5 MPa at 28 days represents a design objective and must be confirmed by cube testing per EN 12390-3. The mix composition is shown in Table 4.

Table 4. Theoretical mix composition of self-compacting concrete BAP (per m^3).

Component	Mass (kg/m^3)	Volume (L/m^3)
CEM III/B 42.5 N-SR	397.7	128.3
Corrective Sand (0/1)	378.1	131.2
Basalt Gravel 0/3	567.2	198.0
Basalt Gravel 3/8	189.1	64.8
Basalt Gravel 8/14	756.3	256.0
Effective Water	158.6	158.6
Superplasticizer Tempo 12	9.15	8.47
Silica Fume (Sikacrete® HD)	23.9	36.7
Entrapped Air	—	18.0
TOTAL	**2481.3**	**1000**
w/c Ratio	**0.376**	**—**

5. Quality Verification and Durability Assessment

Both formulations were verified against the mandatory criteria of EN 206-1 for exposure class XS1. Results are summarised in Table 5. All parameters satisfy the specified limits. The reduced w/c ratio of the BAP (0.376 vs. 0.449 for B40) combined with the silica fume addition is expected to lower the chloride diffusion coefficient (Dcl) below 4×10^{-12} m^2/s, consistent with values reported in the literature for similar CEM III + SF concretes in marine environments [12] [20].

Table 5. EN 206-1 compliance verification for XS1 exposure class.

Parameter (XS1 Class)	Limit	B40	BAP (SCC)
Max Effective W/C Ratio	0.55	0.449	0.376
Min Strength Class	C30/37	C35/45	C35/45
Min Binder Content (kg/m^3)	330	400	421.6
Fines Volume (L/m^3)	110 - 140	~130	126.4
Silica Fume Dosage (kg/m^3)	15 - 30 / m^3	—	23.9

The expected service life of the structures was estimated using the DuraCrete probabilistic chloride diffusion model [21], based on the following input assumptions: surface chloride concentration Cs = 3.5 kg/m^3 of concrete (representative of XS1 tidal-splash zone in tropical West Africa, per DuraCrete Report BE95-1347 Table 4.3); age-adjusted chloride diffusion coefficient D28 = 4.0×10^{-12} m^2/s for the B40 (CEM III, w/c = 0.449) and D28 = 1.5×10^{-12} m^2/s for the BAP (CEM III + silica fume, w/c = 0.376), consistent with literature values for similar binder systems [12] [20]; ageing exponent n = 0.45 for CEM III concretes (DuraCrete R17); critical chloride threshold Ccr = 0.4% by mass of cement for passive reinforcement; nominal cover depths of c = 40 mm (B40) and c = 50 mm (BAP); and a target reliability index $\beta = 1.5$ (probability of depassivation $p_f \approx 6.7\%$), corresponding to a consequence class CC2 structure per EN 1990. Under these assumptions, the estimated time to corrosion initiation exceeds 75 years for the B40 and 100 years for the BAP. These estimates are sensitive to the assumed diffusion coefficients and surface chloride concentration, which should be refined using site-specific data from the Casamance estuary prior to finalizing the durability design.

6. Discussion

The aggregate characterization results confirm that basalt from the Diack quarry presents excellent mechanical properties for structural concrete, with LA and MDE values significantly below the regulatory limits. These values are comparable to those reported for Canary Island and East African basalts used in marine infrastructure [22]. The relatively high fineness modulus of the 0/3 sand (FM = 3.876) is a recognized limitation of crushed quarry sands in Senegal, and the 40% corrective sand blending strategy employed here is consistent with recommended practice in the AFNOR documentation [23].

The selection of CEM III/B over ordinary Portland cement (OPC, CEM I) for an estuarine bridge project is strongly supported by the literature. Bouteiller *et al.* [24] demonstrated reductions of 60% - 70% in chloride permeability for CEM III concrete compared to CEM I at equivalent w/c ratios, while Thomas *et al.* [10] confirmed superior long-term performance of blast-furnace slag cements in tidal and splash zone conditions. The use of CEM III in Senegal is an emerging but growing practice, and this study provides further evidence for its suitability with locally available aggregates.

Comparing the two mix designs, the SCC formulation offers advantages in densely reinforced bridge decks and voided box girder sections where internal vibration is impractical. The lower w/c ratio and silica fume addition of the BAP concrete are expected to yield superior long-term durability, albeit at a slightly higher material cost. The economic trade-off is justified in the context of a 30-year design concession and the high maintenance cost of chloride-damaged structures in West Africa.

A limitation of this study is the absence of experimental validation on hardened concrete specimens (compressive strength at 7, 14, and 28 days; chloride migration test per NT Build 492; rapid chloride permeability test per ASTM C1202). Experimental validation is recommended as the next phase of this research, and a full fresh-state characterization (slump-flow, L-box, V-funnel per EN 12350-8/10/11) should be conducted prior to site implementation of the BAP formulation.

7. Conclusions

This study provides a comprehensive materials and mix-design framework for the use of locally quarried basalt aggregates in bridge-grade concrete intended for the aggressive marine environment of Ziguinchor, Senegal. Physical and mechanical characterization of Diack basalt confirmed full compliance with NF EN 12620 specifications, with Los Angeles abrasion coefficients and Micro-Deval attrition coefficients all well within the thresholds prescribed for structural and bridge applications. These results establish Diack basalt as a reliable, high-performance coarse aggregate source for infrastructure development in the West African sub-region.

Two complementary concrete formulations were developed and assessed against the XS1 marine exposure class requirements of EN 206-1. A conventionally vibrated B40 concrete (C35/45), proportioned by the Dreux-Gorisse method with CEM III/B 42.5 N-SR at 400 kg/m^3 and an effective water-to-cement ratio of 0.449, meets the prescriptive durability thresholds applicable to moderate chloride exposure. A Self-Compacting Concrete of equivalent strength class, designed by the Féret-Bolomey approach and incorporating a ternary binder system—slag cement, silica fume at 23.9 kg/m^3, and a polycarboxylate-based superplasticizer achieves a markedly lower effective w/c of 0.376, conferring enhanced resistance to chloride ingress and offering significant constructability advantages in congested reinforcement zones typical of bridge substructures.

Taken together, the findings demonstrate that the combined use of locally sourced crushed basalt, low-clinker slag cement, and supplementary cementitious materials constitutes a technically sound, resource-efficient, and economically viable strategy for durable concrete construction in West African coastal environments. This approach aligns with broader sustainability objectives by reducing clinker content and valorizing regional mineral resources, without compromising structural or durability performance.

Nevertheless, the conclusions of this study remain at the mixed-design and prescriptive compliance stage. Experimental validation on hardened specimens encompassing compressive strength development, chloride migration coefficients (NT Build 492), carbonation resistance, and reinforcement corrosion initiation is required to substantiate the projected durability benefits. Furthermore, probabilistic service-life modelling integrating site-specific chloride surface concentration and diffusion data from the Casamance estuary will be necessary to quantify design service lives in accordance with the fib Model Code provisions. These investigations are identified as priority directions for future research.

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Conflicts of Interest

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

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