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Effect of Basalt Aggregate Size Distribution and Specific Surface Area on High-Performance Concrete

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Abstract

Optimizing concrete mix design requires understanding how coarse aggregate size distribution and specific surface area (SSA) modulate mechanical response and durability. Using basalt aggregates (9.5, 12.5, 19, and 25 mm) characterized by laser diffraction and BET, this study shows that mixtures with larger aggregates (19–25 mm) achieved up to ≈17% higher 28-day compressive strength (37.93 MPa for 25 mm vs. 32.39 MPa for 9.5 mm) and ≈18% lower water absorption (1.90% for 19 mm vs. 2.31% for 9.5 mm), while mixtures with smaller aggregates (9.5–12.5 mm) exhibited ≈56% greater flexural strength (4.87 MPa vs. 3.13 MPa), ≈38% higher splitting tensile (4.23 vs. 3.07 MPa), and ≈49% higher shear strength (4.04 vs. 2.72 MPa). Pull-out resistance increased with aggregate size (≈48% higher for 25 mm vs. 9.5 mm), consistent with enhanced mechanical anchorage. BET confirmed an inverse SSA – size relation (≈580→≈200 cm^2/g), clarifying ITZ area demand and paste requirements. These outcomes provide a rational basis for tailoring aggregate gradation to balance compressive capacity, flexural/tensile response, and transport resistance for durable, resource-efficient concrete design.

1. Introduction

Concrete is a composite blend of cement, water, and aggregates, the latter of which typically account for approximately 60–80% of the mixture's total volume [1]. Consequently, the attributes of aggregates are pivotal in defining the key performance characteristics of concrete [2, 3]. Among these attributes, the size distribution and specific surface area of coarse aggregates are especially influential [4, 5]. Many past investigations have examined how aggregate properties govern concrete performance: for instance, the authors [6] analyzed the impact of aggregate size and shape on concrete's mechanical behavior, while researchers [7] focused on the effects of aggregate texture on durability. However, these studies frequently generalize conclusions across varied aggregate types, seldom addressing basalt aggregates in particular. Basalt, a volcanic rock noted for its high strength and durability, is widely utilized in concrete [8].

Compared with common granite and limestone aggregates, crushed basalt typically presents a rougher surface texture, higher strength and stiffness, and lower porosity; at larger nominal sizes (lower SSA) this can reduce paste demand, while at smaller sizes the roughness and closer particle spacing intensify interfacial friction and micro-mechanical interlock. These contrasts justify the focused inquiry on basalt [9].

Advanced characterization techniques—such as laser diffraction and X-ray computed tomography—have recently enabled more precise assessments of aggregate size distribution and specific surface area [9]. Leveraging these methods opens opportunities for tailoring concrete mix designs to specific aggregate characteristics [10]. Refining mix designs in this way can also yield tangible benefits for the construction industry, including cost savings, heightened structural integrity, and a reduced environmental footprint through the judicious use of natural resources.

Despite such technological progress, a comprehensive understanding of how basalt aggregates' size distribution and specific surface area affect water absorption and, consequently, concrete mix design remains insufficient [5]. Addressing this gap, the present research undertakes an experimental investigation focused on basalt coarse aggregates' size distribution and specific surface area, with an emphasis on optimizing water absorption and overall concrete performance. By offering detailed experimental data and employing cutting-edge analytical methods, this study aims to advance knowledge of basalt aggregate properties and their influence on concrete, thereby contributing to more durable and sustainable construction materials.

This study addresses the following objectives:

- Quantify the effect of basalt aggregate size on compressive, flexural, splitting tensile, shear, and pull-out strengths.
- Establish the relationship between nominal size and SSA via BET and a paste-wrapping proxy, and link these to water absorption.
- Explain performance trends through an ITZ-focused mechanism tying SSA, paste demand, and aggregate interlock.
- Provide mix-design guidance that balances strength and transport properties for durability-oriented applications.

2. Materials and methods

Chemical admixtures, fibers, and SCMs were intentionally omitted to isolate the role of basalt aggregate size/SSA. This control enables unambiguous attribution of observed effects to aggregate metrics and avoids confounding from rheology-modifying agents.

2.1. Materials

The primary materials employed in this investigation comprise cement, potable water, crushed sand, and basalt coarse aggregates of varying nominal sizes. Detailed properties of each material are itemized below:

Cement. Ordinary Portland Cement (OPC) of grade 42.5N (Dangote brand) was utilized due to its suitability for a wide range of concrete strength classes (C8/10 to C35/45). **Error! Reference source not found.** presents the key physical parameters of the cement, confirming its compliance with requisite standards for general construction applications.

Basalt Coarse Aggregates. Coarse aggregates were derived from a crusher site of China Communications Construction Company, Ltd. (CCCC) and divided into four distinct nominal size categories—9.5 mm, 12.5 mm, 19 mm, and 25 mm. **Error! Reference source not found.** summarizes the physical properties of the basalt samples used in this study.

Crushed Sand. Crushed sand served as the fine aggregate, chosen to ensure consistency and uniform quality across all concrete mixes. **Error! Reference source not found.** outlines its physical properties, while **Error! Reference source not found.** illustrates the particle size distribution.

Water. Potable water was used for batching and curing, thereby ensuring that its quality satisfied for the manufacture and testing of concrete.

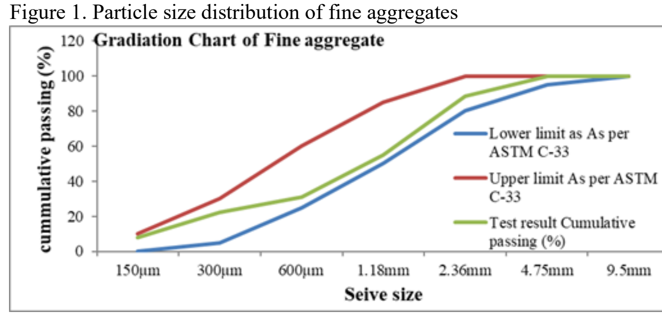
Table 1. Cement physical properties

Cement Type	Normal consistency	Initial setting time (min)	Final setting time (min)	Soundness (mm)
Dangote cement (42.5N)	27%	55	530	0.75

Table 2. Coarse aggregate Physical properties

No	Test Description		Test results			
1	Maximum Nominal Aggregate size		9.5mm	12.5mm	19mm	25mm
2	Moisture Content		2.2	1.77	1.96	1.89%
3	Compacted Unit Weight		1790 kg/m^3	1664 kg/m^3	1650 kg/m^3	1600 kg/m^3
4	Absorption Capacity		3.05%	2.9%	2.56%	2.4%
5	Fineness Modules		1.91	2.96	2.79	3.15
6	Specific Gravity	Bulk	2.55	2.56	2.56	2.57
		Bulk Saturated Surface Dry (BSSD)	2.613	2.68	2.67	2.80
		Apparent	2.74	2.76	2.73	2.74

Figure 1. Particle size distribution of fine aggregates



No	Test Description	Test Result
1	Silt Content	4.42%
2	Moisture Content	1.77%
3	Compacted Unit weight	2570 kg/m^3
4	Absorption Capacity	2.9%
5	Bulk Specific gravity	2.56
6	Apparent Specific gravity	2.76
7	Fineness Modulus	2.96

2.2. Methods

2.2.1. Sample preparation

Basalt aggregates were separated into four size fractions, namely 9.5 mm, 12.5 mm, 19 mm, and 25 mm. Each fraction was weighed and documented individually. To eliminate residual moisture, the aggregates were oven-dried at 105 °C for a duration of 24 h. This protocol minimized variability in subsequent experimental tests and ensured a reliable baseline for measuring water absorption.

2.2.2. Determination of size distribution

Size distribution of the coarse aggregates was ascertained via a combination of traditional sieve analysis ASTM C136/C136M [11] and laser diffraction for finer fractions. Sieve analysis furnished a reliable classification of the coarser particle sizes, while laser diffraction offered greater precision in evaluating the minimal portion of the aggregate gradation.

2.2.3. Specific surface area measurement

To examine the specific surface area (SSA) of the basalt aggregates, two complementary methods were implemented:

a) Brunauer-Emmett-Teller (BET) Method. Aggregates were degassed under vacuum at 300 °C for 2 hours, followed by nitrogen gas adsorption. This technique provides a robust quantitative measure of the SSA, capturing minute variations in surface texture.
b) Paste Wrapping Method. In this secondary procedure, aggregates were encapsulated in a cement paste and subsequently cured. The volume of cement paste adhering to each aggregate was quantified, and the known surface area of the cement particles enabled inference of the aggregate's SSA.

2.2.4. Concrete mix design

Concrete mixtures were formulated in strict accordance with ACI 211.1-91 guidelines [12]. Adjustments to the water–cement ratio were undertaken to compensate for the water absorption properties of each aggregate size. No chemical admixtures were introduced, thereby isolating the influence of aggregate properties on the resulting concrete performance.

2.2.5. Water absorption test on concrete cubes

To evaluate the water absorption behaviour of the concrete, cubes measuring 150 mm × 150 mm × 150 mm were cast and cured for 28 days. Following ASTM C642 standard [13], the cured specimens were weighed, immersed in water for 24 hours, surface-dried, and reweighed. The percentage difference in mass was recorded to quantify water absorption.

2.2.6. Testing of concrete properties

- **Workability.** Slump tests were carried out in accordance with ASTM C143/C143M standard [14]. This enabled a consistent comparison of flow characteristics across all designed mixes.
- **Compressive Strength.** After curing for 7 and 28 days, the specimens were subjected to compression testing as per ASTM C39/C39M standard [15]. The peak loads attained were subsequently converted into compressive strength values, indicating each mixture's load-bearing capacity.
- **Durability.** Durability indicators, including water permeability and chloride ion penetration, were assessed to forecast the long-term performance of the concrete.

2.2.7. Experimental setup

All experiments were conducted under controlled laboratory conditions to eliminate external variables. Principal equipment included standardized sieve sets with mechanical shakers for particle size analyses, a BET surface area analyzer for SSA determination, a concrete mixer for uniform blending of constituents, and an array of mechanical testing apparatuses such as compression, flexure, tensile, and shear testing machines for quantifying mechanical and durability properties.

3. Results and discussion

3.1. Mechanical properties of concrete

Concrete specimens incorporating coarse basalt aggregates of nominal sizes 9.5 mm, 12.5 mm, 19 mm, and 25 mm were tested for compressive, flexural, shear, and tensile strengths. **Error! Reference source not found.** provides a representative view of these test specimens, and **Error! Reference source not found.** summarizes the 28-day mean strengths

derived from the tests.

Figure 2. Concrete test samples for mechanical property determination.

Table 4. 28th day Concrete mechanical testes using 9.5mm, 12.5mm, 19mm, and 25mm coarse aggregates

Concrete Mechanical test	9.5mm CA	12.5mm CA	19mm CA	25mm CA
Compressive strength (Mpa)[a]	32.39	34.04	36.16	37.93
Flexural strength (Mpa) [b]	4.87	4.5	3.92	3.13
Splitting tensile strength (Mpa)[c]	4.23	3.81	3.45	3.07
Shear strength (Mpa)	4.04	3.8	2.88	2.72
Pull out test (Mpa)[d]	7.17	8.71	9.78	10.62

a- 28th day mean strength of test cube samples of 15X15X15 cm sizes.
b-28th day mean strength of test samples of 50X10X10 cm sizes.
c-28th day mean strength of test samples with Diameter of specimen(mm) D= 150, Depth(mm) L = 300.
d- 28th day mean strength of test samples with 10X10X10 cm sizes.

3.1.1. Compressive strength

The results show that concrete containing larger nominal maximum aggregate sizes (19 mm and 25 mm) exhibited higher compressive strengths. Because larger aggregates generally possess a lower specific surface area relative to smaller particles, the required cement paste per unit surface decreases. This more efficient paste utilization often enhances the concrete's load-bearing capacity. Similar findings have been reported by [16] who observed improved interlocking and interfacial transition zones (ITZ) in concretes formulated with larger (up to 25 mm) coarse aggregates.

Relative to 9.5 mm mixes, 25 mm mixes achieved ≈17% higher compressive strength and ≈49% higher pull-out resistance, whereas 9.5–12.5 mm mixes provided ≈56% higher flexural and ≈38% higher splitting tensile strengths. The 19 mm mix minimized water absorption (1.90%). For durability-critical elements, incorporating a coarser fraction can reduce paste demand due to lower SSA, enabling cement optimization while preserving transport resistance; hybrid gradations can balance compressive capacity with serviceability metrics in bending and tension.

3.1.2. Flexural strength

In contrast to compressive strength, mixes containing larger aggregates (19 mm and 25 mm) tended to yield lower flexural strengths compared to those containing 9.5 mm and 12.5 mm aggregates. Previous publications corroborate this tendency, reporting that smaller aggregate sizes (commonly in the range of 10 mm to 12.5 mm) enhance the flexural performance of concrete [17, 18]. The superior flexural resistance is attributed to the closer spacing and more uniform stress distribution that smaller aggregates can provide within the cementitious matrix.

3.1.3. Splitting tensile strength

As with flexural strength, concretes containing larger aggregates (19 mm and 25 mm) demonstrated lower splitting tensile strengths at all measurement intervals. Smaller particles, in contrast, offer enhanced mechanical interlocking, which contributes to a stronger tensile bond across the matrix. This improved bond mechanism facilitates more effective load transfer when the material is exposed to tensile forces.

3.1.4. Shear strength

Tests likewise indicated a decline in shear strength with an increase in nominal maximum aggregate size. Concretes made using 9.5 mm and 12.5 mm aggregates performed more favourably. This reduction in shear capacity can be attributed to the diminished total interfacial surface area of larger aggregates, which lowers the frictional resistance and aggregate interlock.

3.1.5. Pull out test

Pull-out resistance herein denotes the peak bond stress inferred from bar extraction tests, a surrogate for anchorage performance of embedded reinforcement. Its increase with larger aggregates is consistent with enhanced mechanical bearing and confinement. In contrast to the aforementioned trends, pull-out strengths increased in tandem with aggregate size. Specimens using 19 mm and 25 mm coarse aggregates exhibited comparatively higher pull-out values than those with smaller aggregates (9.5 mm and 12.5 mm). Similar conclusions were reached by

[19], who observed that larger aggregate sizes (for instance, 19 mm) resulted in greater pull-out resistance due to the more robust mechanical anchorage between the aggregate and surrounding paste.

3.1.6. Specific surface area (SSA) of coarse aggregates

Error! Reference source not found. and **Error! Reference source not found.** present the results of the specific surface area (SSA) measurements obtained via the paste wrapping method and the Brunauer–Emmett–Teller (BET) technique, respectively. The paste wrapping tests were performed following a modified version of ASTM C457/C457M standard [20]. Concrete specimens were prepared and immersed in water at 20 °C, then subjected to a careful paste removal procedure to evaluate the quality of the aggregate–paste interface. This protocol enabled a direct assessment of the aggregate's external surface area in contact with the cementitious matrix.

Both the paste wrapping and BET methods consistently revealed that the smallest nominal aggregate sizes exhibited substantially higher SSA values (Table 1). These emphasize that finer aggregate fractions furnish more surface area relative to their volume, thereby fostering enhanced interfacial bonding with cement. Conversely, larger aggregates demonstrated lower SSA, indicative of diminished surface area for potential paste interaction. The data thus underscore an inverse correlation between nominal aggregate size and specific surface area: the coarser the aggregate, the less surface area is accessible for bond formation within the concrete matrix.

Decreasing nominal size increases SSA, expanding the paste–aggregate contact area and the volumetric fraction of ITZ. At smaller sizes, closer particle spacing promotes crack deflection and finer bridging, elevating flexural and tensile responses; at larger sizes, reduced paste coverage per unit area and fewer interfaces favour denser packing, lower connectivity of capillary pores, and higher compressive strength with reduced absorption and permeability.

3.2. Durability test results

3.2.1. Ultrasonic Pulse Velocity (UPV) tests

Ultrasonic Pulse Velocity (UPV) tests were conducted on concrete mixtures containing basalt coarse aggregates of nominal sizes 9.5 mm, 12.5 mm, 19 mm, and 25 mm. The data reveal that larger aggregate sizes (19 mm and 25 mm) consistently yield higher UPV values across various curing ages than mixes employing smaller aggregates (9.5 mm and 12.5 mm). Elevated UPV measurements signify superior concrete quality with fewer voids and enhanced homogeneity [21]. Use of larger aggregates form a denser microstructure, reducing interstitial voids and thereby improving the ultrasonic wave transmission.

3.2.2. Salt attack test

The salt attack test (often referred to as the Sodium Sulfate Soundness test) assesses concrete durability under salt-laden conditions [21]. In this study, cylindrical specimens were cast and cured, then immersed in a sodium chloride (NaCl) solution while undergoing an imposed electrical current, in accordance with ASTM C1202 [22]. This accelerated procedure compels chloride ions to penetrate the concrete, mirroring prolonged salt exposure in real-world environments. The outcomes demonstrate that mixes with 19 mm and 25 mm coarse aggregates exhibited shallower chloride penetration depths than those containing 9.5 mm and 12.5 mm particles. The superior resistance to chloride ingress among specimens with larger aggregates suggests a reduced pore network continuity and enhanced protective capacity in salt-exposed conditions.

3.2.3. Permeability test

Permeability assessments were likewise performed following ASTM C1202 [22]. After water curing at 20 °C for specified intervals (7, 14, and 28 days), concrete specimens were subjected to a 6-hour electrical charge passage test, enabling an evaluation of the concrete's resistance to chloride infiltration [23]. The results indicate that mixtures prepared with coarser aggregates generally manifested lower permeation depths in mm compared to those featuring smaller nominal aggregate sizes. This finding reinforces the notion that the internal configuration of larger aggregates can diminish pore connectivity, thereby restricting fluid movement and enhancing the overall durability performance of the hardened concrete.

3.2.4. Water Absorption capacity test

Water absorption tests were performed in alignment with ASTM C642 [13]. Concrete cubes (15 × 15 × 15 cm) were cast, cured in water at 20 °C, oven-dried, and subsequently immersed in water for a predefined duration. The percentage increase in mass attributable to absorbed water was recorded as the water absorption capacity. As illustrated in Table 8, concrete mixes incorporating larger nominal maximum aggregate sizes (19 mm and 25 mm) exhibited relatively lower water absorption rates than those formulated with smaller aggregates (9.5 mm and 12.5 mm).

Table 5. SSA results of coarse aggregates obtained from paste wrapping test method.

Sample	Wt. before wrapping (gm)	Wt. After Wrapping (gm)	Change in weight (gm)	Surface area(mm^2)	Specific surface area(mm^2/gm)	Average specific surface area (mm^2/gm
25 mm	15.36	16.14	0.78	2934.64	191.06	197.62
25 mm	15.41	16.23	0.82	3085.13	200.20	
25 mm	15.49	16.32	0.83	3122.75	201.60	
19 mm	7.77	8.19	0.42	1580.19	203.37	206.17
19 mm	8.24	8.71	0.47	1768.31	214.60	
19 mm	8.63	9.09	0.46	1730.68	200.54	
12.5 mm	2.22	2.41	0.19	714.85	322.00	329.77
12.5 mm	2.05	2.24	0.19	714.85	348.71	
12.5 mm	2.48	2.69	0.21	790.09	318.59	
9.5 mm	1.32	1.52	0.2	752.47	570.05	583.87
9.5 mm	1.07	1.24	0.17	639.60	597.76	
9.5 mm	1.16	1.34	0.18	677.22	583.81	

This outcome aligns with comparable studies demonstrating that coarser aggregates reduce the total surface area available for water infiltration and minimize the number of micro-voids in the concrete matrix [24].

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Table 6. BET test result of specific surface area for 9.5 mm, 12.5mm, 19 mm, and 25 mm coarse aggregates.

	Channel: 1				Channel: 2				Channel: 3			
Sample Name	9.5 mm	12.5 mm	19 mm	25 mm	9.5 mm	12.5 mm	19 mm	25 mm	9.5 mm	12.5 mm	19 mm	25 mm
Tube Number	1	1	1	1	2	2	2	2	3	3	3	3
Tare Weight (gm)	10.0750	10.0750	10.0750	10.0750	10.1310	10.1310	10.1310	10.1310	10.2312	10.2312	10.2312	10.2312
Sample Weight(gm)	1.1624	1.1624	1.1624	1.1624	1.0724	1.0724	1.0724	1.0724	1.3233	1.3233	1.3233	1.3233
Specific Surface Area (cm^2/gm)	568.264	318.564	205.255	193.243	592.264	354.543	217.643	202.236	585.245	314.124	198.987	202.987
Vm	0.014	0.014	0.014	0.014	0.018	0.018	0.018	0.018	0.021	0.021	0.021	0.021
BET Const	146.044	146.044	146.044	146.044	149.249	149.249	149.249	149.249	143.248	143.248	143.248	143.248

* Degas Temp. (°C) = 150 and Degas Time(min) =60

Table 1. Summary of important test results from the experimental setup.

	1. Compressive strength Concrete Mix design results							
	9.5mm		12.5mm		19mm		25mm	
Test age (day)	7^{th}	28^{th}	7^{th}	28^{th}	7^{th}	28^{th}	7^{th}	28^{th}
Failure Load (KN)	477.17	728.70	510.13	765.93	619.90	813.57	490.30	716.57
Compressive Strength (MPa)	21.21	32.39	22.67	34.04	27.55	36.16	21.79	31.85
Unit Weight (Kg/m^3)	2333.53	2337.43	2366.22	2369.28	2389.83	2401.78	2350.12	2362.67
	2. Flexural strength Concrete Mix design results							
	9.5mm		12.5mm		19mm		25mm	
Test age (day)	7^{th}	28^{th}	7^{th}	28^{th}	7^{th}	28^{th}	7^{th}	28^{th}
Failure Load (KN)	6.72	10.82	6.39	10.00	6.21	8.72	5.93	6.96
Flexural Strength (MPa)	3.03	4.87	2.87	4.50	2.79	3.92	2.67	3.13
	3. Splitting tensile strength results							
	9.5mm		12.5mm		19mm		25mm	
Test age (day)	7^{th}	28^{th}	7^{th}	28^{th}	7^{th}	28^{th}	7^{th}	28^{th}
Tensile Strength (MPa)	2.87	4.23	2.79	3.81	2.72	3.45	2.49	3.07
	4. Water Absorption Capacity Test Results							
	9.5mm		12.5mm		19mm		25mm	
Water Absorption (%)	2.31		2.14		1.90		2.19	

By offering fewer pathways and interfaces for water ingress, mixes with 19 mm and 25 mm aggregates thus show improved resistance to saturation. Consequently, appropriate selection and grading of coarse aggregates can be pivotal in mitigating moisture uptake and enhancing the long-term performance of concrete structures resistance to saturation. Consequently, appropriate selection and grading of coarse aggregates can be pivotal in mitigating moisture uptake and enhancing the long-term performance of concrete structures.

3.2.5. Sorptivity Test

Sorptivity tests were executed in alignment with ASTM C1585 [25], using concrete specimens cured in water at 20 °C for 28 days. Each specimen was partially submerged, and the incremental increase in mass attributed to capillary action was recorded at systematic intervals. The derived sorptivity values indicated that concrete mixtures containing larger nominal maximum aggregate sizes (19 mm and 25 mm) exhibited lower water absorption rates compared with those formulated using smaller aggregates (9.5 mm and 12.5 mm). These findings indicate that reduced surface area and more efficient packing of larger aggregates contribute to decreased capillary suction. Consequently, the strategic selection of coarser aggregate sizes can significantly mitigate water ingress, thereby enhancing the concrete's long-term durability in moisture-sensitive environments.

Table 8. 28^{th} day mean water absorption test results

Concrete test samples*	Water Absorption (%)
With 9.5mm CA	2.31
With 12.5mm CA	2.14
With 19mm CA	1.90
With 25mm CA	2.19

4. Conclusion

The findings of this study confirm that both the size distribution and specific surface area (SSA) of basalt coarse aggregates exert a profound influence on concrete's water absorption characteristics and mechanical performance. Concrete mixtures formulated with smaller nominal aggregate sizes (9.5 mm and 12.5 mm) demonstrated superior flexural, tensile, and shear strengths, largely due to enhanced mechanical interlocking and increased overall SSA, whereas mixtures with larger aggregates (19 mm and 25 mm) showed higher compressive strength, reduced permeability, and lower water absorption rates.

From a practical standpoint, these insights underscore the importance of deliberate aggregate selection and gradation in optimizing concrete mix design. Striking a balance between high compressive strength and adequate flexural or tensile performance requires carefully blending different aggregate sizes and considering their respective SSA. The study further highlights the critical relationship between aggregate properties and concrete durability, particularly under conditions involving water or chloride ingress.

Despite these notable contributions, certain avenues warrant further exploration. Future work could broaden the experimental scope by integrating chemical admixtures or supplementary cementitious materials (SCMs) to examine potential synergies with basalt aggregates. Additionally, long-term field evaluations under varying climatic conditions would help to validate and refine the laboratory-scale findings. Finally, adopting advanced characterization techniques-such as microstructure analysis using scanning electron microscopy (SEM) or digital image correlation (DIC)—could offer deeper insights into the interfacial transition zones (ITZ) and crack propagation mechanisms within concrete. By pursuing these directions, researchers and practitioners alike can better harness the inherent advantages of basalt aggregates, leading to more resilient and sustainable concrete infrastructures.

Declaration of competing interest

The authors declare that they have no competing interests.

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