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Crushed Granite Residue as a High-Performance and Sustainable Alternative to River Sand for Concrete

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Abstract

The construction sector in Burkina Faso faces increasing challenges related to the scarcity and environmental impact of natural river sand extraction. In this context, quarry by-products, such as crushed granite sand (CGS), represent a potential alternative that remains under-exploited. This experimental study evaluated the feasibility of substituting natural river sand (NS) with CGS in the formulation of hydraulic concrete. Five concrete mixtures were prepared with substitution levels of 0%, 25%, 50%, 75%, and 100% CGS, while maintaining a constant water-to-cement ratio of 0.47. Workability was controlled by adjusting the dosage of the superplasticizer. The concrete samples were tested for density and porosity, compressive and tensile strength, ultrasonic pulse velocity, capillary absorption, and resistance to acid attack. The incorporation of CGS significantly improved the mechanical and durability properties of concrete. At 28 days, the compressive strength of CGS100 mix reached 39.33 MPa, compared to 30.64 MPa for the reference mix CGS0. The improved performance is attributed to the higher fines content and angular particle shape of CGS, which enhances packing density and intergranular bonding. This study demonstrates that CGS can effectively replace NS in hydraulic concrete without compromising performance. In contrast, it enhances both strength and durability while promoting the sustainable use of locally available CGS materials. Therefore, CGS represents a promising solution for addressing the dual challenges of environmental preservation and material supply in Burkina Faso and similar contexts.

Keywords

Concrete, Crushed Granite Sand, River Sand, Mechanical Performance,

Local Construction Materials

1. Introduction

Concrete is the most widely used construction material. Its widespread use is attributed to its excellent mechanical performance, his long service life and his relatively low cost compared with other structural materials. As rapid urbanization, population growth, and infrastructure development continue to increase in developing countries, concrete demand is projected to rise steadily over the coming decades. Already, demand for concrete constituents, especially aggregates, has reached unprecedented levels. Aggregates account for 70% - 80% of concrete volume, whereas fine aggregates represent 30% - 40% and play a crucial role in determining its fresh and hardened properties. Owing to its favorable grading and workability characteristics, natural river sand (NS) has traditionally been preferred for concrete production. However, the supply of high-quality natural sand is becoming increasingly scarce in many regions, leading to a significant increase in construction costs. Moreover, the intensive and often uncontrolled extraction of river deposits causes severe environmental impacts, including resource depletion, riverbank erosion, ecosystem destabilization, and loss of riparian vegetation [1] [2]. In response, several countries have restricted or prohibited the overexploitation of marine and river sand, thereby encouraging the exploration of sustainable local alternatives, such as crushed quarry materials.

In Burkina Faso, recent studies on mining-induced land-use changes have revealed a significant expansion of quarry areas around major cities over the past decades. A total of 257 extraction sites have been identified, of which 48% were gravel quarries, 47% clay quarries, and the remainder granite and sand quarries [3]. Despite this growth, crushed sand produced as a byproduct in gravel plants remains largely underutilized in concrete production. Its current use is mostly limited to secondary applications such as curbstones, paving blocks, and certain geotextiles. In the absence of established technical guidelines or market outlets, large volumes of this material are stockpiled at production sites without being fully valorized. This underutilization stands in stark contrast to the growing demand for concrete sand and mounting supply constraints of natural river sand. Furthermore, the cost of concrete can be reduced by increasing the amount of crushed stone sand [4].

Several researchers have reported that CGS can serve as a viable alternative to NS in concrete production, with most studies focusing on strength-related parameters [5]-[9]. The improved performance has generally been attributed to the angular shape of CGS particles and their filler effect, which enhances particle packing and the interfacial transition zone [10] [11].

However, the performance of crushed sand concrete is highly dependent on the mineralogical characteristics of the parent rock, particle size distribution, fines content, and local mix design practices. Consequently, results reported for one geographical region cannot be directly applied elsewhere. In Burkina Faso, despite the abundance of granite quarry by-products, their use in structural concrete remains limited. Moreover, only a few studies have investigated both the mechanical performance and durability of concrete made with locally available CGS. This lack of local scientific evidence has limited its acceptance in engineering practice and national construction specifications.

Therefore, this study aimed to experimentally evaluate the feasibility of replacing NS with locally produced CGS in Grade 25 hydraulic concrete, which is the most commonly specified concrete class for building and civil engineering applications in Burkina Faso. A target 28-day compressive strength of 25 MPa was selected to represent typical construction practice. The investigation assessed the influence of CGS on fresh properties, density, porosity, compressive and splitting tensile strengths, ultrasonic pulse velocity, capillary water absorption, and resistance to sulfuric acid attack.

2. Material and Methods

2.1. Material Used

The crushed aggregates used in this study were obtained by crushing granite rock extracted from the GLOBEX Construction quarry, located approximately 20 km from the city of Ouagadougou in Burkina Faso. Three main aggregate fractions were produced at this site: sand 0/4 (CGS), gravel 5/15 and coarse gravel 15/25. The physical and mechanical properties of coarse aggregates are listed in **Table 1**.

Table 1. Physical and mechanical properties of crushed granite aggregates.

Properties	Aggregate size 5 - 15 (mm)	Aggregate size 15 - 25 (mm)
Maximum size (mm)	15	25
Bulk Density (kg/m^3)	1510	1450
Specific density (kg/m^3)	2630	2570
Los Angeles abrasion value (%)	22.1	22.1
Water absorption (24 h) (%)	2.47	2.74

Natural river sand (NS) was used as the reference fine aggregate. It was collected from the Dakola River, which is located approximately 100 km from Ouagadougou. To ensure equivalent experimental conditions for crushed granite sand (CGS), the NS was sieved to 4 mm and washed to remove impurities, such as clay, silt, and organic debris. Particle size analysis of the aggregates was performed in accordance with NF EN 933-1 [12]. The resulting gradation curves are presented in **Figure 1** which shows the grain size distributions of both NS and CGS.

Both sands exhibited well-graded particle size distributions, with a uniformity coefficient (Cu) greater than 2 and a curvature coefficient (Cc) close to 1, indicating a lack of pronounced predominance of any single fraction. This continuity reflects a favorable particle arrangement that enables the formation of a dense granular skeleton in the concrete. As shown in **Table 2**, the fineness moduli of the two sands range between 2.8 and 3.2, indicating a predominance of coarse particles. Such grading is expected to produce high-strength concrete with a reduced workability. It is also noted that CGS contains a higher fines content (6.29%), which effectively fills the voids between coarse aggregates, whereas NS, with only 0.76%, plays a much less significant role in this respect within the concrete matrix.

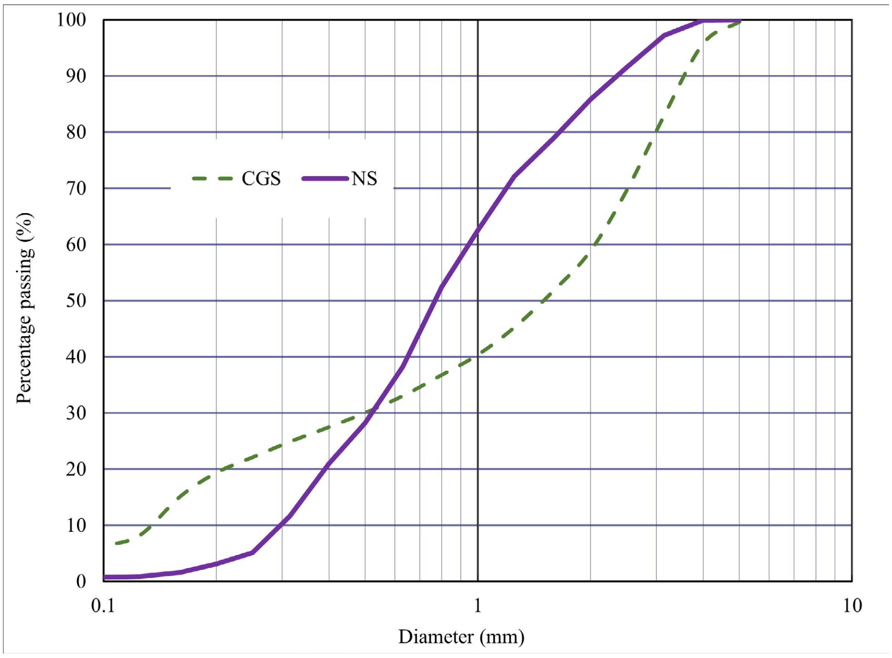

Figure 1. Gradation of the natural sand (NS) and sand from crushed granite (CGS).

Table 2. Physical properties of NS and CGS.

Properties	Crushed granite sand (CGS)	Natural Sand (NS)
Maximum size (mm)	4	4
Bulk Density (kg/m^3)	1620	1590
Specific density (kg/m^3)	2640	2540
Finess modulus	3.12	2.85
Water absorption (24 h) (%)	9.16	5.27

The binder used was CEM II/B-M (P-L) 42.5 N cement, locally produced by CIM BURKINA, in accordance with EN 197-1 [13]. Mixing water was supplied by the local distribution network. A modified acrylic polymer-based superplasticizer, acting as a rheology modifier, was incorporated to enhance the workability of the concrete.

The concrete mix design was established following the Dreux-Gorisse method, which is widely employed in local construction practices for optimizing the granular skeleton. Trial mixes were initially performed and subsequently adjusted to meet the practical workability requirements. The final nominal mixing proportions are listed in **Table 3**.

Five concrete mixtures were prepared by substituting natural river sand (NS) with crushed granite sand (CGS) at replacement levels of 0%, 25%, 50%, 75%, and 100% by mass. To ensure consistency while maintaining a constant water-to-cement ratio, the dosage of the superplasticizer was adjusted for each mixture.

Immediately after casting, all specimens were covered with a plastic sheet to minimize moisture loss and stored in the laboratory at room temperature. After 24 h, the specimens were demolded and cured by immersion in water at 20˚C ± 2˚C until the designated testing age.

Table 3. Mix proportions of the concrete.

Mixture	% of CGS	Cement (kg/m^3)	NS (kg/m^3)	CGS (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	S[a] (%)
CGS0	0%	350	681.1	0.0	1131.6	164	0.6
CGS25	25%	350	518.4	172.8	1129.8	164	0.8
CGS50	50%	350	358.7	358.7	1111.9	164	0.9
CGS75	75%	350	186.7	560.1	1093.1	164	1.0
CGS100	100%	350	0.0	816.0	1023	164	1.6

[a]. Superplasticizer.

2.2. Methods

Several tests were conducted to determine the physical and mechanical properties of the prepared concrete specimens. For each concrete mixture, three specimens were prepared for every test. The reported values correspond to the average of the three measurements.

Fresh concrete density was measured immediately after mixing using a standardized container of known volume. Different specimen geometries were used according to the other test requirements. Cylindrical specimens of 100 mm diameter × 200 mm height were used for compressive strength, splitting tensile strength, and ultrasonic pulse velocity (UPV) tests. Specimens 100 mm in diameter and 100 mm height were prepared for dry density, apparent porosity, and capillary water absorption measurements. For the acid attack test, the same diameter specimens and 50 mm in height were used.

Compressive strength, splitting tensile strength, UPV measurements, dry density, apparent porosity, and capillary water absorption were determined after 28 days of curing. The resistance to sulfuric acid attack was performed on concrete specimens after 90 days of water curing.

A one-way analysis of variance (ANOVA) was performed to evaluate the effect of crushed granite sand CGS replacement on the measured concrete properties. When significant differences were detected ($p < 0.05$), Tukey's honestly significant difference test was used for pairwise comparisons between mixtures.

2.2.1. Fresh Concrete Density

The fresh density of the concrete was determined using the gravimetric method, which involves filling a standardized container of known volume with freshly mixed concrete and compacting it in successive layers. The filled container was then weighed and the density was calculated as the ratio of the measured mass to the container volume. This parameter provides an indication of the degree of compaction and homogeneity of the fresh mix and plays a key role in predicting the mechanical performance and durability of hardened concrete.

2.2.2. Dry Density and Apparent Porosity

The dry density and apparent porosity of the concrete specimens were determined using the gravimetric method following the general procedure described in ASTM C642 [14] and RILEM recommendations. Each specimen was first oven-dried at 105˚C ± 5˚C until a constant mass was achieved and the dry mass (Md) was recorded. The samples were then fully saturated with water under vacuum and subsequently weighed under two conditions: suspension in air (Mo) and immersion in water (Mw). These mass measurements were introduced into equations Equation (1) and Equation (2) to calculate the dry density and apparent porosity of the concrete. This method enables a reliable assessment of the pore volume accessible to water, providing an indirect indicator of concrete durability.

$$\rho_d = M_d * \rho_\omega / (\text{Mo} - \text{Mw}) \tag{1}$$

$$\varepsilon = (\text{Mo} - \text{Md}) / (\text{Mo} - \text{Mw}) \tag{2}$$

where ρ_d is the apparent density of the concrete sample, ρ_ω is the density of water, and ε is the apparent porosity of the concrete sample.

2.2.3. Mechanical Tests of Concretes

Compression tests were performed in accordance with NF EN 12390-3 [15]. The properties were determined after 28 days. A hydraulic press with a maximum capacity of 2000 kN at a constant speed load (0.5 MPa/s) was used.

The indirect tensile strength of concrete was evaluated using the splitting tensile test, also known as the Brazilian test, in accordance with the relevant standard [16]. In this procedure, a cylindrical specimen was placed horizontally between the platens of a testing machine and loaded along two opposite sides until failure.

An UPV test was performed. This is a nondestructive test that assesses the compactness and potential strength of concrete by measuring the travel time of ultrasonic waves through the material. This test method can be used to assess the uniformity and relative quality of concrete and to indicate the presence of voids and cracks. The device consisted of a pulse generator equipped with a transmitter, receiver, and timing system that recorded the interval between the emission and detection of pulses. In this study, the test was conducted using a Pundit apparatus (**Figure 2**) in accordance with ASTM C597 [17]. Once the specimen with flat faces was placed between the transducers and the specimen height was entered, the ultrasonic pulse velocity was directly displayed on the screen in meters per second (m/s).

Figure 2. Experimental device of the ultrasonic pulse velocity test.

2.2.4. Capillary Water Absorption Test

The water absorption test was conducted in accordance with the RILEM TC 116-PCD recommendations [18], which specify the determination of capillary water absorption in concrete. This method evaluates the rate of mass increase in a specimen as a function of time, resulting from water absorption when only one surface is exposed to water.

In this study, the procedure was applied to cylindrical specimens measuring 100 mm in diameter and 100 mm in height. Each specimen was placed in a shallow water container with an immersion depth not exceeding 3 mm. The cylindrical side surfaces were carefully sealed to ensure unidirectional water flow and to prevent lateral evaporation. The amount of absorbed water was determined by successively weighing the specimens at predetermined time intervals. The results are expressed as the absorbed water per unit surface area (kg/m^2) and plotted as a function of the square root of time. The results provide an index of the capillary porosity and transport properties of concrete.

2.2.5. Resistance to Acid Attack

An acid resistance test was conducted on the concrete specimens to quantify the mass loss induced by sulfuric acid (H_2SO_3) exposure. Cylindrical samples with a diameter of 10 cm and height of 5 cm were first saturated in water and then immersed in a sulfuric acid solution with a pH of 3. Sulfuric acid was selected because it is one of the most common acids in the environment (acid rain, industrial effluents, groundwater, agricultural fermentation residues, etc.) and is a major cause of concrete degradation [19]. The pH of the solution was monitored and maintained at 3 (±0.01) throughout the experiment. Mass loss was evaluated after 7, 14, 21, and 28 days of immersion. It was expressed as a percentage of the initial mass of each specimen according to the following relationship (Equation (3)):

$$ML = (Mo - Mt) * 100 / Mo \quad (3)$$

where Mo is the initial mass of the specimen (g) and Mt, the mass of the specimen after t days of immersion in the acid solution.

3. Results and Discussion

3.1. Fresh Concrete Density

The density of fresh concrete is shown in Figure 3.

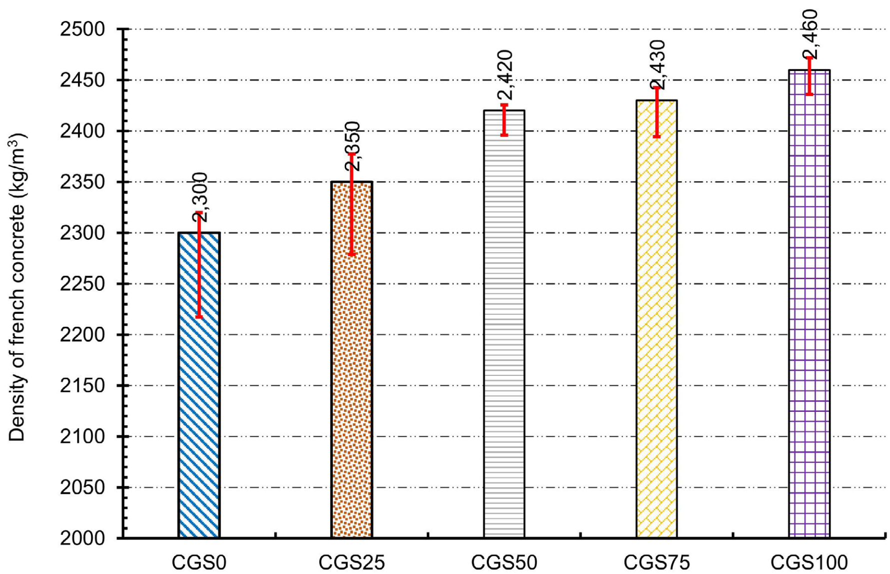

Figure 3. Density of fresh concrete.

The results indicate that the fresh density of concrete increases progressively with the replacement level of NS by CGS. This trend can be attributed to the higher specific gravity of CGS compared to that of NS, which directly contributes to the greater unit weight of the mixtures. In addition, the angular particle shape and well-graded distribution of the CGS enhance the packing of the granular skeleton, resulting in reduced intergranular voids and improved compactness of the fresh mix. The angularity and higher surface area of the CGS particles tends to reduce the workability of the mixes, as reflected by the lower slump values, necessitating the use of more superplasticizers (Table 3). However, the ANOVA results revealed that the differences among mixtures were not statistically significant ($p = 0.108$), indicating that the observed increase should be interpreted as a general tendency rather than a conclusive effect of CGS incorporation.

3.2. Dry Density and Apparent Porosity

The evolution of the apparent dry density is presented in Figure 4(a). The results show a slight increase in dry density with increasing replacement of NS by CGS.

The average dry density increased from 2362 kg/m³ for the reference concrete (CGS0) to 2412 kg/m³ for CGS100. The one-way ANOVA indicated that the differences among mixtures were not statistically significant ($p > 0.05$). Therefore, although the increase in dry density is observed in this study, it should be interpreted as a general tendency rather than a statistically confirmed effect of CGS incorporation.

Figure 4(b) shows the variation in the porosity accessible to water of concrete as a function of the CGS replacement level. The reference mix CGS0 exhibited the highest porosity (≈9.6%). As the substitution rate of CGS increased, a progressive reduction in porosity was observed, reaching a minimum value of approximately 8.2% at CGS75. This trend reflects the beneficial effect of CGS in improving the granular skeleton and filling intergranular voids more efficiently, thereby limiting the connectivity of the capillary pores.

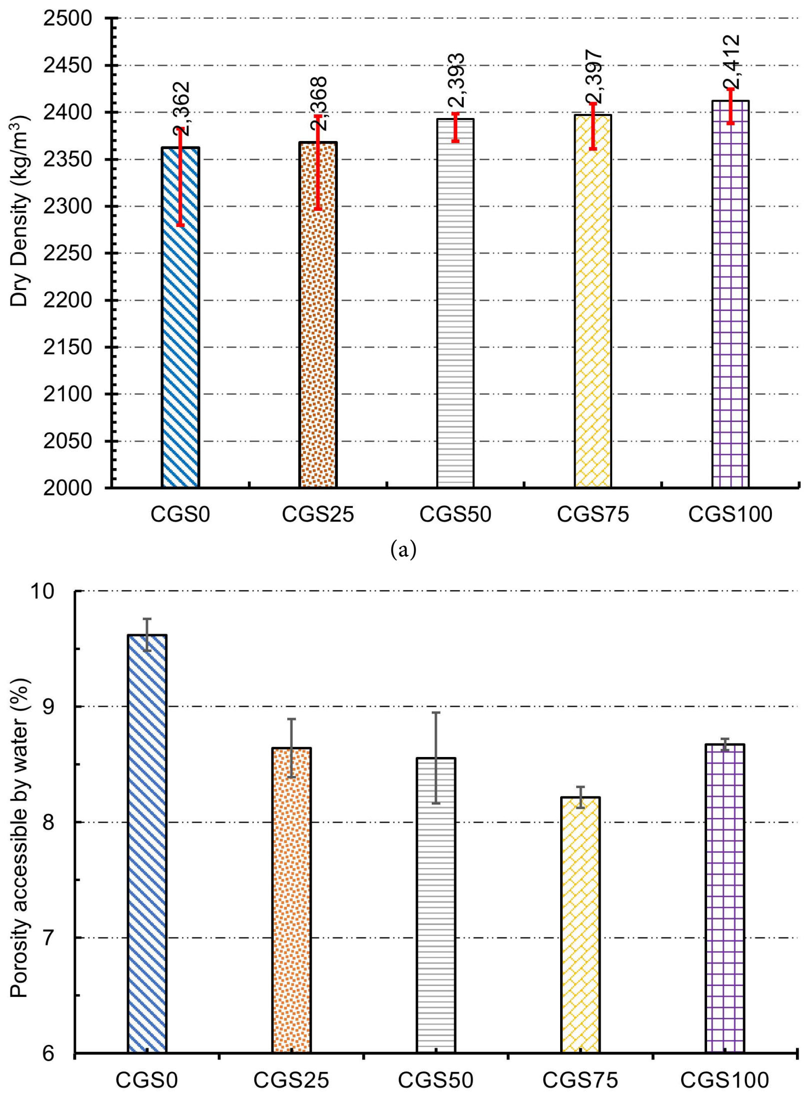

Figure 4. Dry density (a) and Porosity accessible by water of concrete specimens (b).

At 100% substitution, porosity increased slightly (≈8.7%), but it remained lower than that of the reference mix CGS0. This moderate rise can be attributed to the angular particle shape and relatively high fines content of CGS. While these characteristics generally enhance particle interlock and packing efficiency, they also increase the specific surface area and consequently the water demand of the mixture. When this additional water requirement is not fully compensated through mix adjustment, the formation of residual microvoids may occur, leading to a slight increase in porosity. In contrast, the minimum porosity observed at CGS75 substitution indicates an optimal granular packing state. At this substitution level, the fine particles of CGS effectively fill the intergranular voids created by coarser particles, resulting in a denser and more homogeneous matrix without excessive water demand.

The ANOVA results indicated that CGS replacement significantly influenced the porosity accessible to water of concrete ($F = 9.10$, $p = 0.002$). Tukey's test showed that CGS100 exhibited significantly lower porosity than the other mixtures CGS25, CGS50 and CGS75 ($p < 0.05$). That's confirm the beneficial effect of crushed granite sand on concrete densification.

3.3. Mechanical Properties

The compressive strengths of the concrete specimens after 28 days are shown in Figure 5. All mixtures significantly exceeded the target strength of B25 concrete, with a steady increase in compressive strength as the substitution rate increased. The lowest strength is observed for the reference mix (CGS0) with 30.6 MPa, while the mixtures incorporating CGS show significantly higher values, reaching a maximum of 39.3 MPa for CGS100. That represents a gain of nearly 28%. ANOVA revealed a statistically significant effect of CGS replacement on the compressive strength of concrete ($F = 14.24$, $p < 0.001$). Tukey's post hoc test indicated that the concrete CGS100 exhibited significantly higher compressive strength than all other mixtures ($p < 0.05$). Conversely, no statistically significant differences were

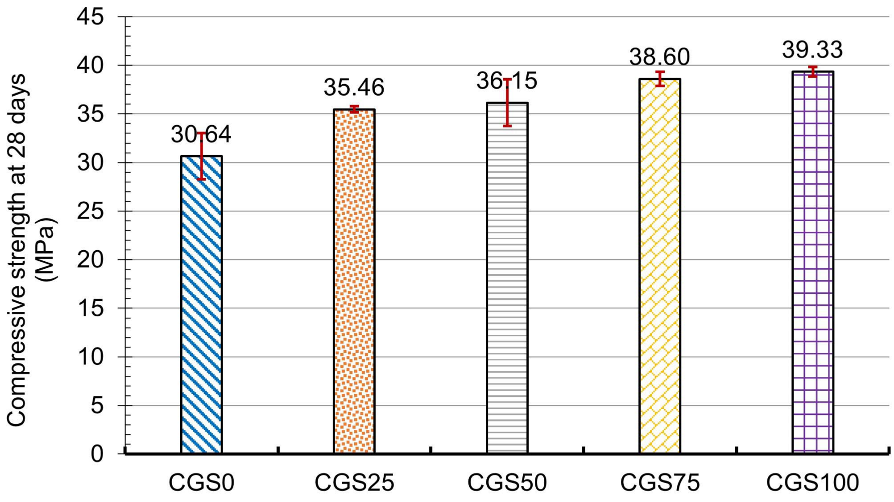

Figure 5. Compressive strength at 28 days.

observed among the intermediate replacement levels (CGS25-CGS75), suggesting that although compressive strength increased progressively with CGS content, only complete replacement produced a statistically distinct improvement.

This improvement in compressive strength can mainly be attributed to the enhanced particle packing provided by the crushed granite sand, its higher fines content, and the rough texture of the particles, which promotes a stronger bond between the cement paste and aggregates. These results are consistent with those of previous studies [20]-[22]. Previous studies have shown that fine mineral particles can improve cement hydration through filler and nucleation effects. By providing additional surfaces for the precipitation of hydration products, these particles may accelerate the formation of C-S-H and contribute to a denser microstructure [23] [24]. Recent reviews have further confirmed that finely divided mineral additions can enhance hydration kinetics and refine pore structure through physical filling and nucleation mechanisms [25] [26]. However, since no mineralogical or microstructural characterization was performed in the present study, these mechanisms are discussed only as potential explanations reported in the literature rather than direct evidence from the current investigation.

The results of the tests reported a gradual increase in the splitting tensile strength as the percentage of CGS increased (**Figure 6**). The strength increased from 4.845 MPa for CGS0 to 5.16 MPa for CGS100, corresponding to an overall improvement of approximately 6.5%. The highest strength was achieved with the complete replacement of natural sand, indicating that the alternative aggregate offered superior performance under tension. But, no statistically significant differences were observed among the five mixtures (F = 1.46, p = 0.286). Although the slight increase in the average tensile strength with increasing CGS content, the observed variations remained within the experimental variability.

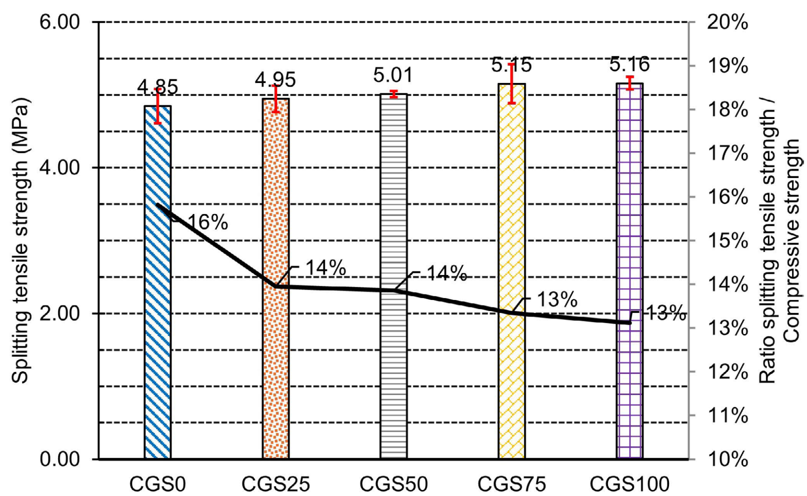

Figure 6. Splitting tensile strength results.

The tensile-to-compressive strength ratio was approximately 16% for concrete containing 100% natural sand and decreased progressively with sand substitution, reaching about 13% at full replacement. This reduction reflects the greater rigidity of concretes incorporating CGS, in which the increase in compressive strength is more pronounced than that in tensile strength. Consequently, although CGS concretes exhibit higher strength, they may display a more brittle failure behavior.

Finally, the ultrasonic pulse velocity measurements (**Figure 7**) show a clear increase with the substitution of NS by CGS compared to the reference concrete. ANOVA revealed that UPV was also significantly affected by the replacement level ($F = 11.28$, $p = 0.001$). Pairwise comparisons revealed that CGS100 achieved significantly higher pulse velocities than the reference concrete and CGS25 ($p < 0.05$), while no significant differences were found among the intermediate replacement levels.

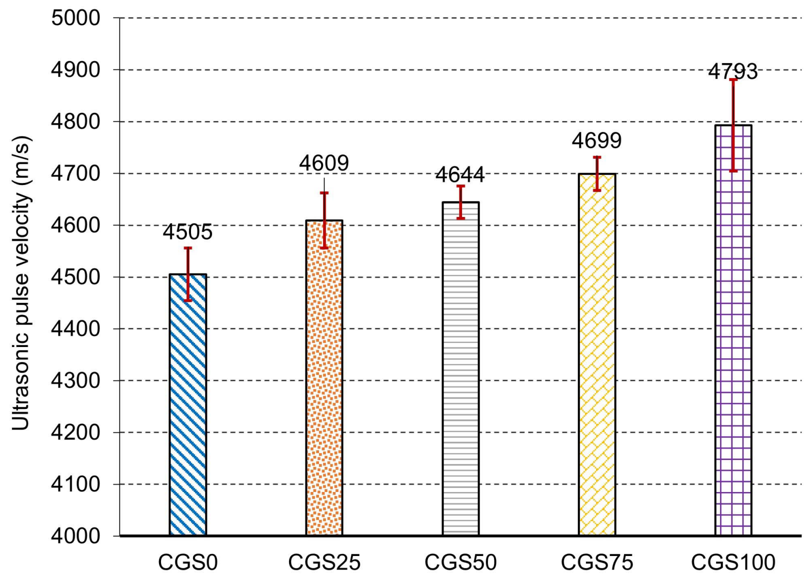

Figure 7. Ultrasonic pulse velocity results.

The UPV technique is widely used to assess concrete quality by evaluating material homogeneity, detecting cracks, voids, and internal defects, and monitoring structural changes that may develop over time. Since ultrasonic pulse velocity is closely related to the compactness and elastic modulus of concrete [20], the higher UPV values obtained confirm that concretes incorporating CGS exhibit a denser internal structure and improved overall quality. These findings are in good agreement with the observed enhancements in mechanical strength.

3.4. Durability

3.4.1. Capillary Water Absorption

Figure 8 shows the variations in the quantity of water absorbed per unit area according to the square root of time for the tested concrete. This indicates that the capillary absorption coefficient decreases with increasing replacement of NS with CGS.

CGS0 exhibited the highest absorption, whereas CGS100 exhibited the lowest.

This trend was attributed to the finer fraction of CGS, which improved particle packing, reduced pore connectivity, and enhanced matrix compactness. Singh *et al.* [27] observed that water absorption of concrete samples containing granite custing waste reduced up to a substitution level of 55%. The fine particles of CGS enhanced the densification of the concrete matrix, thereby leading to lower water absorption. Other authors demonstrated that at the same w/c ratio, the water absorption and sorptivity of the concrete mixes decrease with increasing percentage of granite powder up to 50% replacement of natural fine aggregate [28].

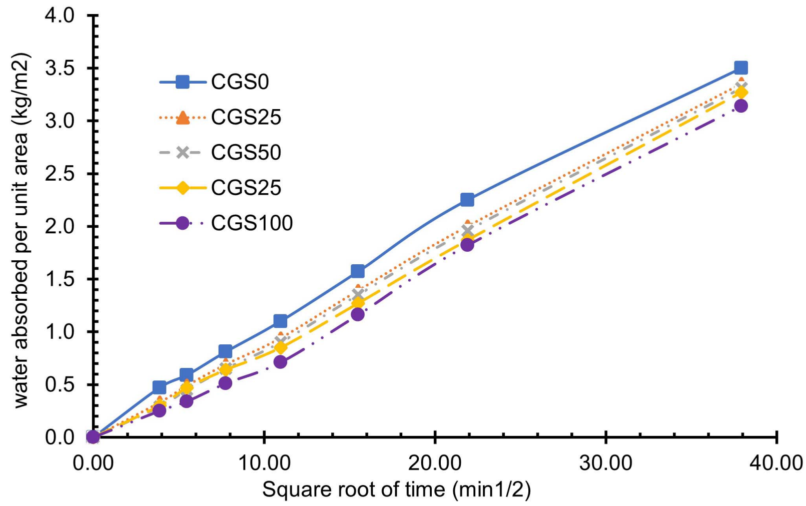

Figure 8. Kinetics of absorption of concrete.

3.4.2. Resistance to Acid Attack

Figure 9 illustrates the mass loss of the different concrete mixtures exposed to sulfuric acid over time.

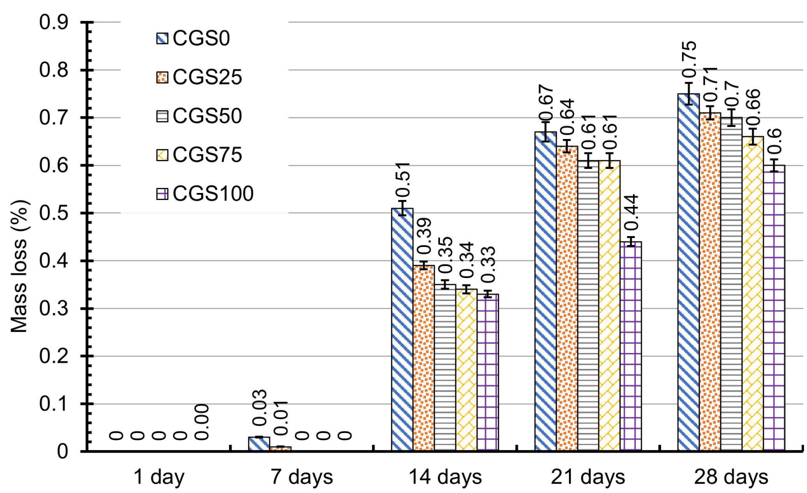

Figure 9. Mass loss for acid attack test.

The results show that the control concrete formulated with 100% river sand (CGS0), undergoes the highest mass losses, reaching 0.51%, 0.67%, and 0.75% at

14, 21, and 28 days, respectively. In contrast, increasing the substitution rate with CGS significantly reduced mass loss. CCGS100 recorded values of 0.33%, 0.44%, and 0.60% at the same ages, corresponding to reductions of 35%, 34%, and 20% compared with the control mix at 14, 21, and 28 days respectively.

4. Conclusions

This study demonstrates that Crushed Granite Sand (CGS) is a technically sound and sustainable alternative to Natural River Sand (NS) in concrete formulations. The results imply that replacing NS with CGS improved both mechanical and durability-related properties. The highest performance was achieved with CGS100, which exhibited the greatest compressive strength together with lower porosity, reduced capillary water absorption, higher ultrasonic pulse velocity, and improved resistance to acid attack.

From a practical perspective, however, CGS75 appears to provide the most balanced solution. Although CGS100 delivered the best overall performance, the additional gains obtained beyond 75% replacement were relatively limited compared with the substantial increase in superplasticizer demand required to maintain the target workability. Consequently, CGS75 offers an attractive compromise between mechanical performance, durability, workability, and admixture consumption, making them particularly suitable for routine construction applications.

The results highlight the potential of CGS to reduce dependence on natural river sand while simultaneously valorizing locally available quarry by-products. Wider adoption of CGS could therefore contribute to more sustainable concrete production and improved resource management in Burkina Faso and similar regions.

Further research should investigate the long-term durability of CGS concrete under aggressive environmental conditions, as well as its microstructural characteristics and performance in reinforced concrete applications. Such studies would provide additional support for the development of technical specifications and national standards promoting the use of crushed granite sand in structural concrete.

Author Contributions

Conceptualization, N.S. and A.M.; methodology, Y.B.T., N.S. and P.N.; validation, A.M.; formal analysis, Y.B.T; investigation, Z.S.; data curation, Y.B.T; writing: original draft preparation, Y.B.T; writing: review and editing, N.S., P.N. and A.M.; visualization, N.S.; supervision, A.M.; project administration, A.M.; All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

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

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