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EFFECT OF PARTIAL REPLACEMENT OF RIVER SAND WITH QUARRY DUST ON THE WORKABILITY AND COMPRESSIVE STRENGTH OF CONCRETE

By

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Abstract

The increasing demand for natural river sand for concrete production has created a need for alternative fine aggregates that can reduce dependence on naturally occurring resources while maintaining satisfactory concrete performance. This study investigated the effect of partial replacement of river sand with quarry dust (QD) on the grading characteristics, fresh-concrete workability and compressive-strength development of concrete. River sand was progressively replaced with QD at 0–100% in 10% increments, while the other mix parameters were maintained under the experimental conditions of the study. Aggregate grading was characterized, and the fresh concrete was evaluated using slump and compaction-factor tests. Compressive strength was determined at 7, 14, 21 and 28 days using four replicate specimens for each combination of QD replacement and curing age. The results showed that increasing QD content progressively reduced slump, indicating increasing restriction of fresh-concrete mobility. Compaction factor increased to a maximum at 50% QD replacement before declining at higher replacement levels. Compressive strength followed a similar optimum response: strength increased progressively up to 50% QD and subsequently decreased. The 50% QD mixture recorded the highest mean compressive strengths of 22.65, 24.50, 25.13 and 27.10 N/mm² at 7, 14, 21 and 28 days, respectively, compared with 19.33, 21.20, 22.30 and 24.50 N/mm² for the control concrete. Two-way analysis of variance confirmed highly significant effects of both QD replacement and curing age on compressive strength ($p < 0.001$), with a significant QD replacement × curing-age interaction. The findings indicate that moderate QD incorporation can provide a favourable balance between aggregate packing and fresh-state behaviour, while excessive replacement becomes detrimental to workability and strength. Under the conditions investigated, 50% QD replacement represents the optimum level.

Keywords: *Quarry dust; river sand; concrete; workability; compressive strength; fine aggregate replacement; sustainable construction*

1. INTRODUCTION

Concrete is one of the most widely used construction materials because of its versatility, durability and relatively low cost. Fine aggregate, conventionally obtained from natural river sand, is an important component of concrete and contributes to the packing and workability of the fresh mixture. Increasing demand for construction sand, however, has intensified river-sand extraction, with associated environmental impacts including riverbed degradation, bank erosion and disturbance of aquatic ecosystems. The environmental consequences of intensive sand extraction have been documented in relation to river systems and their associated ecosystems (Padmalal & Maya, 2014). The increasing demand for suitable fine aggregate therefore creates a need to investigate alternative materials that can reduce dependence on natural river sand.Quarry dust (QD) is a fine by-product generated during the crushing and processing of rocks for aggregate production. Its angular particles and relatively rough surfaces distinguish it from naturally occurring river sand and can influence both aggregate packing and the behaviour of fresh and hardened concrete. However, instead of considering it as a waste material, there is a productive use of a material produced in

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large quantities during quarrying operations, as QD can be used as a fine aggregate replacement in concrete (AL-Kharabsheh et al., 2022).

Previous studies have shown the potential of QD to partially replace the river sand in cement-based materials. Balamurugan and Perumal (2013) reported that partial replacement of sand by QD could improve the compressive strength of concrete and the response is dependent on the replacement level. Similarly, Rajapaksha and Sooriyaarachchi (2009) studied the use of QD as a substitute for river sand and confirmed its possibility as a fine aggregate in concrete. More recent studies also demonstrated that QD can be effectively incorporated into cement masonry blocks affecting the mechanical and durability characteristics (Sundaralingam et al., 2022).

The engineering effect of QD replacement is nevertheless not necessarily linear. The finer particles introduced by QD can modify the grading and packing characteristics of the aggregate system. At appropriate replacement levels, this may contribute to a denser granular arrangement and improved mechanical performance. However, increasing QD content also increases the proportion of fine particles and, consequently, the surface area requiring wetting. This may increase the water demand and negatively affect the workability of the fresh concrete. Therefore, the balance between these competing effects is important in determining the replacement level at which QD provides the most favorable overall performance (Rajapaksha & Sooriyaarachchi, 2009; AL-Kharabsheh et al., 2022).

Research in Nigeria has also demonstrated the potential of QD in cement-based construction materials. For example Anya and Osadebe (2015) studied the partial replacement of sand with QD in sandcrete blocks and observed changes in structural performance with increasing replacement. Aliyu et al. (2021) also investigated the use of quarry dust in cement–sand mortar. These studies demonstrate the growing interest in quarry-derived fines as alternative materials in Nigerian construction, but the behaviour of QD as a replacement for river sand in concrete requires further systematic investigation under locally relevant material and mixture conditions.

An important consideration is that the optimum QD content cannot necessarily be generalized across different concrete mixtures. Aggregate grading, particle shape, material characteristics, water/cement ratio and curing conditions can all influence the response of the resulting concrete. Consequently, a systematic investigation covering a broad range of replacement levels is useful for establishing the point at which the potential benefits of QD incorporation are outweighed by its effects on fresh-concrete workability and hardened performance.

The present study therefore investigates the effect of replacing river sand with QD over a broad range of 0–100% replacement, using eleven replacement levels at 10% intervals. The study evaluates the particle-size characteristics of the aggregate materials, the influence of QD replacement on fresh-concrete workability using slump and compaction-factor tests, and the development of compressive strength at 7, 14, 21 and 28 days. Four replicate concrete cubes were tested for each combination of replacement level and curing age, providing the basis for evaluating the variability of the measured compressive-strength response.

The specific objectives of the study were to: (i) characterize the physical and particle-size-distribution properties of the aggregate materials; (ii) determine the effect of QD replacement on the workability of fresh concrete; (iii) evaluate the development of compressive strength over the range of QD replacement levels and curing ages investigated; and (iv) identify the replacement level that provides the most favourable balance between fresh-concrete workability and hardened-concrete strength.

The study consequently seeks to establish whether QD can provide an effective partial replacement for river sand under the specified experimental conditions and, importantly, to determine the replacement range within which its incorporation is beneficial rather than simply assuming that increasing QD content will continuously improve concrete performance.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in the experimental programme were cement, river sand, quarry dust, crushed granite coarse aggregate and water. All aggregates were locally sourced in Abia State, southeastern Nigeria. Ordinary Portland Cement (Elephant brand, Grade 53) was obtained from Timber and Building Market, Aba. The cement had a measured specific gravity of 3.15.

The fine aggregates comprised sharp river sand obtained from Aba waterside and quarry dust obtained from Uturu. The aggregates were oven-dried at 105 ± 5°C for 24 h and subsequently sieved before batching. Crushed granite obtained from Uturu was used as coarse aggregate. Potable water obtained from the laboratory water supply was used for mixing and curing.

2.2 Characterisation of Aggregate Materials

Particle-size distribution was determined by sieve analysis. Specific gravity and water absorption were also determined for the aggregate materials. The resulting grading and physical characteristics are consolidated in Table 1.

Table 1. Physical and grading characteristics of the aggregate materials

Property	Cement	River sand	Quarry dust	Granite	Unit
Specific gravity	3.15	2.65	2.65	2.70	–
Water absorption	–	1.70	2.10	0.80	%
Fineness	–	2.78	3.12	6.85	–

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modulus					
Passing 4.75 mm	–	98.85	99.34	–	%
Passing 0.075 mm	–	1.93	11.45	–	%

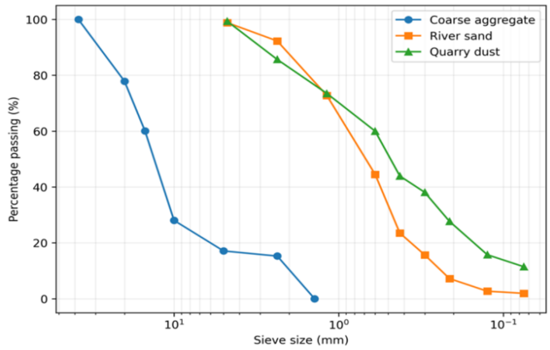

Figure 1. Particle-size distribution curves of the aggregate materials.

2.3 Mix Proportion and Experimental Programme

A nominal mix ratio of 1:1.5:3 (cement:fine aggregate:coarse aggregate) by mass was adopted with a fixed water/cement ratio of 0.50. River sand was replaced by quarry dust at 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100%. The total fine-aggregate mass was maintained at 4.60 kg per batch.A total of 176 concrete cubes measuring 100 mm × 100 mm × 100 mm were cast, comprising 11 replacement levels × 4 replicate specimens × 4 curing ages. The specimens were tested at 7, 14, 21 and 28 days. Workability was evaluated at selected replacement levels of 0%, 25%, 50%, 75% and 100%.

Table 2. Concrete mix proportions incorporating quarry dust

QD replacement (%)	Cement (kg)	QD (kg)	Sand (kg)	Coarse aggregate (kg)	Water (kg)
0	3.10	0	4.60	9.30	1.55
10	3.10	0.46	4.14	9.30	1.55
20	3.10	0.92	3.68	9.30	1.55
30	3.10	1.38	3.22	9.30	1.55
40	3.10	1.84	2.76	9.30	1.55
50	3.10	2.30	2.30	9.30	1.55
60	3.10	2.76	1.84	9.30	1.55
70	3.10	3.22	1.38	9.30	1.55
80	3.10	3.68	0.92	9.30	1.55
90	3.10	4.14	0.46	9.30	1.55
100	3.10	4.60	0	9.30	1.55

2.4 Testing Procedures

Slump and compaction-factor tests were used to assess fresh-concrete workability. For hardened concrete, the cubes were demoulded after 24 h and immersed in water maintained at 23 ± 2°C until the designated testing ages. Compressive strength was determined by dividing the maximum applied load by the cube cross-sectional area of 10,000 mm². The compression testing machine had a maximum capacity of 2000 kN and a loading rate of 3.0 kN/s.

2.5 Statistical Analysis

The four individual compressive-strength measurements for each QD replacement level and curing age were treated as the primary observations. Mean, sample standard deviation (SD) and coefficient of variation (CV) were calculated for each condition. A two-way analysis of variance was used to evaluate the effects of QD replacement, curing age and their interaction on compressive strength. Statistical interpretation was based on the replicate observations rather than on the pre-existing averages. Unusual individual measurements were retained because independent laboratory evidence was not available to justify their removal.

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3. RESULTS AND DISCUSSION

3.1 Particle-Size Distribution and Aggregate Characteristics

The aggregate grading characteristics provide the physical basis for interpreting the subsequent workability and strength responses. The river sand had a fineness modulus of 2.78, whereas the quarry dust had a higher fineness modulus of 3.12. More importantly, only 1.93% of the river sand passed the 0.075 mm sieve compared with 11.45% for the quarry dust. The QD was therefore appreciably richer in fine particles than the river sand.

The particle-size-distribution curves in Figure 1 further demonstrate the difference between the two fine aggregates. Quarry dust consistently contains a larger proportion of particles in the finer size range. This difference is important because replacing river sand with QD changes both the grading and the total surface area of the fine-aggregate system. At moderate replacement levels, the additional fines can improve packing of the granular skeleton; at high replacement levels, however, the increased fine fraction can increase water demand and restrict fresh-concrete mobility. This explanation agrees with the reported observations that QD can provide beneficial packing while increasing the water required to achieve a specified workability (Rajapaksha & Sooriyaarachchi, 2009; AL-Kharabsheh et al., 2022).

3.2 Fresh-Concrete Workability

The workability response is summarized in Table 3 and Figure 2. Slump decreased progressively from 31 mm at 0% QD to 6 mm at 100% QD. The compaction factor, in contrast, increased from 0.81 at the control condition to 0.84 at 50% QD before declining to 0.82 at 100% QD.

The decrease of slump gradually indicates that the increase of QD limits the mobility of the fresh concrete gradually. The response is consistent with the higher fine-particle content of QD, which increases the surface area to be wetted and decreases the free water available for particle lubrication. Similar increases in water demand with inclusion of QD have been reported previously (Rajapaksha & Sooriyaarachchi, 2009; Sundaralingam et al., 2022).

The compaction-factor response is particularly informative because it does not decrease monotonically. The increase from 0.81 to 0.84 up to 50% QD suggests that moderate incorporation of the finer material can improve the packing and cohesiveness of the fresh granular system. Beyond 50%, the compaction factor decreases, indicating that the increasing fine fraction begins to impose a stronger workability penalty than the packing benefit can compensate for. Thus, the fresh-state results point to an intermediate replacement range as the most favourable balance between packing and mobility.

Table 3. Workability characteristics of fresh concrete

QD replacement (%)	Slump (mm)	Compaction factor	Workability rating
0	31	0.81	Medium
25	22	0.83	Low–Medium
50	15	0.84	Low
75	10	0.83	Very Low
100	6	0.82	Very Low

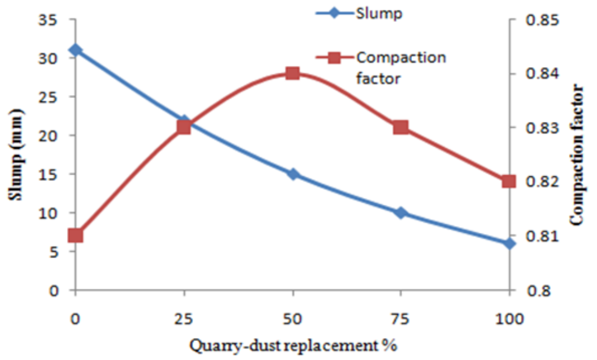

Figure 2. Effect of quarry-dust replacement on fresh-concrete workability: slump and compaction factor.

3.3 Compressive Strength Development

The compressive-strength results presented on Table 4 show a clear optimum response to QD replacement. At every curing age investigated, strength increased progressively from the control condition to 50% QD and then decreased as QD replacement increased further. The consistency of this response across 7, 14, 21 and 28 days indicates that the optimum is not an isolated age-specific result.

At 7 days, the mean strength increased from 19.33 N/mm² for the control to 22.65 N/mm² at 50% QD. The corresponding values at 14, 21 and 28 days were 21.20, 22.30 and 24.50 N/mm² for the control and 24.50, 25.13 and 27.10 N/mm² at 50% QD, respectively. The 28-day strength at 50% QD was therefore 10.61% higher than the control.

Beyond the optimum, strength decreased progressively. At 28 days, mean strength declined from 27.11 N/mm² at 50% QD to 24.82, 23.62, 22.77, 22.16 and 20.24 N/mm² at 60%, 70%, 80%, 90% and 100% QD, respectively. This post-optimum decline is consistent with the workability results: increasing QD beyond the intermediate range increases the fine-particle demand of the mixture while the water/cement ratio remains fixed.

The response is consistent with the filler and packing effects reported for QD concrete. At moderate replacement, finer particles can occupy voids within the aggregate skeleton and contribute to a denser arrangement. However, the same

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increase in fines can increase water demand and reduce workability at high replacement levels, resulting in a trade-off between packing benefit and fresh-state compactability (Balamurugan & Perumal, 2013; Rajapaksha & Sooriyaarachchi, 2009; AL-Kharabsheh et al., 2022). The optimum replacement observed here is also broadly comparable with the 50% optimum reported by Balamurugan and Perumal (2013), although other material systems have produced different optimum levels, emphasizing the dependence of the optimum on aggregate and mixture characteristics.

Curing age increased compressive strength across the replacement range. The control mixture increased from 19.27 N/mm² at 7 days to 24.51 N/mm² at 28 days, while the 50% QD mixture increased from 22.66 to 27.11 N/mm². The magnitude of the QD effect therefore varies with curing age rather than remaining constant.

Table 4. Mean compressive strength and variability of concrete at different curing ages

QD replacement (%)	7 days	14 days	21 days	28 days
0	19.33	21.20	22.30	24.50
10	19.61	21.44	23.08	24.91
20	20.44	22.06	23.20	25.31
30	20.97	22.90	23.78	25.82
40	21.31	23.28	24.45	26.39
50	22.65	24.50	25.13	27.10
60	20.33	23.06	23.08	24.81
70	19.31	21.37	21.88	23.61
80	18.21	19.98	20.91	22.76
90	17.71	19.39	20.20	22.20
100	16.25	17.40	18.35	20.33

3.3.1 Statistical Evidence

The two-way analysis of variance based on the four individual observations per experimental condition indicated highly significant effects of QD replacement and curing age on compressive strength ($p < 0.001$ for both factors). The QD replacement × curing-age interaction was also significant ($F(30,132) = 14.997$, $p < 0.001$), demonstrating that the magnitude of the QD effect varied with curing age. The corresponding partial effect sizes were very large for QD replacement ($\eta p^2 = 0.9969$) and curing age ($\eta p^2 = 0.9963$), while the interaction also represented a large effect ($\eta p^2 = 0.7732$).

The replicate variability was generally small relative to the corresponding mean strengths, although several conditions exhibited higher dispersion. For example, the 7-day 60% QD group had an SD of 0.27 N/mm² and the 14-day 60% QD group had an SD of 0.50 N/mm². These observations were retained in the analysis rather than removed without independent evidence of measurement error. the analysis rather than removed without independent evidence of measurement error.

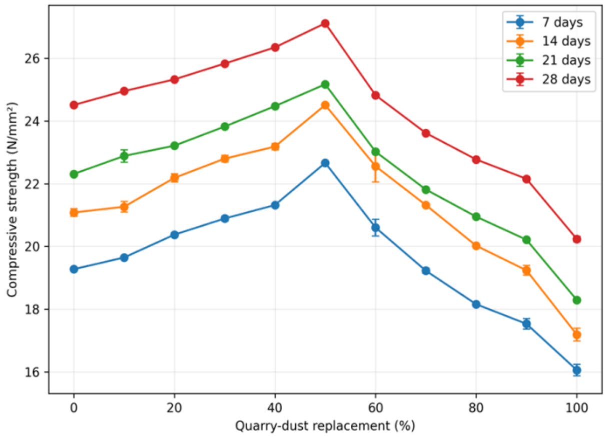

Figure 3. Effect of quarry-dust replacement on compressive strength at 7, 14, 21 and 28 days. Error bars represent ±1 standard deviation (n = 4).

3.4 Integrated Engineering Interpretation

The combined results demonstrate that the influence of QD on concrete performance cannot be explained by compressive strength alone. The response reflects the interaction among aggregate grading, fresh-concrete workability, curing age and hardened strength. The results indicate an initial beneficial effect of QD incorporation, followed by deterioration when the replacement level exceeds an intermediate optimum.

At low to moderate replacement levels, the additional fine particles introduced by QD modify the grading of the fine-aggregate system and can occupy voids between larger particles. This provides a plausible packing mechanism for the progressive increase in compressive strength from 0 to 50% QD. The strength increase occurs together with a reduction in slump, indicating that the packing benefit is accompanied by increasing demand on fresh-concrete mobility.

The optimum response occurs at 50% QD replacement. At this level, the concrete attained the highest mean compressive strength at every curing age: 22.65 N/mm² at 7 days, 24.50 N/mm² at 14 days, 25.13 N/mm² at 21 days and 27.10 N/mm² at 28 days. This consistent optimum indicates a favourable balance between the beneficial packing contribution of QD and the increasingly restrictive influence of its fine-particle content.

Beyond 50% replacement, the balance changes. Compressive strength decreases at 60–100% QD while fresh-state mobility becomes progressively more restricted. Under the fixed water/cement ratio used here, the larger quantity of fine particles increases the surface area requiring wetting. Consequently, the additional fines eventually impose a greater penalty on workability and effective consolidation than the packing benefit they provide. The strength reduction beyond the optimum is therefore consistent with a transition from packing-dominated behaviour at moderate QD contents to increasing water-demand and compactability constraints at high QD contents.

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The significant QD replacement × curing-age interaction further indicates that the magnitude of the QD effect depends on curing age. The optimum, however, remained at 50% at every age investigated. The finding should therefore be interpreted as the optimum under the specific materials, mixture proportions, water/cement ratio and curing conditions of this study rather than as a universal replacement limit.

4. CONCLUSIONS

i. Quarry dust was appreciably finer than the river sand used in the study. Its fineness modulus was 3.12 compared with 2.78 for river sand, and 11.45% passed the 0.075 mm sieve compared with 1.93% for the river sand.
ii. Increasing QD replacement progressively reduced slump from 31 mm at 0% replacement to 6 mm at 100% replacement. The compaction factor increased from 0.81 to 0.84 at 50% QD and then decreased to 0.82 at 100% showing an intermediate balance between better packing and increasing fine particle demand.
iii. Compressive strength increased with QD replacement up to 50% and subsequently decreased at all curing ages investigated. The 50% QD mixture recorded the highest mean strengths of 22.65, 24.50, 25.13 and 27.10 N/mm² at 7, 14, 21 and 28 days, respectively.
iv. At 28 days, the 50% QD mixture was 10.61% stronger than the control concrete, whereas complete replacement produced 20.33 N/mm², representing a 17.02% reduction relative to the 24.50 N/mm² control.
v. Two-way ANOVA based on the four individual observations for each experimental condition showed highly significant effects of QD replacement and curing age on compressive strength ($p < 0.001$), together with a significant QD replacement × curing-age interaction ($p < 0.001$).
vi. Under the materials, mix proportions, fixed water/cement ratio and curing conditions investigated, 50% replacement of river sand with quarry dust provided the most favourable overall balance between fresh-concrete behaviour and compressive strength. The result should not be generalized as a universal optimum for all concrete mixtures.

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