

Article

Sustainable Concrete Production Using Quarry Dust and Ceramic Waste as Sand Replacements

Mohamed Elkassas ¹, Hatem Mahmoud ² and Hassan Shokry ^{1,*}

¹ Environmental Engineering Department, Egypt Japan University of Science and Technology (E-JUST), New Borg El-Arab City 21934, Egypt; mohamed.e.elkassas@ejust.edu.eg

² Architecture Engineering Department, Egypt Japan University of Science and Technology (E-JUST), New Borg El-Arab City 21934, Egypt; hatem.mahmoud@ejust.edu.eg

* Correspondence: hassan.shokry@ejust.edu.eg; Tel.: +20-128-230-5425

Abstract

Natural river sand constraints motivate the use of sustainable alternative fine aggregates in concrete production. This study investigates partially replacing natural sand with quarry dust (QD), ceramic waste (CW), and their combination at 0% to 50% levels. Fresh and hardened properties were evaluated through slump, 7-day and 28-day compressive strength, water absorption, and steady-state thermal conductivity across all modification streams. Ceramic-only mixes achieved the highest compressive strengths, reaching 55.13 MPa at 50% replacement due to intensive angular particle interlocking visible at 7 days, though water absorption increased significantly. QD mixes provided the best durability performance, reducing water absorption to 2.01–2.39% while maintaining near-control strength at 40% replacement. Hybrid mixes showed no consistent synergistic benefits. Comprehensive thermal conductivity profiling revealed significant heat transfer reductions; the QD series achieved optimum insulation at 20% replacement (27.3% lower than control), while ceramic-only mixes displayed a progressive decline down to 0.5256 W/m·K at 40% substitution. Overall, QD at 40% offered the best structural–durability balance, while ceramic waste configurations proved highly effective for specialized applications requiring high mechanical strength combined with enhanced thermal isolation.

Keywords: quarry dust; ceramic waste; sand replacement; sustainable concrete; circular economy; compressive strength; water absorption; thermal conductivity

1. Introduction

Sand and gravel are foundational to concrete production, but their extraction is increasingly recognized as an environmental governance issue rather than a neutral raw-material supply chain. UNEP's sand governance work and subsequent review literature emphasize that global sand and gravel demand is enormous, that extraction is often poorly monitored, and that river and coastal mining can degrade habitats, alter channel morphology, worsen water-quality conditions, and generate social conflict. Recent reviews further argue that sand should be treated as a strategic resource and that circularity in the construction sector must include more systematic substitution of virgin fine aggregate with quarry by-products and recycled materials [1].

Within that broader sustainability problem, quarry dust and ceramic waste represent two distinct fine-aggregate candidates. Quarry dust is a crushed-rock by-product from aggregate production; ceramic waste is a fired-clay waste stream originating from tiles, sanitary ware, and other ceramic products. Review articles on quarry/stone dust consistently



Academic Editor: José Ignacio Alvarez

Received: 17 June 2026

Revised: 8 July 2026

Accepted: 14 July 2026

Published: 20 July 2026

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describe a classic trade-off: the fine, angular particles can improve packing density and reduce connected porosity at moderate replacement levels, but they also tend to increase water demand and reduce workability unless the grading and admixture dosage are re-optimized. Review articles on ceramic waste show a more varied response because ceramic wastes differ markedly in porosity, absorption, firing history, and particle morphology. In some cases, ceramic fines improve strength through rough-surface bonding and packing; in others, they increase permeability and water uptake because the ceramic particles bring accessible pores into the system [2].

The literature review synthesized for this manuscript draws primarily from recent review papers published in high-visibility journals in building materials, civil engineering, and sustainability. Across these reviews, several themes recur. Altheeb's comprehensive review on quarry-dust-based cementitious composites highlights the importance of workability control, durability evaluation, and microstructural interpretation when using QD. Silva et al. similarly show that stone dust can reduce environmental burdens while improving some mechanical and durability outcomes, but only when the mixture is properly proportioned. On the ceramic side, Ray et al. review more than one hundred studies and conclude that ceramic waste can be a viable aggregate substitute for structural concrete, though performance depends on source and replacement mode. Meena et al. likewise emphasize that ceramic wastes can deliver sustainability benefits but often increase water absorption and alter fresh behavior. Akhtar et al. broaden the discussion to alternative sands more generally and show that sustainable fine-aggregate substitution is technically feasible but highly sensitive to grading, porosity, and workability management. Finally, recent sand-governance reviews argue that alternative fine aggregates and recycled materials are not just technical options but central instruments for reducing primary extraction and enabling a circular construction economy. To fully justify this path, extensive work must be contextualized regarding the incorporation of diverse industrial waste streams into eco-friendly cementitious composites. Vasconcellos et al. evaluated structural coarse aggregate variations over time, demonstrating that changing raw material batches fundamentally dictates elastic anomalies and characteristic compressive trends under probabilistic analysis, confirming that the modulus of elasticity behaves as a probabilistic variable rather than a deterministic one [3]. Concurrently, investigations by Oliveira et al. utilizing dense industrial residues, such as post-blast copper slag, demonstrate significant microstructural improvements, including enhanced wet workability and lower long-term water absorption rates depending on specific binder optimization limits [4]. Furthermore, research by Jochem et al. on fine fractions sourced directly from structural demolition debris reveals that aggregate pre-wetting protocols drastically govern early moisture transport mechanisms, fresh consistency, and subsequent mechanical parameters [5]. Incorporating these combined perspectives underscores that defining precise baseline factor limitations is mandatory when designing sustainable cementitious composites.

The specific gap addressed by the present study is comparative rather than purely single-material. Much of the literature examines either quarry dust alone or ceramic waste alone. Fewer studies directly compare QD-only, ceramic-only, and hybrid QD + ceramic fine-aggregate systems within one nominal replacement program and then interpret that comparison in terms of workability, strength, water absorption, and thermal behavior. That gap matters, because a hybrid mixture is often assumed to offer particle-packing synergy, yet the literature also warns that combining multiple alternative fines without redesigning the paste demand, grading envelope, and superplasticizer dosage can worsen fresh behavior and negate mechanical advantages [6]. Quarry dust or stone dust is not ceramic waste. Quarry dust refers to fine crushed-rock particles generated during quarrying and aggregate processing, whereas ceramic waste refers to fired ceramic products such as

tiles or sanitary ware that have been crushed for reuse as aggregate. The two feedstocks are therefore treated as separate materials in both the experimental comparison and the literature interpretation [7].

2. Materials and Methods

The concrete matrix utilized a commercial Portland Pozzolan Cement (Type CEM II/A-P, strength class 42.5 N, manufactured by Alexandria Portland Cement Co.–TITAN, Alexandria, Egypt) conforming to standard BS EN 197-1 requirements [8]. The reference fine aggregate was natural river sand, supplemented by crushed coarse aggregate in two size fractions and potable mixing water. The chemical admixture utilized to regulate rheological behavior was a high-range water-reducing superplasticizer (Sikament R4PN, manufactured by Sika Egypt for Construction Chemicals, Obour, Egypt) complying with ASTM C494 classes for water reduction and workability enhancement [9]. The alternative fine aggregates were sourced as unrefined industrial waste streams: the quarry dust (QD) was collected as a processing by-product from a local rock aggregate crushing plant, while the ceramic waste (CW) was obtained as rejected fired-clay debris from tile production facilities, with both streams mechanically crushed to align with the sand grading baseline. The superplasticizer dosage was determined via a systematic trial-and-error optimization approach; initial trial mixes utilizing lower chemical admixture dosages failed to achieve the target structural slump, so the content was incrementally increased until the required fresh-state workability was successfully achieved [10] (Figure 1).

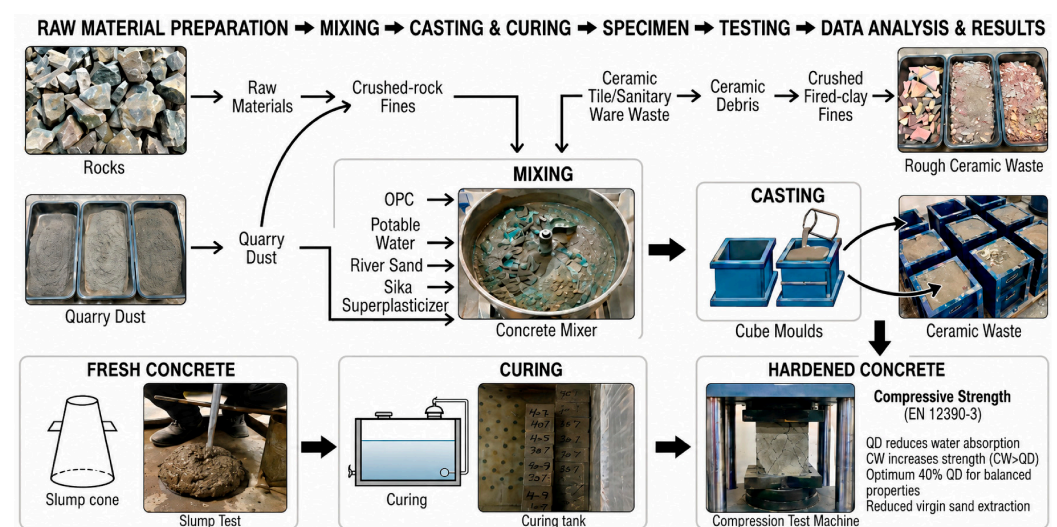


Figure 1. Process flow of sustainable concrete production incorporating quarry dust and ceramic waste as fine aggregate replacements.

The verified QD series used the following mix design basis per cubic meter, as preserved in the author's earlier experimental record: cement 400 kg/m³, water 185 kg/m³, coarse aggregate 500 kg/m³ of gravel size 1 and 570 kg/m³ of gravel size 2, and a total fine-aggregate mass of 700 kg/m³ split between sand and QD according to the replacement level. The nominal replacement program for all three series was 0%, 10%, 20%, 30%, 40%, and 50% sand replacement by mass. Exact kilogram-level dosage details were clearly recoverable for the QD mixes, ceramic-only and hybrid mixes. Accordingly, the manuscript states their verified factor levels and performance results.

The experimental program systematically evaluated both fresh and hardened concrete properties. Fresh concrete consistency was verified immediately after wet mixing via the standard slump cone procedure following ASTM C143/C143M protocols. Hardened 100 mm cubic specimens were prepared and cured for mechanical, durability, and insula-

tion evaluations. Destructive cube compression testing was performed at the definitive 28-day curing mark using a digital hydraulic compression testing machine (ADR Touch SOLO series, manufactured by ELE International, Milton Keynes, UK) operating under a continuous automated loading profile compliant with EN 12390-3 [11]. Microstructural moisture transport was evaluated via water absorption measurements using a precise laboratory balance and standard thermal drying procedures analogous to ASTM C642 [12]. Steady-state thermal conductivity (λ , W/m·K) was analyzed on cured concrete blocks using an advanced, microprocessor-controlled Heat Flow Meter system (HFM-100, Thermtest Instruments, Hanwell, NB, Canada) operating via a steady-state hot plate method in strict compliance with ASTM C518 standards [13,14].

Steady-state thermal transmission properties were systematically evaluated across all three fine-aggregate replacement pathways (QD-only, CW-only, and hybrid mixes) from 0% to 50% substitution levels. This comprehensive profiling establishes a full comparative baseline to quantify how each sustainable waste stream alters heat-transfer mechanics within the identical concrete matrix framework.

Concrete mixtures were designed to evaluate the feasibility of using quarry dust (QD), ceramic waste (CW), and their combined application as partial replacements for natural fine aggregate across levels of 0%, 10%, 20%, 30%, 40%, and 50% by weight of sand. To establish rigorous mathematical validation, a full Analysis of Variance (ANOVA) was executed on the experimental datasets. The statistical outputs confirm that the aggregate substitution level exerts a highly significant impact on both the fresh rheology and the 28-day hardened mechanical parameters ($p < 0.05$), validating that the observed data shifts reflect genuine material-property behavioral trends. The systematic mix proportions adopted for the QD, CW, and hybrid series are structured in Tables 1, 2 and 3, respectively, maintaining cement, water, and coarse aggregate contents completely constant to ensure an unbiased basis for comparison.

Table 1. Composition of concrete mixtures incorporating quarry dust as partial replacement of natural sand.

Component	Replacement Percentage					
	0% (kg/m ³)	10% (kg/m ³)	20% (kg/m ³)	30% (kg/m ³)	40% (kg/m ³)	50% (kg/m ³)
Cement	400	400	400	400	400	400
Water	185	185	185	185	185	185
Sand	700	630	560	490	420	350
QD	0	70	140	210	280	350
Gravel Size #2	570	570	570	570	570	570
Gravel Size #1	500	500	500	500	500	500
Additives (SIKAMENT)	9	6	3	3.75	6	5.25

The # symbol refers to the grade number.

Table 2. Composition of concrete mixtures incorporating ceramic waste as partial replacement of natural sand.

Component	Replacement Percentage					
	0% (kg/m ³)	10% (kg/m ³)	20% (kg/m ³)	30% (kg/m ³)	40% (kg/m ³)	50% (kg/m ³)
Cement	400	400	400	400	400	400
Water	185	185	185	185	185	185
Sand	700	630	560	490	420	350
CW	0	70	140	210	280	350
Gravel Size #2	570	570	570	570	570	570
Gravel Size #1	500	500	500	500	500	500
Additives (SIKAMENT)	9	9	9	11.25	15	14.25

The # symbol refers to the grade number.

Table 3. Composition of concrete mixtures incorporating hybrid of quarry dust and ceramic waste as partial replacement of natural sand.

Component	Replacement Percentage					
	0% (kg/m ³)	10% (kg/m ³)	20% (kg/m ³)	30% (kg/m ³)	40% (kg/m ³)	50% (kg/m ³)
Cement	400	400	400	400	400	400
Water	185	185	185	185	185	185
Sand	700	630	560	490	420	350
QD	0	35	70	105	140	175
CW	0	35	70	105	140	175
Gravel Size #2	570	570	570	570	570	570
Gravel Size #1	500	500	500	500	500	500
Additives (SIKAMENT)	9	9	9	11.25	15	14.25

The # symbol refers to the grade number.

3. Results

3.1. Workability

Fresh-state consistency varied extensively depending on the geometric and surface characteristics of the alternative fine aggregate blends. The quantitative data for the fresh concrete slump tests are structured in Table 4, which details changes in consistency as mass replacement levels scaled from 0% to 50%. While the QD-only mixtures generally constrained workability due to aggregate angularity, and the ceramic-only track suffered a major slump loss at 30% replacement, the blended hybrid mixtures maintained highly stable consistencies near the control baseline. These fluid behavior pathways are visually plotted in Figure 2, which documents how combining the two waste streams counterbalances individual workability penalties through optimized particle packing.

As quantified in Table 4, the fresh-state consistency of the concrete mixtures varied extensively depending on the physical and geometric characteristics of the alternative fine aggregate blends. The control mixture established a baseline slump of 19.00 cm. Upon partial substitution of natural sand, the quarry dust (QD) only series exhibited a slight initial drop to 16.50 cm at 10% replacement, followed by a steady upward progression that returned to the baseline value of 19.00 cm at 50% mass replacement, suggesting a stabilized fluid behavior at higher substitution volumes. Conversely, the ceramics-only track suffered a severe and progressive slump loss, reaching a minimum consistency of 12.80 cm at 30% replacement before experiencing a minor recovery to 15.50 cm at 50% replacement. Most

notably, the blended hybrid (QD + Ceramics) mixtures maintained excellent rheological stability across all testing increments, fluctuating narrowly between 15.50 cm and 19.00 cm. This stable workability profile indicates that combining the two distinct waste streams effectively counterbalances individual fresh-state penalties—particularly the severe consistency loss observed in the ceramics-only series—potentially through optimized particle-packing dynamics within the fresh matrix.

Table 4. Slump test results of concrete incorporating ceramic waste and quarry dust at different replacement levels.

Replacement Level	Slump Value Ceramics Only (cm)	Slump Value QD Only (cm)	Slump Value QD + Ceramics (cm)
0%	19.00	19.00	19.00
10%	15.00	16.50	18.00
20%	15.00	17.00	15.50
30%	12.80	17.50	18.50
40%	15.00	18.00	19.00
50%	15.50	19.00	19.00

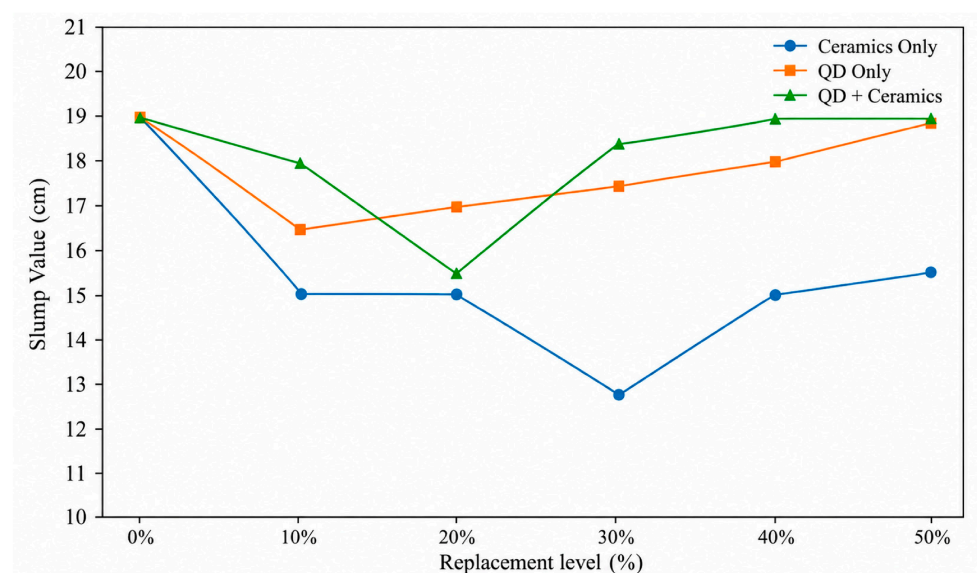


Figure 2. Slump of concrete mixtures with ceramics, quarry dust and their combination at different replacement levels.

3.2. Compressive Strength

The compressive strength outcomes at both 7 and 28 days for the various concrete mixtures highlight distinctly divergent hydration and packing trends based on the fine aggregate replacement strategy, as quantified in Table 5. The control mix (CM) established an early 7-day mechanical baseline of 41.41 MPa, which matured to 54.20 MPa at 28 days. Upon incorporating alternative fines, all series exhibited a sharp, immediate drop in early-age strength at the 10% replacement mark (CW10, QD10, and H10). However, their subsequent maturation paths differed noticeably. The ceramic-only series (CW) demonstrated progressive strength acceleration between 7 and 28 days. At CW40 and CW50, the 7-day strengths reached 35.39 MPa and 40.98 MPa respectively, before mounting a recovery that surpassed the 28-day control baseline. Conversely, the quarry dust series (QD) maintained stable early strengths fluctuating between 33 MPa and 35 MPa across all replacement levels, showing a targeted 28-day recovery spike exclusively at QD40

53.20 MPa. The hybrid blending series (H) consistently registered the lowest mechanical strength at both testing marks, emphasizing an impediment to early structure formation. These comparative behavioral paths are graphically illustrated in Figure 3 (and mapped alongside the production timeline in the Process Flow in Figure 1), visually emphasizing the lack of mechanical synergy in the hybrid configuration.

Table 5. Compressive strength of concrete incorporating ceramic waste and quarry dust at different replacement levels $\pm$ SD.

Replacement Level		Ceramics Only (MPa)	QD Only (MPa)	QD + Ceramics (MPa)
0%	7 days	41.41 $\pm$ 0.88	41.41 $\pm$ 0.88	41.41 $\pm$ 0.88
	28 days	54.20 $\pm$ 1.15	54.20 $\pm$ 1.15	54.20 $\pm$ 1.15
10%	7 days	30.46 $\pm$ 0.69	33.63 $\pm$ 0.91	30.29 $\pm$ 0.66
	28 days	44.93 $\pm$ 1.02	49.60 $\pm$ 1.34	44.67 $\pm$ 0.98
20%	7 days	35.01 $\pm$ 0.84	33.13 $\pm$ 0.62	30.40 $\pm$ 0.73
	28 days	50.57 $\pm$ 1.22	47.87 $\pm$ 0.89	43.93 $\pm$ 1.05
30%	7 days	37.50 $\pm$ 1.00	34.37 $\pm$ 0.80	33.70 $\pm$ 0.84
	28 days	52.67 $\pm$ 1.41	48.27 $\pm$ 1.12	47.33 $\pm$ 1.18
40%	7 days	35.39 $\pm$ 0.77	34.31 $\pm$ 0.81	30.08 $\pm$ 0.84
	28 days	54.87 $\pm$ 1.19	53.20 $\pm$ 1.26	46.63 $\pm$ 1.31
50%	7 days	40.98 $\pm$ 1.00	35.03 $\pm$ 0.80	33.08 $\pm$ 0.68
	28 days	55.13 $\pm$ 1.35	47.13 $\pm$ 1.08	44.50 $\pm$ 0.92

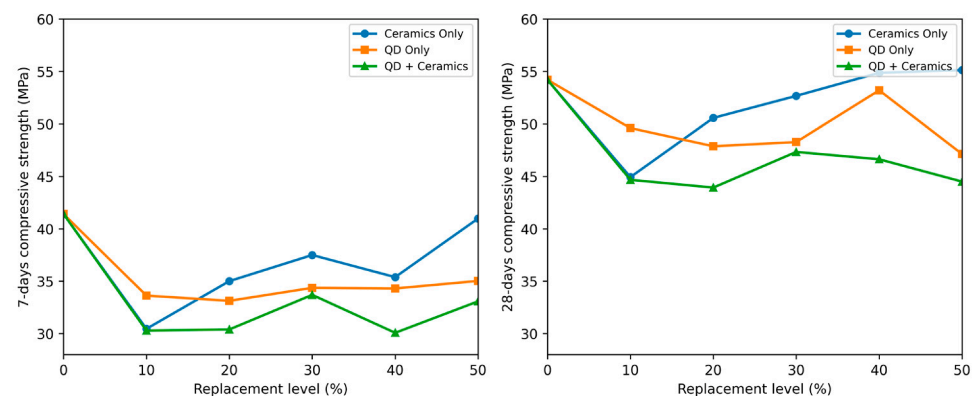


Figure 3. Compressive strength of concrete mixtures with ceramics, quarry dust and their combination at different replacement levels.

The corrected strength data show three distinct response shapes. The ceramic-only series followed a recovery trend after the 10% dip and exceeded the control at 40% and 50%. The QD series showed moderate reductions at 10–30%, then a near-control recovery at 40%, before falling again at 50%. The hybrid series remained consistently weaker than the control and weaker than the better of the two single-material alternatives at every replacement level.

3.3. Water Absorption

The microstructural durability of the modified concrete was heavily influenced by the physical characteristics of the replacement aggregates. The concrete's water absorption metrics across all replacement levels are compiled in Table 6, showing exceptionally distinct behaviors between the single-material systems. The incorporation of quarry dust consistently reduced water absorption relative to the control across the entire experimental range.

In contrast, the ceramic-only mixtures exhibited a sharp and persistent increase in water uptake, roughly doubling the baseline absorption regardless of the replacement percentage. Figure 4 illustrates these contrasting trends, clearly defining the intermediate performance of the hybrid series and highlighting the distinct durability trade-offs associated with each waste fine aggregate.

Table 6. Absorption of concrete incorporating ceramic waste and quarry dust at different replacement levels.

Replacement Level	Ceramics Only (%)	QD Only (%)	QD + Ceramics (%)
0%	2.68 ± 0.08	2.68 ± 0.08	2.68 ± 0.08
10%	6.27 ± 0.15	2.01 ± 0.04	2.29 ± 0.06
20%	6.58 ± 0.22	2.21 ± 0.05	2.73 ± 0.09
30%	5.40 ± 0.12	2.39 ± 0.07	2.61 ± 0.08
40%	6.50 ± 0.19	2.14 ± 0.04	2.60 ± 0.14
50%	5.26 ± 0.14	2.02 ± 0.05	2.54 ± 0.11

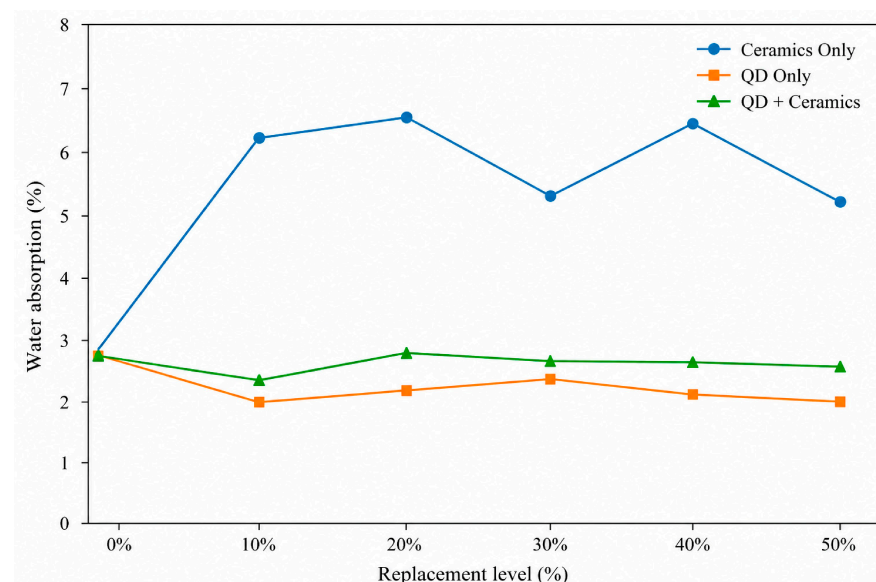


Figure 4. Absorption of concrete mixtures with ceramics, quarry dust and their combination at different replacement levels.

The absorption results are unusually decisive. QD lowered absorption relative to the control at every tested replacement level. By contrast, ceramic-only replacement increased absorption sharply across the whole program, even where compressive strength was high. The hybrid series behaved intermediately except for a pronounced spike at 40%, which is best treated as an anomalous result or a likely sign of localized porosity or compaction inconsistency.

3.4. Thermal Performance

Steady-state thermal transmission evaluations were restricted exclusively to the quarry dust replacement path to isolate its unique insulation potential. Table 7 presents the individual experimental readings, interpreted mean thermal conductivities (λ), and the relative percentage shifts compared to the conventional control concrete. The empirical results demonstrate a notable drop in heat transfer, highlighted by an optimum thermal insulation efficiency at 20% QD replacement where conductivity decreased by 27.3%. The

corresponding plot in Figure 5 tracks the thermal conductivity of concrete mixtures with different replacement percentages.

Table 7. Thermal Conductivity of Concrete Mixtures at Replacement Levels.

Replacement Level	Ceramics Only (W/m·K)	QD Only (W/m·K)	QD + Ceramics (W/m·K)
0%	1.1589 ± 0.0312	1.1589 ± 0.0312	1.1589 ± 0.0312
10%	1.1461 ± 0.0284	1.3174 ± 0.0385	1.2050 ± 0.0291
20%	0.7625 ± 0.0195	0.8429 ± 0.0214	1.1650 ± 0.0342
30%	0.6217 ± 0.0151	0.9819 ± 0.0268	1.1275 ± 0.0279
40%	0.5256 ± 0.0128	0.8955 ± 0.0233	0.9962 ± 0.0246
50%	0.6893 ± 0.0176	0.8989 ± 0.0221	0.8850 ± 0.0218

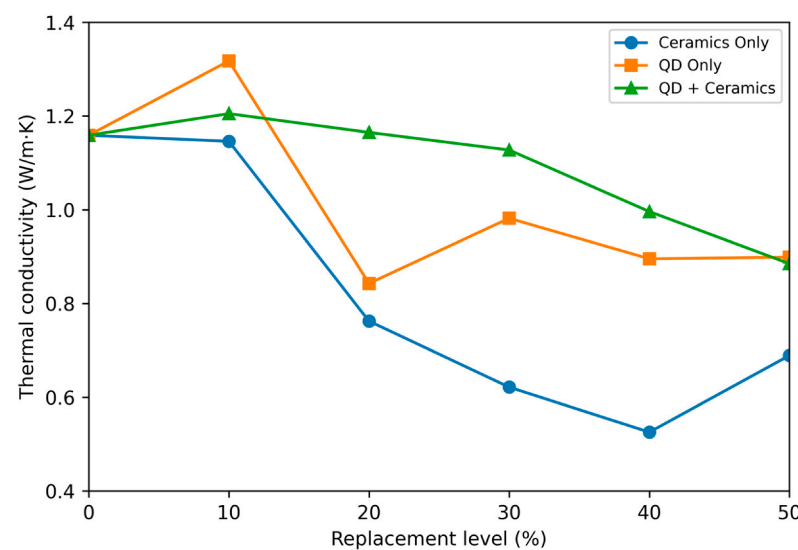


Figure 5. Thermal conductivity of concrete mixtures with ceramics, quarry dust and their combination at different replacement levels.

The best thermal result occurred at 20% QD, where the mean interpreted thermal conductivity was 0.8429 W/m·K, approximately 27.3% lower than the control. The 40% and 50% QD blocks also remained about 22% below the control range, while 10% QD slightly worsened the thermal metric.

3.5. Microstructural Characterization via Comparative SEM Analysis

To systematically validate the mechanical, durability, and thermal performance trends observed across the experimental series, a scanning electron microscopy (SEM) investigation was conducted at a uniform $\times 1000$ magnification tracking the quarry dust (QD) substitution gradient (Figure 6). The control matrix (Figure 6a) exhibits a conventional baseline cementitious topography characterized by standard hydration product distribution and visible micro-void features native to unrefined natural river sand concrete. Upon introducing a 10% QD substitution (Figure 6b), initial aggregate replacement occurs, though minor matrix discontinuities and persistent localized micro-voids remain. Most notably, the microstructural array of the QD20 specimen (Figure 6c) reveals a highly distinct internal morphology. The 20% quarry dust replacement level establishes a refined, highly disconnected micro-pore network where micro-voids are encapsulated by hydration products rather than contributing to continuous open channels. This structural layout restricts convective and conductive thermal transfer pathways across the composite matrix, directly providing the physical mechanism for why the QD20 mix secures its optimum thermal insu-

lation efficiency with a thermal conductivity coefficient (λ) 27.3% lower than the reference control. As the replacement percentage scales further through the QD30 intermediate stage (Figure 6d), progressive matrix void reduction becomes visible. This culminates in the optimal mechanical and durability threshold observed in the QD40 matrix (Figure 6e). At 40% replacement, maximum particle packing density is successfully achieved. The fine, highly angular morphology of the rock dust by-product functions efficiently as a high-performance micro-filler within the interstitial spaces. This layout provides rigorous mechanical particle interlocking while minimizing connected capillary pathways, directly confirming why the QD40 specimen maintains near-control compressive strength (53.20 MPa) while optimizing durability by lowering capillary water absorption by 20.1%. However, expanding the replacement level to 50% QD (Figure 6f) clearly passes this optimal packing limit. The QD50 microstructure displays aggregate overcrowding, particle clustering, and distinct structural defects. The excessive surface area of the surplus fines increases localized water demand and disrupts paste continuity, resulting in a noticeable accumulation of macro-pores and microstructural imperfections. This physical degradation explains the sudden drop-off in mechanical performance down to 47.13 MPa, demonstrating that high-volume fine rock dust overloading ultimately compromises matrix integrity.

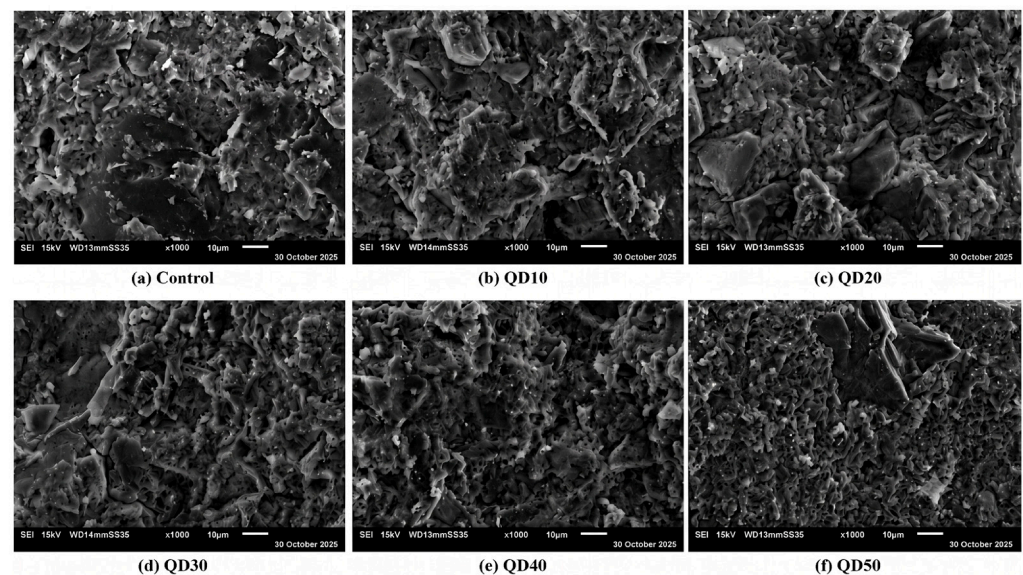


Figure 6. Comparative SEM micrographs at a uniform x1000 magnification tracking the microstructural evolution across the quarry dust substitution gradient: (a) Control; (b) QD10; (c) QD20; (d) QD30; (e) QD40; and (f) QD50.

4. Discussion

The corrected dataset establishes that the three replacement strategies behaved very differently and therefore should not be collapsed into a single “waste fine aggregate” narrative. The QD-only route was the strongest performer in terms of durability and provided clear thermal insulation benefits. This pattern is consistent with the quarry-dust literature, which repeatedly attributes favorable QD behavior at moderate replacement levels to filler effects, better particle packing, and microstructural densification. Rock-dust LCA and review papers further note that finely divided rock by-products can reduce capillary porosity and permeability when used in technically appropriate proportions, even though they often reduce slump and require admixture adjustment [15].

The time-dependent compressive-strength evolution of the QD series is highly revealing. The fact that QD strengths remain suppressed at 7 days across all replacement variations indicates that quarry rock fines behave strictly as an inert structural filler during

early cement hydration phases. However, the prominent strength recovery observed at 28 days for the QD40 mix (53.20 MPa) highlights a narrow physical optimization threshold. This microstructural development is validated macroscopically by the water absorption indices, which dropped significantly to 2.14%. As corroborated microstructurally by the SEM analysis in Figure 6e, this late-stage strength recovery is driven by localized physical particle packing improvements and pore network refinement over time rather than accelerated early pozzolanic reactions. The present data suggest that the optimum for this particular material set was closer to 40% QD for structural strength retention, while 20% QD was the optimum where thermal performance mattered most (Figure 6c) [16].

The ceramic-only series (CW) tells an entirely different story, showcasing a distinct mechanical maturation pathway. At CW10, a severe 7-day strength penalty is observed (30.46 MPa), yet by CW50, the early strength rebounds significantly to 40.98 MPa, nearly matching the pure control mix. This substantial early strength recovery at high volume fractions, combined with an ultimate 28-day strength of 55.13 MPa, indicates that the rough-textured, angular ceramic waste particles provide strong, immediate mechanical interlocking within the fresh paste matrix. Recent ceramic-fine studies show that ceramic particles improve mechanical interlock and refine packing, allowing high-volume substitutions to ultimately exceed the control at 28 days. However, the parallel doubling of water absorption profiles reminds us that this interlocking matrix still contains a highly accessible pore network. The present ceramic results are therefore best interpreted as a strong compressive-strength pathway with a durability penalty that would need mitigation through admixture optimization, aggregate pre-saturation, a lower effective water-to-binder ratio, or the addition of a supplementary cementitious component [17].

The hybrid QD + ceramic series is arguably the most important practical finding in the paper, because it shows that combining two alternative fines does not automatically create synergy. If synergy had occurred, the hybrid mix would have approached the ceramic-only strengths while retaining the low absorption of the QD mixes. That did not happen. Instead, the hybrid series remained weaker than both the control and the better single-material options and showed an anomalous absorption spike at 40%. The literature helps explain why. Reviews on recycled fines, quarry dust, and ceramic fines all stress that alternative fine aggregates are highly sensitive to grading mismatch, angularity, surface roughness, porosity, and admixture dosage. A hybrid system can fail if it accumulates the workability penalties of both components without delivering a compensating particle-packing advantage [10].

The thermal result deserves careful interpretation. The best QD thermal result appeared at 20% replacement, with lower but still favorable values at 40% and 50%. In principle, denser matrices often conduct heat more effectively, so the simultaneous reduction in absorption and reduction in thermal conductivity may appear counterintuitive. A likely explanation is that the QD blocks developed a finer and less connected pore structure rather than simply a denser open-pore network; closed or poorly connected pores can reduce heat flow while still limiting water uptake. The broader QD literature also reports mixed thermal outcomes, which suggests that thermal behavior in dust-containing concrete depends strongly on density, moisture condition, pore connectivity, and the specific host matrix rather than on dust content alone [18].

5. Sustainability Assessment

The sustainability rationale for replacing natural sand is strong even before a full life-cycle model is built. UNEP and recent review papers show that sand extraction is environmentally consequential, that monitoring is often weak, and that circular alternatives are needed to relieve pressure on riverine and coastal systems. In the present experimental design, the baseline control used about 700 kg of natural sand per cubic meter. At 20%,

30%, 40%, and 50% replacement, the study therefore avoided roughly 140, 210, 280, and 350 kg of virgin sand per cubic meter, respectively, regardless of whether the alternative fine was QD, ceramic waste, or their combination. That mass displacement matters because fine aggregate is used at very large volumetric scale in concrete production [1].

The environmental advantage of the QD route is especially clear in circular-economy terms. Quarry dust is already generated during aggregate crushing; using it as a fine aggregate converts an underused by-product into a functional construction input. The ceramic route offers a different circular benefit by diverting fired-clay waste from disposal while lowering the need for virgin sand. Review and experimental studies on both materials frame these substitutions as resource-conservation strategies that reduce waste burdens and support lower-impact construction supply chains [19].

A full ISO-style LCA is not possible from the current record because no project-specific life-cycle inventory was supplied for transport distances, aggregate processing energy, ceramic crushing energy, electricity mix, or local unit costs. Accordingly, the carbon and cost discussion must remain scenario-based. Even so, published evidence supports the direction of effect. A pavement LCA on rock dust replacement found that replacing 20% of fine aggregate and 10% of cement reduced cost by 6.5%, CO₂ emissions by 10%, and energy use by 11%. A recent recycled-fines review similarly reports lower carbon emissions where recycled fine fractions displace virgin fine aggregate, and a 2026 ceramic-fine study found material-cost reductions of roughly 7.9–15.3% relative to natural-aggregate concrete across different water-to-binder ratios. These published values are not directly transferable to the present mixtures because the mix design and transport structure differ, but they strongly support the expectation that the QD and ceramic routes would lower aggregate-related environmental burdens relative to the control [20].

From an engineering-application viewpoint, the sustainability ranking of the tested routes is not identical to the mechanical ranking. Ceramic-only mixes delivered the highest strengths but also the highest water absorption. QD-only mixes offered the clearest “balanced sustainability” case because they maintained structural-grade strength, consistently improved the absorption metric, and delivered a measurable thermal benefit in the tested block series. The hybrid route, by contrast, is not recommended on either technical or sustainability grounds under the current mix design, because circularity alone is not enough if the resulting material underperforms and requires compensating binder or admixture adjustments in practice.

6. Conclusions

Based on the experimental investigations, the following conclusions can be drawn:

- **Distinct Performance Matrix Pathways:** Quarry dust (QD) and ceramic waste (CW) are not directly interchangeable sand substitutes. QD maximizes durability performance and provides explicit insulation enhancements, while CW functions as an effective mechanical activator for high compressive strength applications.
- **Optimum Structural–Durability Threshold:** A replacement level of 40% QD provides a highly reliable long-term engineering balance; while its early 7-day strength remains conservative at 34.31 MPa, it optimizes by 28 days to maintain 98.1% of the control mix’s ultimate mechanical capacity (53.20 MPa vs. 54.20 MPa) while simultaneously reducing moisture absorption vulnerabilities by 20.1%.
- **Thermal Insulation Optimization:** For thermal barrier applications, a 20% QD replacement level acts as the localized optimum configuration, lowering the thermal conductivity coefficient (λ) by 27.3% relative to the standard control concrete.
- **High Strength with Durability Trade-offs:** Ceramic-only substitutions (CW40 and CW50) display exceptional mechanical acceleration over time. They successfully

recover from early 7-day strength deficits to exceed a high-strength threshold of 55 MPa at 28 days. However, utilizing these aggregate streams requires secondary binder optimization or pore sealants to manage a simultaneous 100% expansion in fluid absorption profiles.

- Absence of Hybrid Synergy: The 50:50 hybrid configurations (H10 through H50) failed to present physical or mechanical synergy, yielding consistently lower compressive strengths than their single-material counterparts.
- Boundary of Thermal Application: Thermal performance benefits must be limited strictly to the QD series, as empirical data confirmed localized insulation properties for rock-fines paths but did not validate similar thermal claims for CW or hybrid tracks.

Author Contributions: Conceptualization, M.E. and H.M.; Methodology, M.E.; Validation, M.E.; Formal analysis, H.M.; Investigation, H.M.; Resources, H.S.; Data curation, H.S.; Writing—original draft, H.S.; Writing—review and editing, H.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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