MECHANICAL AND DURABILITY PROPERTIES OF MATERIAL

Assessment of Mechanical and Durability Performance of Concrete Incorporating Waste Tiles, Broken Bricks and Recycled Concrete By-Products

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Published November 2026

Abstract

The increasing demand for natural aggregates and the growing volume of construction and demolition waste (CDW) create environmental and resource-management challenges for the construction sector. This study evaluates the feasibility of using waste ceramic tiles as a partial replacement for fine aggregate and crushed broken bricks and recycled concrete by-products (CBP) as complete replacements for coarse aggregate in M20-grade concrete. Nine mix combinations (G1–G9) were developed using 10%, 20% and 30% tile replacement of fine aggregate and different brick–CBP proportions at 100% coarse-aggregate replacement. Recycled aggregates were characterized by relatively high water absorption (approximately 5–15%) and lower specific gravity/density (approximately 2.0–2.4) than natural aggregates. The reported average compressive strengths were 6.06 MPa at 3 days, 14.18 MPa at 7 days and 20.89 MPa at 28 days. Among the mixes, G2 achieved the highest reported 28-day strength of 23.30 MPa, 16.5% above the nominal 20 MPa target, with 20% tile replacement and a 50:50 brick-to-CBP coarse aggregate blend. G3 achieved 21.77 MPa at 28 days with 30% tile replacement. Ultrasonic pulse velocity (UPV) ranged from 3.5 to 4.2 km/s, with the highest value recorded for G2. Durability interpretation indicates that higher recycled aggregate contents may increase water absorption and permeable voids; however, several durability indicators discussed in the thesis were inferred from literature correlations rather than directly measured. The study identifies G2 as the preferred performance-oriented mix and G3 as an alternative where greater tile-waste utilization is prioritized. The findings support further controlled use of locally processed CDW aggregates, subject to quality assurance and additional durability validation.

Keywords: Recycled aggregate concrete; construction and demolition waste; ceramic tiles; broken bricks; concrete by-products; compressive strength; ultrasonic pulse velocity; sustainable construction

1 Introduction

1.1 Background and rationale

Concrete is one of the most widely used construction materials, and natural aggregates constitute a substantial proportion of its volume and mass. Continued extraction of aggregates from quarries and riverbeds can contribute to landscape disturbance, river-system degradation, resource depletion and transportation-related emissions. At the same time, building construction, renovation and demolition generate substantial quantities of waste, including ceramic tiles, broken bricks and discarded concrete. Where these materials are disposed of in open areas or landfills, they occupy valuable land and may create dust and other environmental impacts.

Recycling suitable CDW as aggregate offers a potential route to reduce demand for virgin materials while diverting waste from disposal. Recycled concrete aggregates, ceramic waste and crushed brick have each been investigated in concrete. Previous studies report that performance depends on source material, processing, particle grading, replacement percentage and water absorption (Hameed et al., 2023; Tamayo et al., 2020; Zhang et al., 2023). Recycled particles commonly have more irregular surfaces and greater porosity than natural aggregates, which can influence fresh-concrete workability, density, strength and durability.

1.2 Research problem and gap

Although individual recycled materials have been studied, fewer investigations have examined the combined use of waste tiles in the fine fraction and broken bricks with recycled concrete by-products in the coarse fraction. The performance of such combined mixtures is not straightforward because the constituents differ in density, absorption, shape and strength. In addition, research often emphasizes compressive strength while giving less attention to durability, microstructure, field performance and the relationship between material properties and concrete performance.

1.3 Aim and objectives

The aim of this study is to assess the mechanical performance and durability-related characteristics of M20 concrete incorporating waste tiles, broken bricks and recycled concrete by-products, and to identify suitable replacement combinations for potential application in Surkhet, Nepal. The specific objectives are to: (i) characterize the recycled aggregate materials; (ii) compare nine mix combinations with different fine- and coarse-aggregate replacement levels; (iii) evaluate compressive strength at 3, 7 and 28 days and concrete quality using UPV; (iv) examine durability-related indicators using available test evidence and literature correlations; and (v) identify preferred mixes while considering material efficiency, cost and environmental implications.

1.4 Scope

The investigation is based on materials sourced in Surkhet District and laboratory-scale concrete specimens. It focuses on M20 concrete, with tiles replacing 10–30% of fine aggregate and broken bricks plus CBP replacing 100% of coarse aggregate. The findings should not be generalized to other locations or material sources without local characterization and trial mixes.

2 Materials and research methodology

2.1 Materials

The principal materials were cement, natural sand, natural coarse aggregate, waste ceramic tiles, broken bricks and recycled concrete by-products. Waste materials were collected from demolition or construction-related sources in Surkhet District, then crushed and sieved to obtain aggregate fractions suitable for concrete production. The origin and previous service history of some CBP could not be fully traced, which is a limitation when interpreting variability.

The thesis reports recycled aggregate specific gravity/density values of approximately 2.0–2.4, compared with approximately 2.6–2.8 for natural aggregates. Recycled aggregate water absorption was approximately 5–15%, compared with around 1–3% for natural aggregates. Bulk density of the

recycled aggregates was reported in the range of 1,200–1,600 kg/m^3. The recycled particles were generally angular and irregular, with rougher surfaces than natural aggregates.

Table 1. Reported properties of recycled and natural aggregates.

Property	Recycled aggregates (reported)	Natural aggregates (reported)
Specific gravity / particle density	2.0–2.4	2.6–2.8
Water absorption	5–15%	1–3%
Bulk density	1,200–1,600 kg/m^3	Higher; source-specific
Particle shape / texture	Angular, irregular, relatively rough	Generally more regular

2.2 Mix proportions

Nine mixes were prepared using the nominal M20 proportion of 1:1.5:3 (cement:fine aggregate:coarse aggregate). Tiles replaced 10%, 20% or 30% of the fine aggregate. The coarse aggregate was fully replaced by broken bricks and CBP in varying proportions. Table 2 summarizes the mix matrix.

Table 2. Replacement combinations for mixes G1–G9.

Mix	Tiles (% of fine agg.)	Sand (% of fine agg.)	Broken brick (% of coarse agg.)	CBP (% of coarse agg.)
G1	10	90	50	50
G2	20	80	50	50
G3	30	70	50	50
G4	10	90	15	85
G5	20	80	20	80
G6	30	70	25	75
G7	10	90	85	15
G8	20	80	80	20
G9	30	70	75	25

Coarse aggregate replacement by recycled materials was 100% in every mix.

2.3 Specimen preparation and curing

Concrete was mixed using a conventional laboratory mixer. The reported procedure involved combining the aggregate fractions and cement, followed by mixing for approximately 3–5 minutes. Workability was assessed using a slump test. Concrete was placed in 150 mm × 150 mm × 150 mm cube moulds in layers and compacted using vibration. Specimens were demoulded after approximately 24 hours and cured under water until the designated testing ages. The thesis describes a minimum of three cubes per mix and testing age; however, the summary table available for this manuscript presents selected mix-age test records rather than a complete nine-mix dataset at every age.

2.4 Mechanical and non-destructive testing

Compressive strength was assessed on 150 mm cube specimens at 3, 7 and 28 days. The loaded area of each cube was 22,500 mm^2, and compressive strength was calculated as the maximum applied load divided by the loaded area. The thesis cites IS 516-1959 / ASTM C39 for compressive testing and reports a loading rate of 0.2–0.4 MPa/s. Hardened density was calculated from specimen mass and volume.

UPV testing was conducted on 28-day specimens in accordance with IS 13311 (Part 1):1992. UPV was used as a non-destructive indicator of concrete homogeneity and internal quality. The reported values ranged from 3.5 to 4.2 km/s.

2.5 Durability assessment and analytical approach

The thesis describes water absorption testing under ASTM C642, including 24-hour and 72-hour immersion procedures. However, the results and discussion explicitly state that the overall durability tests were not completed directly in the laboratory and that water absorption and other durability indicators were interpreted using relationships reported in the literature. Accordingly, the water absorption and permeable-void ranges presented below are treated as estimates, not measured experimental outcomes. Chloride penetration, carbonation, sulfate attack, freeze–thaw, acid resistance and drying shrinkage were not directly tested.

The analysis compared strength development with nominal M20 reference values, considered density and UPV as indicators of concrete quality, and used a multi-criteria selection approach. The thesis describes weighting compressive strength at 40%, replacement level at 30% and density at 30% when selecting the preferred mix. Economic and environmental benefits were assessed as indicative estimates based on local availability, processing and potential aggregate substitution.

3 Results and discussion

3.1 Material characteristics

The recycled aggregates differed materially from natural aggregates. Their greater absorption (5–15%) indicates a need to account for moisture condition during batching, since dry recycled particles can absorb part of the mixing water and reduce effective water availability. Their lower density (2.0–2.4) also contributes to the lower hardened density reported for the recycled aggregate concrete. Angularity and surface irregularity can improve mechanical interlock but may reduce workability and increase water demand. These characteristics highlight the importance of preconditioning, moisture correction, grading control and consistent processing.

3.2 Fresh concrete properties

The thesis reports that workability decreased as the proportion of recycled aggregate increased. This trend is consistent with the higher absorption and irregular particle shape of the recycled materials. Slump observations were used to compare mixtures, and the thesis notes that admixtures such as superplasticizers may be needed to maintain workability at higher replacement levels. No complete numerical slump dataset was available in the thesis summary used for this manuscript; therefore, specific slump values are not reported. Fresh-concrete temperature and setting behavior were described as generally normal.

3.3 Compressive strength

Across the reported results, average compressive strength increased with curing age. The overall average values were 6.06 MPa at 3 days, 14.18 MPa at 7 days and 20.89 MPa at 28 days. The reported ranges were 4.75–6.78 MPa, 11.92–17.78 MPa and 17.59–23.30 MPa, respectively. The 28-day average was slightly higher than the nominal 20 MPa M20 target. The lower early-age average suggests that strength development may be slower than the nominal reference values at early curing ages, making curing and early-age loading precautions important.

Table 3. Age-wise compressive-strength summary reported in the thesis.

Age (days)	Number of summarized results	Strength range (MPa)	Average strength (MPa)	Standard deviation (MPa)
3	3	4.75–6.78	6.06	1.02
7	3	11.92–17.78	14.18	3.05
28	3	17.59–23.30	20.89	2.86

The individual mix-age summary identifies G2 as the strongest 28-day mixture at 23.30 MPa, followed by G3 at 21.77 MPa. G9 recorded 17.59 MPa at 28 days and therefore did not reach the nominal 20 MPa target in the reported result. The selected 3-day records ranged from 4.75 to 6.78 MPa, while selected 7-day records ranged from 11.92 to 17.78 MPa. Because the available summary does not provide a complete matrix of all nine mixes tested at all three ages, the age-wise averages should be interpreted as the thesis-reported summary and not as a fully balanced statistical comparison of all 27 mix-age combinations.

Table 4. Mix-wise strength and density records available in the thesis summary.

Mix	Test age (days)	Reported average strength (MPa)	Reported density range (g/cm^3)
G1	7	17.78	2.163–2.284
G2	28	23.30	2.189–2.218
G3	28	21.77	2.186–2.260
G4	3	6.78	2.040–2.148
G5	7	12.84	2.198–2.299
G6	3	6.66	2.151–2.175
G7	3	4.75	2.041–2.145
G8	7	11.92	2.097–2.232
G9	28	17.59	2.128–2.251

3.4 Hardened density and UPV

Hardened concrete density was reported between 2.04 and 2.30 g/cm^3, with most observations between 2.10 and 2.25 g/cm^3. These values are lower than the typical range cited for conventional concrete (approximately 2.3–2.4 g/cm^3), consistent with the lower density of recycled aggregates. The thesis reports a positive association between density and compressive strength, indicating that denser specimens generally exhibited higher strength. This relationship is plausible because lower porosity and better compaction can contribute to improved load-bearing performance.

UPV values ranged from 3.5 to 4.2 km/s. G2 recorded the highest value (4.2 km/s), G3 recorded 4.0 km/s and G9 recorded 3.5 km/s. The thesis interprets values above 3.5 km/s as indicative of good to excellent concrete quality under the cited IS 13311 classification. UPV should nevertheless be interpreted as a quality and uniformity indicator rather than a substitute for compressive-strength testing.

3.5 Durability-related performance

The thesis estimates water absorption of approximately 5–8% for mixes with lower fine-aggregate tile replacement (10–20%) and 8–12% for higher replacement (30%), based on strength-related literature correlations. It also estimates permeable void content of approximately 12–15% at lower replacement levels and 15–20% at higher replacement levels. These figures suggest a potential increase in connected pore space as recycled aggregate content increases. They are not direct measurements from the present laboratory programme and must not be interpreted as such.

Literature-based interpretation further suggests that mixes with higher compressive strength and density, particularly G2 and G3, may have better resistance to ingress-related deterioration than lower-strength mixes. The thesis discusses potential chloride permeability, carbonation and sulfate-resistance trends using published correlations. Since these tests were not conducted on the study specimens, no definitive durability classification or service-life conclusion can be drawn. Direct testing under relevant exposure conditions is required before structural use in aggressive environments.

3.6 Microstructural considerations

No scanning electron microscopy, X-ray diffraction, mercury intrusion porosimetry or comparable microstructural testing was carried out. The thesis interprets the likely behavior using published research: recycled aggregate concrete may contain multiple interfacial transition zones (ITZs), residual adhered mortar and a more heterogeneous pore structure than conventional concrete. Higher aggregate absorption and irregular particle surfaces may contribute to increased porosity and water transport. These mechanisms provide a plausible explanation for the observed density-strength relationship, but they remain literature-based interpretations rather than microstructural findings from this experiment.

3.7 Identification of preferred mixes

G2 was identified as the primary recommended mix. It contains 20% tile replacement in the fine aggregate fraction and a 50:50 blend of broken bricks and CBP replacing 100% of the coarse aggregate. Its reported 28-day compressive strength was 23.30 MPa, equivalent to 16.5% above the 20 MPa target, and its reported density was 2.204 g/cm^3. It also recorded the highest UPV value (4.2 km/s). The combination of strength, full coarse-aggregate substitution and substantial waste utilization makes G2 the strongest overall candidate in the thesis assessment.

G3 is the secondary recommendation where increased tile-waste utilization is a priority. It contains 30% tiles in the fine aggregate fraction and the same 50:50 brick–CBP coarse aggregate blend. Its reported 28-day strength of 21.77 MPa exceeded the nominal M20 target, and its UPV was 4.0 km/s. Compared with G2, G3 increases fine-aggregate waste utilization but has a lower reported strength.

Table 5. Comparison of the two preferred alternative mixes.

Criterion	G2 (primary option)	G3 (secondary option)
Tile replacement of fine aggregate	20%	30%
Coarse aggregate replacement	100%	100%
Broken brick : CBP	50:50	50:50
28-day compressive strength	23.30 Mpa	21.77 MPa
UPV	4.2 km/s	4.0 km/s
Reported density	2.204 g/cm^3	2.230 g/cm^3
Recommended emphasis	Strength-performance balance	Greater tile-waste utilization

3.8 Economic and environmental implications

The thesis estimates material-cost savings of approximately 15–30% compared with conventional natural-aggregate concrete, depending on local waste availability, sorting, crushing, grading, transportation and quality-control costs. Use of locally sourced recycled materials may reduce haulage requirements and provide value to materials that would otherwise require disposal. These savings are indicative and should be verified through a project-specific cost comparison that includes processing, testing, rejected material and quality-assurance costs.

At district scale, the thesis estimates that a medium-sized municipality in Surkhet with approximately 50,000 m^2 of annual construction activity could generate around 2,000–2,500 tonnes of CDW, based on an assumed generation rate of 40–50 kg/m^2. If 30% of this material were suitable for recycling, approximately 600–750 tonnes of natural aggregate could potentially be substituted annually. At national scale, the thesis uses an estimated 1.5–2.0 million tonnes of CDW per year and suggests that 450,000–600,000 tonnes of natural aggregates could potentially be substituted if 30% were recovered and processed.

The thesis further presents indicative national benefits of NPR 2–4 billion in savings, 50,000–70,000 tonnes of CO_2-equivalent emissions avoided and 2,000–3,000 employment opportunities. These are scenario-based extrapolations, not outcomes measured by a life-cycle assessment or a national waste audit. Their realization would depend on reliable waste inventories, material suitability, processing infrastructure, transport distances, market demand and regulatory acceptance. The broader environmental contribution is consistent with circular-economy principles and SDG 12 on responsible consumption and production.

4 Conclusion

This study investigated the use of waste ceramic tiles, broken bricks and recycled concrete by-products as aggregate substitutes in M20-grade concrete. Nine mix combinations were designed with 10–30% tile replacement of fine aggregate and 100% replacement of coarse aggregate by different brick–CBP blends. The main conclusions are as follows:

1. Recycled aggregates had higher reported water absorption (approximately 5–15%) and lower specific gravity/density (approximately 2.0–2.4) than natural aggregates. Their angular and irregular particle shapes, together with higher absorption, reduced fresh-concrete workability as replacement increased.

2. The thesis-reported average compressive strengths were 6.06 MPa at 3 days, 14.18 MPa at 7 days and 20.89 MPa at 28 days. The 28-day average slightly exceeded the nominal M20 target, although early-age strength was comparatively low.

3. G2 achieved the highest reported 28-day compressive strength of 23.30 MPa and UPV of 4.2 km/s. Its mix used 20% tiles in the fine aggregate fraction and a 50:50 blend of broken bricks and CBP as full coarse-aggregate replacement. G3 also exceeded the M20 target with 21.77 MPa and is a reasonable alternative where higher tile utilization is desired.

4. Reported hardened density ranged from 2.04 to 2.30 g/cm^3, and UPV ranged from 3.5 to 4.2 km/s. The thesis identifies a positive relationship between density and compressive strength.

5. Durability findings require cautious interpretation. Water absorption (5–12%) and permeable-void content (12–20%) are estimated from literature relationships; comprehensive direct durability testing was not completed. The present evidence therefore supports further investigation rather than an unconditional claim of long-term durability.

6. Indicative economic analysis suggests 15–30% material-cost savings, while national-scale environmental and employment benefits remain scenario estimates requiring validation through detailed local data and life-cycle assessment.

Overall, G2 is recommended as the preferred mix for further validation and potential pilot applications. G3 is a secondary option where maximizing tile-waste utilization is an important objective. Before use in structural construction, the selected mixes should be validated through replicated testing, project-specific mix design, moisture correction, quality control and direct durability assessment.

5 Limitations and recommendations for further study

The study was limited to laboratory-scale specimens and materials collected from selected sources in Surkhet District. The source history of some concrete by-products was uncertain. The available summary data do not provide a complete nine-mix by three-age strength matrix, limiting detailed statistical comparisons between every mixture. Comprehensive durability tests and direct microstructural analysis were not conducted, and the economic and environmental estimates were not based on a full life-cycle assessment.

- Repeat the mix programme with at least three specimens for every mix at each testing age and report individual results, mean, standard deviation and coefficient of variation.
- Conduct direct water absorption and permeable-void testing, together with chloride penetration, carbonation, sulfate resistance, freeze–thaw and drying-shrinkage tests at appropriate ages.
- Extend testing to 90 days, 180 days and one year to assess later-age strength and durability trends.
- Use SEM, XRD, EDS and pore-structure analysis to investigate the interfacial transition zones, residual mortar and pore distribution.
- Undertake field trials and monitor structural performance under local exposure conditions before wider structural application.
- Develop a project-specific life-cycle cost and environmental assessment, including collection, sorting, crushing, screening, transport, quality assurance and end-of-life considerations.

Acknowledgment

The authors acknowledge the guidance and academic support provided by the Central Department of Civil Engineering, Graduate School of Engineering, Mid-West University, and the assistance of individuals who contributed to the laboratory and research process.

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