

Utilization of Building Demolition Waste Materials for Sustainable Granular Sub-Base Design: Experimental Characterisation, ANN-Based Prediction and Life-Cycle Cost Assessment

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Abstract

This study evaluates the technical feasibility, predictive-modelling potential and economic sustainability of building demolition waste used as granular sub-base (GSB) material for flexible pavement construction. The experimental programme considered three material systems: Set I (Building-Waste GSB blended with Conventional GSB under Grade I gradation), Set II (the same blends under Grade II gradation), and Set III (a multi-material blend of BW-GSB, Conventional GSB, recycled brick aggregate and ceramic/tile waste). Tests included specific gravity, water absorption, Los Angeles abrasion, aggregate impact value, Modified Proctor compaction, soaked and unsoaked CBR, and 7-day UCS. A 100% BW-GSB mix reached 24.8% soaked CBR, while a 50:50 BW-GSB:Conventional blend raised it to 36.5%. The multi-material S3-C3 mix achieved 40.1% soaked CBR and the highest UCS of 0.68 MPa. ANN predictions closely tracked the experiments ($R^2 = 0.932$ for soaked CBR and 0.897 for UCS). Life-cycle cost assessment confirmed that a GSB road is the most economical alternative, with 48.97% and 62.11% savings over bitumen and concrete roads respectively.

Keywords: *Construction and demolition waste; granular sub-base; recycled aggregates; CBR; UCS; ANN; life-cycle cost analysis; sustainable pavement.*

I. INTRODUCTION

The continuous growth of urban infrastructure has intensified demand for high-quality pavement aggregates while simultaneously generating large quantities of construction and demolition waste (CDW). Pavement layers consume large volumes of granular material—especially in sub-base and base courses—making them suitable outlets for recycled aggregates when engineering requirements are met. Recent reviews report that CDW aggregates can be used in base and sub-base layers provided gradation, strength, absorption, durability and environmental controls are properly addressed [1], [2]. The scarcity of natural aggregates and the environmental cost of quarrying have created a strong need for circular-material strategies in pavement engineering [3], [4]. Granular sub-base (GSB) is a critical layer because it distributes wheel-load stresses, controls drainage, separates the subgrade from upper layers and contributes to rutting resistance. Recycled concrete aggregate, crushed brick, ceramic waste, reclaimed asphalt pavement and mixed demolition debris have all been explored as partial substitutes for virgin aggregates [5]–[10]. Their performance, however, is highly sensitive to porosity, mineral composition, angularity, fine fraction and moisture susceptibility. A direct one-to-one replacement is therefore often insufficient; engineered blending and quality assurance are required to satisfy MoRTH and IRC requirements. Artificial-intelligence techniques have emerged as useful tools for predicting pavement-material performance from limited laboratory data [17]–[20]. Artificial neural networks (ANN) can capture the non-linear relationships between mix composition and outputs such as CBR, UCS, MDD and moisture response, reducing trial-and-error testing. This paper integrates three perspectives—experimental characterisation, ANN-based prediction, and life-cycle cost assessment—to establish whether demolition-waste GSB can be both structurally adequate and economically attractive.

II. LITERATURE REVIEW

Khan et al. reviewed recycled CDW aggregates in pavement base and sub-base layers and stressed that physical, mechanical and environmental properties must be assessed before field adoption [1]. Pourkhorshidi et al. concluded that recycled aggregates are feasible in unbound layers under controlled gradation and compaction [2], while Mohanty et al. identified variability, durability and the lack of performance standardisation as key challenges [3]. These works establish the sustainability context but underscore the need for local experimental datasets. Zhang et al. reported that processed building-related CDW can satisfy grading and mechanical requirements for embankments [11]. Arulrajah et al. showed that geotechnical and geo-environmental properties vary widely across recycled concrete, crushed brick, waste rock, reclaimed asphalt and recycled glass [6]. Cabalar and co-workers found that the strength of crushed brick, dragged asphalt and crushed concrete sub-bases depends strongly on mix ratio and soil interaction [12]. Studies on ceramic waste indicate that hard ceramic particles enhance interlocking and abrasion resistance when blended appropriately [8], [9], whereas brick-rich aggregates are more porous and raise water absorption [13]–[16]. The literature therefore supports a multi-material approach in which weaker recycled fractions are balanced by dense, hard fractions such as conventional crushed aggregate or ceramic/tile waste. Life-cycle cost and sustainability studies show that recycled-aggregate pavement layers reduce virgin-aggregate use, hauling cost and landfill burden [21]–[24], although savings are project-specific. Machine-learning studies have applied ANN, support-vector regression and hybrid optimisation to predict strength, resilient modulus and durability [17]–[20], [28]–[30], while cautioning that model reliability depends on data quality and proper validation against physical tests. In this work, ANN is used only as a prediction and interpretation aid; experimental data remain the primary basis for material selection and pavement-design justification.

III. MATERIALS AND METHODOLOGY

The methodology assessed demolition-waste GSB using physical, mechanical, compaction, strength and cost criteria. The four constituent materials were Building-Waste GSB (BW-GSB), Conventional GSB, Recycled Brick Aggregate (RBA) and Ceramic/Tile Waste (CTW). Three experimental sets were studied: Set I (Grade I BW-GSB/Conventional blends), Set II (Grade II blends) and Set III (multi-material recycled blends). Table 1 summarises the constituent-material properties and their engineering behaviour.

Table 1. Material properties and expected engineering behaviour.

Material	Sp. Gravity	Water Abs. (%)	LA (%)	Abr. (%)	AIV (%)	Description
BW-GSB	2.35–2.55	2.5–5.5	28–40		22–32	Mixed demolition debris, rough angular texture
Conv. GSB	2.60–2.70	0.5–2.0	18–25		12–18	Quarried crushed stone reference aggregate
RBA	1.85–2.20	8–15	35–50		28–40	Porous crushed fired-clay brick aggregate
CTW	2.30–2.60	0.1–0.8	15–22		10–16	Hard ceramic/tile waste, low absorption

Conventional GSB is the densest and least absorptive material, forming a strong benchmark. BW-GSB has moderate density and acceptable abrasion resistance but contains old mortar that raises absorption. RBA is the weakest (8–15% absorption) and cannot dominate a mix, whereas CTW—with very low absorption and high hardness—acts as a corrective fraction. This justifies the blending strategy in which weaker recycled fractions are combined with stronger conventional and ceramic fractions.

Table 2. Experimental mix matrix (proportions in %).

Mix ID	Set	Gradation	BW-GSB	Conv-GSB	RBA	CTW
S1-C1	Set I	Grade I	100	0	0	0
S1-C2	Set I	Grade I	75	25	0	0
S1-C3	Set I	Grade I	50	50	0	0
S1-C4	Set I	Grade I	25	75	0	0
S1-C5	Set I	Grade I	0	100	0	0
S2-C1	Set II	Grade II	100	0	0	0
S2-C2	Set II	Grade II	75	25	0	0
S2-C3	Set II	Grade II	50	50	0	0
S2-C4	Set II	Grade II	25	75	0	0
S2-C5	Set II	Grade II	0	100	0	0
S3-C1	Set III	Multi	60	20	20	0
S3-C2	Set III	Multi	50	20	20	10
S3-C3	Set III	Multi	50	10	20	20
S3-C4	Set III	Multi	40	10	30	20
S3-C5	Set III	Multi	30	20	30	20

Set I progressively replaces BW-GSB with Conventional GSB under Grade I gradation; Set II repeats this under finer Grade II gradation to isolate the gradation effect; Set III introduces RBA and CTW to study multi-material recycling. This structure separates material effects from gradation effects while developing a practically meaningful recycled blend. The constituent proportions of every mix are illustrated in Fig. 1.

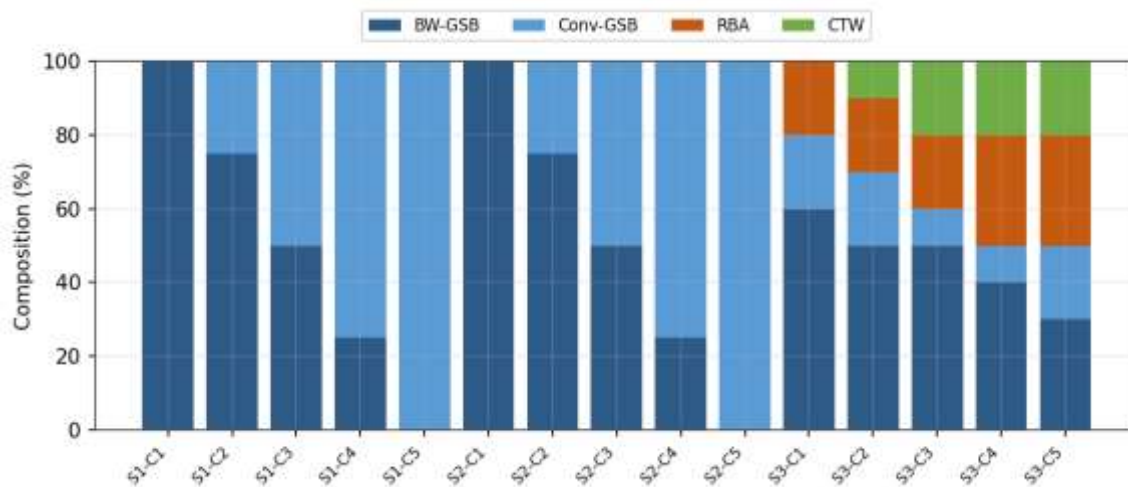


Fig. 1. Material composition of all fifteen experimental GSB mixes.

Table 3. Laboratory tests and standards.

Test	Standard	Purpose in GSB assessment
Specific gravity	IS:2386 Part III	Aggregate density and volumetric behaviour
Water absorption	IS:2386 Part III	Moisture susceptibility and porosity
LA abrasion	IS:2386 Part IV	Resistance to wear and degradation
Aggregate impact value	IS:2386 Part IV	Resistance to sudden impact load
Modified Proctor	IS:2720 Part 8	MDD and OMC for compaction control
CBR	IS:2720 Part 16	Bearing capacity (soaked/unsoaked)

UCS	IS:2720 Part 10	Short-term compressive strength and binding
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CBR is the most important parameter for sub-base design because it directly indicates bearing capacity, while UCS assesses particle bonding. Combining these with density, durability and moisture tests gives a complete engineering picture rather than relying on a single indicator.

IV. RESULTS AND DISCUSSION

Table 4 consolidates the experimental response of all fifteen mixes. In Set I, as Conventional GSB increases, specific gravity rises from 2.41 to 2.67, water absorption falls from 4.82% to 1.45%, soaked CBR climbs from 24.8% to 48.2%, and UCS from 0.38 to 0.63 MPa. Set II follows the same trend but yields slightly lower CBR and UCS because the finer Grade II gradation reduces aggregate-skeleton stability. The key sustainability result appears in Set III: despite lower density, the S3-C3 mix reaches 40.1% soaked CBR and the highest UCS (0.68 MPa), proving that well-designed multi-material recycling can be structurally adequate.

Table 4. Consolidated experimental results for all GSB mixes.

Mix	SG	WA%	LA%	AIV%	MDD	OMC%	U-CBR	S-CBR	UCS
S1-C1	2.41	4.82	38.4	29.8	1.842	9.8	32.4	24.8	0.38
S1-C2	2.48	3.91	34.1	26.4	1.891	9.1	38.6	30.2	0.45
S1-C3	2.54	3.12	30.2	23.1	1.948	8.4	44.8	36.5	0.52
S1-C4	2.61	2.24	26.8	19.5	1.995	7.8	49.2	41.8	0.58
S1-C5	2.67	1.45	22.4	15.8	2.041	7.2	54.6	48.2	0.63
S2-C1	2.40	5.02	39.0	30.0	1.824	10.4	30.8	22.6	0.35
S2-C2	2.47	4.08	35.0	27.0	1.874	9.7	36.4	28.4	0.42
S2-C3	2.53	3.24	31.0	24.0	1.928	9.0	42.2	34.1	0.49
S2-C4	2.60	2.35	27.5	20.5	1.978	8.3	46.8	39.6	0.54
S2-C5	2.66	1.52	23.2	16.5	2.024	7.6	52.1	46.0	0.59
S3-C1	2.36	5.84	37.8	28.6	1.798	10.8	36.4	28.2	0.41
S3-C2	2.40	5.12	34.4	25.8	1.836	10.2	41.8	33.6	0.54
S3-C3	2.43	4.56	30.6	22.4	1.868	9.6	48.2	40.1	0.68
S3-C4	2.39	5.28	32.2	24.1	1.824	10.1	44.6	36.8	0.61
S3-C5	2.44	4.98	31.8	23.6	1.848	9.8	46.8	38.4	0.58

A. Physical and Durability Behaviour

Specific gravity and water absorption show a strong inverse relationship (Fig. 2): denser mixes absorb less water. Set III values stay lower (SG 2.36–2.44) owing to porous RBA, yet CTW limits S3-C3 absorption to 4.56%. Durability (Fig. 3) improves with Conventional GSB content—LA abrasion falls from 38.4% to 22.4% in Set I—while S3-C3 records the best multi-material durability (LA 30.6%, AIV 22.4%) thanks to the hard, angular CTW fraction. All selected blends remain within practical durability limits.

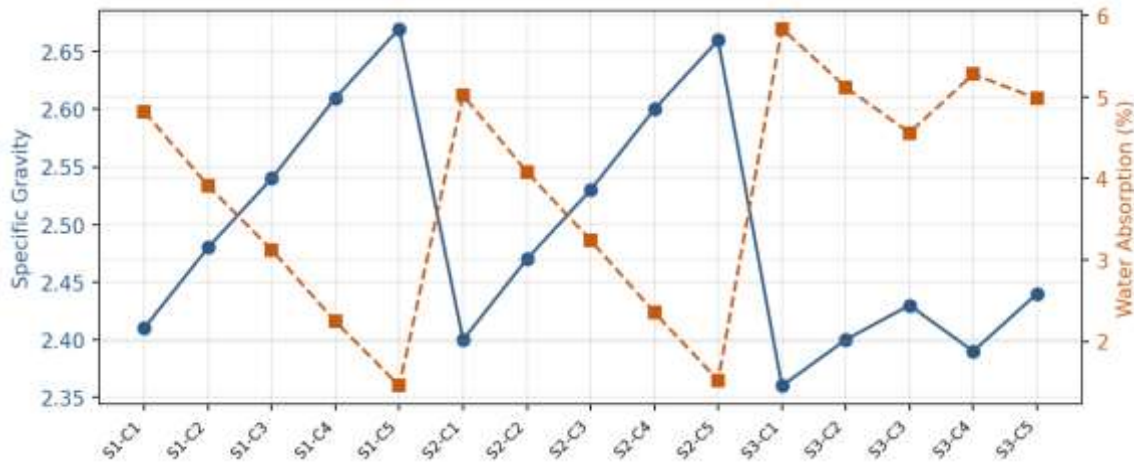


Fig. 2. Specific gravity and water absorption of GSB mixes.

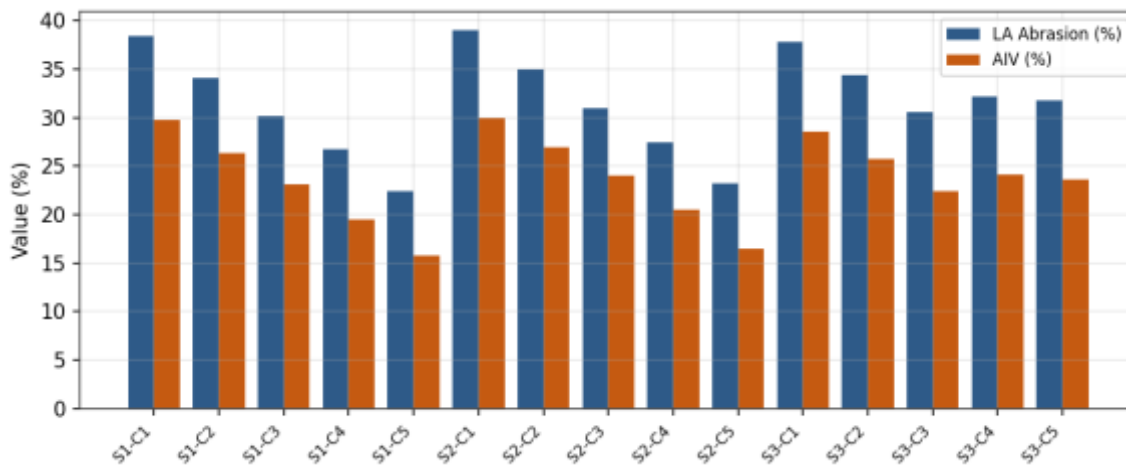


Fig. 3. LA abrasion and aggregate impact value of GSB mixes.

B. Compaction, Bearing Capacity and Strength

Modified Proctor results (Fig. 4) show MDD rising with Conventional GSB content (1.842→2.041 g/cc in Set I) and OMC falling; Set III gives lower MDD because of porous recycled particles, but S3-C3 still attains a workable 1.868 g/cc at 9.6% OMC. The CBR results (Fig. 5) are central to design: S1-C3 (50% BW-GSB) reaches 36.5% soaked CBR, comfortably above the 30% minimum, and S3-C3 reaches 40.1%. The gap between unsoaked and soaked CBR reflects moisture weakening in porous recycled materials. UCS (Fig. 6) increases with Conventional GSB, but the standout is S3-C3 at 0.68 MPa—the highest of all mixes despite only 10% Conventional GSB—indicating that CTW and fine recycled fractions improve inter-particle bonding.

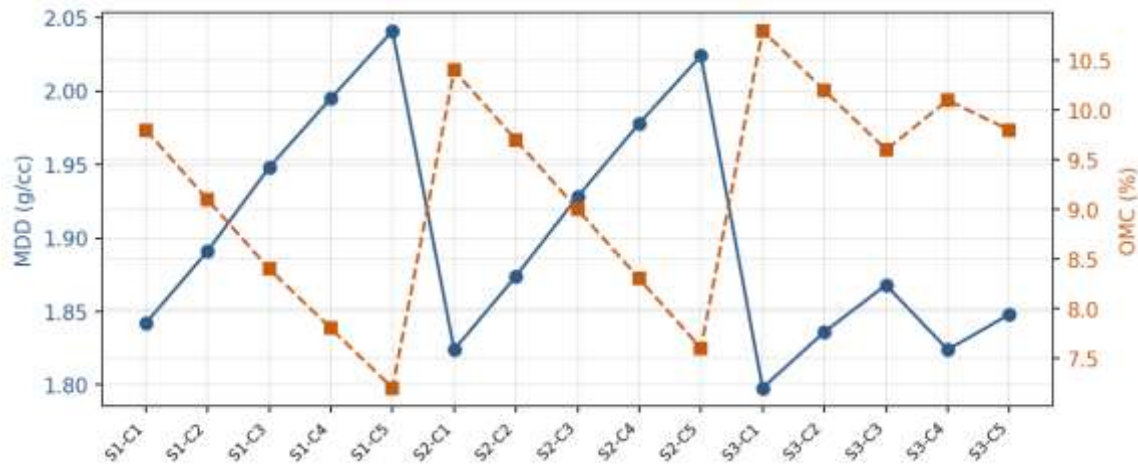


Fig. 4. Modified Proctor compaction behaviour (MDD and OMC).

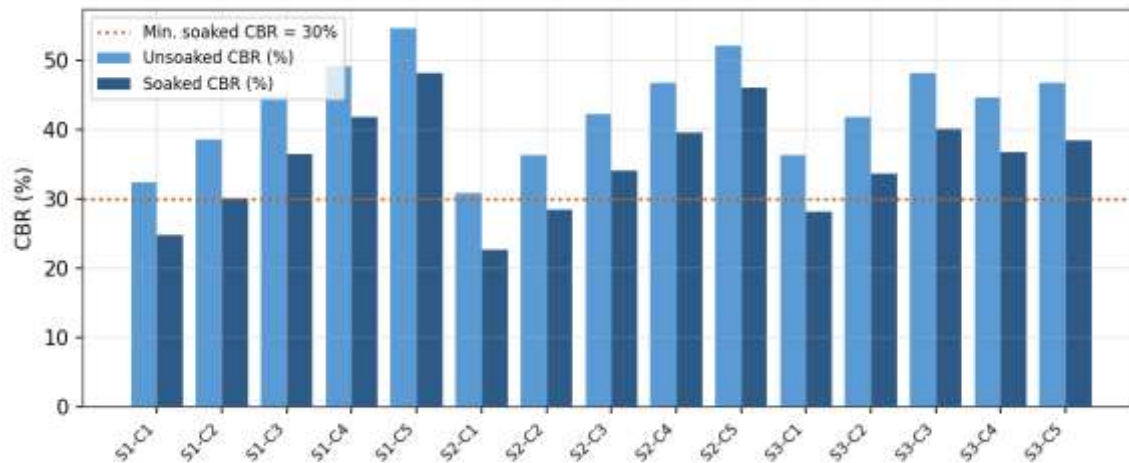


Fig. 5. Unsoaked and soaked CBR for all GSB mixes.

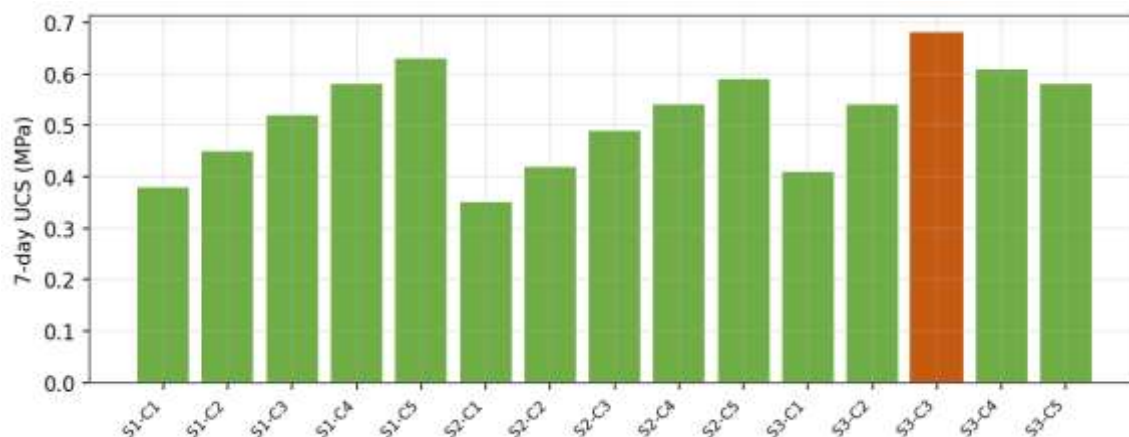


Fig. 6. 7-day UCS of GSB mixes (S3-C3 highlighted).

C. ANN-Based Prediction

An ANN trained on the experimental dataset was evaluated using R^2 , RMSE and MAE. Predicted values (Table 5) closely follow measured trends—for the best sustainable mix S3-C3 the predicted soaked CBR (40.40%) and UCS (0.702 MPa) match the measured 40.1% and 0.68 MPa almost exactly. The model slightly under-predicts the extreme 100% Conventional mix S1-C5, as expected when ANNs trained on small datasets smooth boundary values.

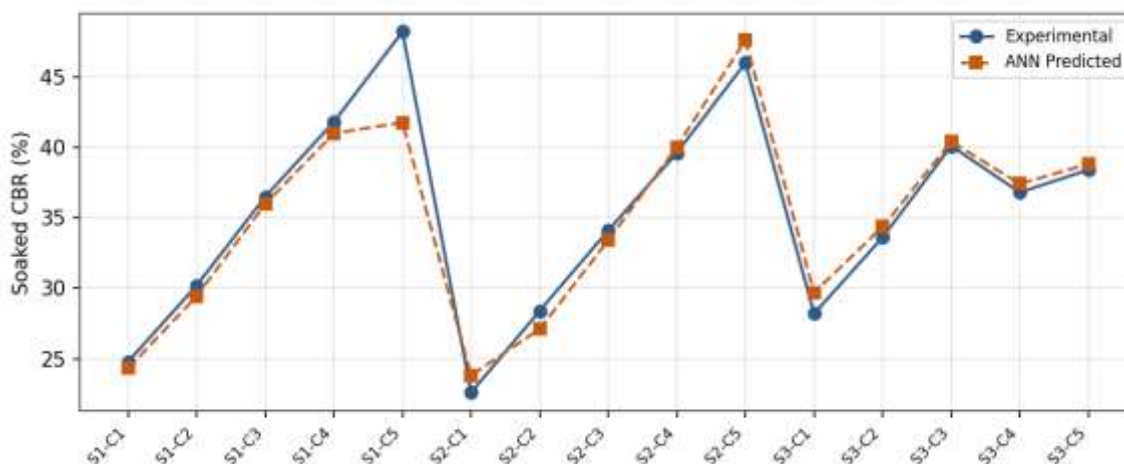
Table 5. ANN-predicted key properties (selected outputs).

Mix	Pred SG	Pred MDD	Pred U-CBR	Pred S-CBR	Pred UCS
S1-C1	2.434	1.837	31.73	24.32	0.353
S1-C3	2.537	1.939	45.30	35.98	0.522
S1-C5	2.638	2.011	48.56	41.76	0.550
S2-C3	2.528	1.919	42.13	33.40	0.464
S2-C5	2.702	2.019	54.21	47.62	0.572
S3-C1	2.354	1.786	36.86	29.69	0.465
S3-C3	2.425	1.868	49.74	40.40	0.702
S3-C4	2.392	1.823	46.88	37.41	0.626
S3-C5	2.431	1.846	47.98	38.81	0.593

Table 6. ANN model performance metrics.

Output Parameter	R ²	RMSE	MAE
Specific Gravity	0.9680	0.0178	0.0134
Water Absorption	0.9721	0.2311	0.1915
MDD	0.9831	0.0099	0.0071
OMC	0.9632	0.2039	0.1631
Unsoaked CBR	0.9169	1.9513	1.3395
Soaked CBR	0.9317	1.8823	1.1895
UCS	0.8966	0.0305	0.0236
LA Abrasion	0.9777	0.7355	0.5661
AIV	0.8975	1.3528	0.6890

MDD is predicted most accurately ($R^2 = 0.983$), followed by LA abrasion (0.978), water absorption (0.972) and specific gravity (0.968). Soaked and unsoaked CBR give 0.932 and 0.917, while UCS and AIV are lower (≈ 0.896) because they depend on micro-bonding and particle contact that composition alone captures imperfectly. The comparison plots (Figs. 7–8) and regression plots (Figs. 9–10) confirm that predictions cluster around the ideal line, and Fig. 11 summarises predictive reliability across all nine outputs. ANN is thus an effective trend-prediction and screening tool, but not a replacement for experimental validation.


Fig. 7. Experimental vs. ANN-predicted soaked CBR.

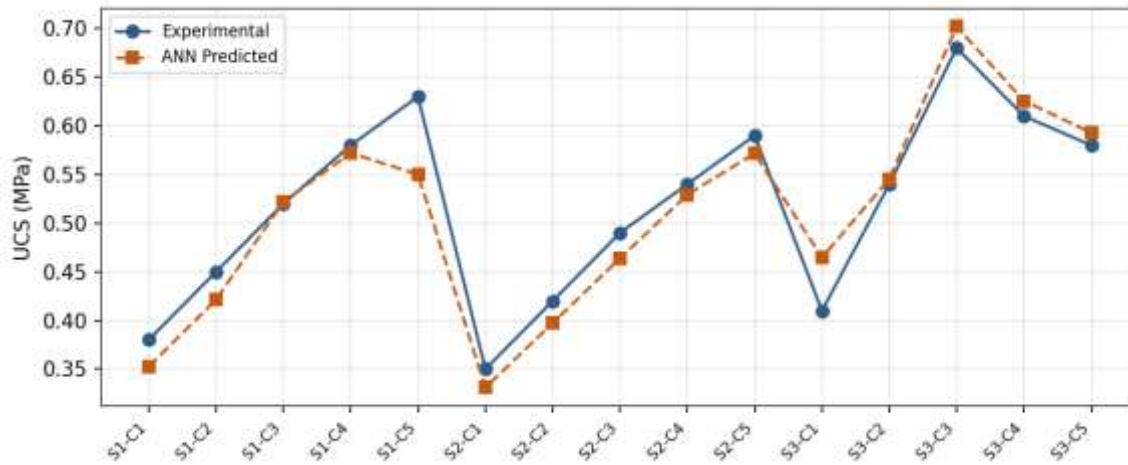


Fig. 8. Experimental vs. ANN-predicted UCS.

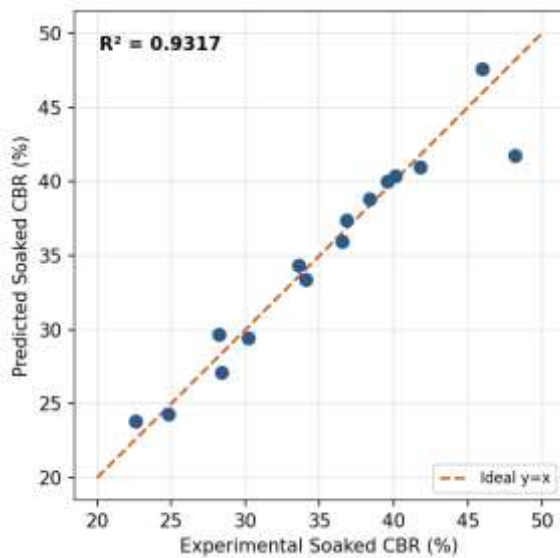


Fig. 9. Regression: soaked CBR.

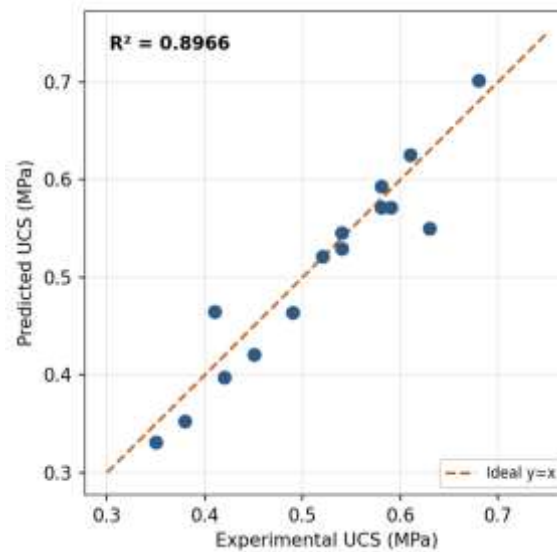


Fig. 10. Regression: UCS.

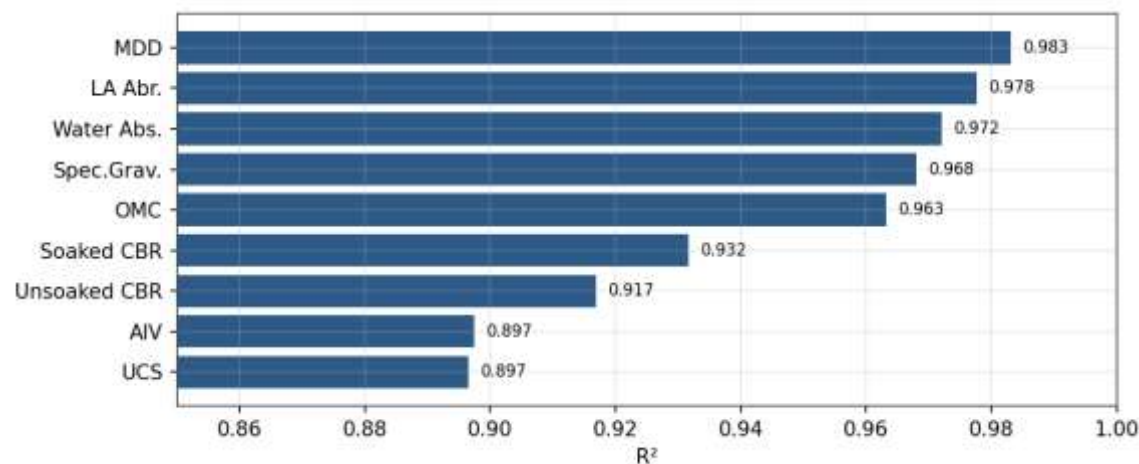


Fig. 11. ANN R² performance across output parameters.

D. Pavement Design and Life-Cycle Cost

Pavement design followed IRC:37-2018 principles. Life-cycle cost analysis (LCCA) was performed for a 1 km × 7 m section over a 10-year period at a 6% discount rate, comparing only GSB, bitumen and concrete roads. Table 7 compares the three preferred GSB alternatives: the conventional S1-C5 needs 300 mm thickness, the 50:50 S1-C3 needs 350 mm, and the multi-material S3-C3 needs only 325 mm—just 25 mm more than the conventional reference despite a much higher recycled content (Fig. 14).

Table 7. Pavement design comparison of selected GSB alternatives.

Pavement Case	S-CBR (%)	UCS (MPa)	MDD (g/cc)	GSB t (mm)	Role
Conv. GSB (S1-C5)	48.2	0.63	2.041	300	Reference option
50:50 blend (S1-C3)	36.5	0.52	1.948	350	Balanced sustainable
Multi-material (S3-C3)	40.1	0.68	1.868	325	Best recycled option

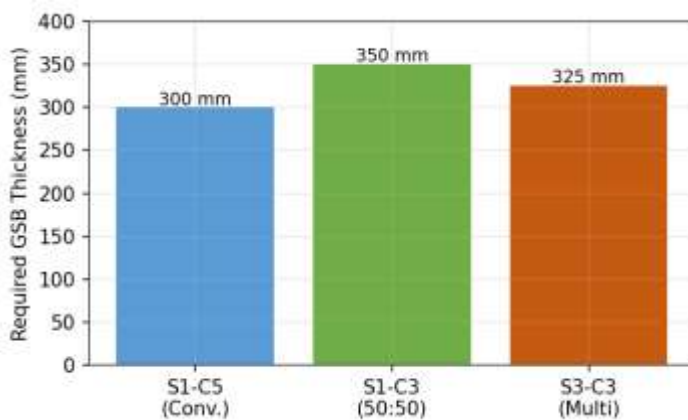


Fig. 14. Required GSB thickness for selected alternatives.

The LCCA (Table 8) shows the GSB road costs only Rs. 97.81 lakh, versus Rs. 191.68 lakh for bitumen and Rs. 258.16 lakh for concrete (Fig. 15). This translates into savings of 48.97% over bitumen and 62.11% over concrete (Table 9, Fig. 17). The large gap over concrete is driven by concrete's high initial cost, while the saving over bitumen also reflects bitumen's frequent maintenance. When recycled GSB materials such as S3-C3 are used, these economic gains are reinforced by reduced virgin-aggregate consumption and landfill diversion.

Table 8. Life-cycle cost components (Rs. lakh).

Road Type	Initial	PW Annual Maint.	PW Major Maint.	Total LCC
GSB Road	73.50	18.03	6.28	97.81
Bitumen Road	129.50	38.64	23.54	191.68
Concrete Road	224.00	23.18	10.98	258.16

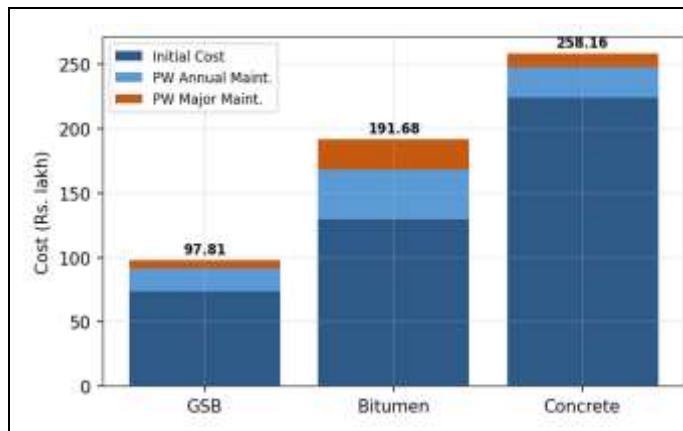


Fig. 15. LCC components by road type.

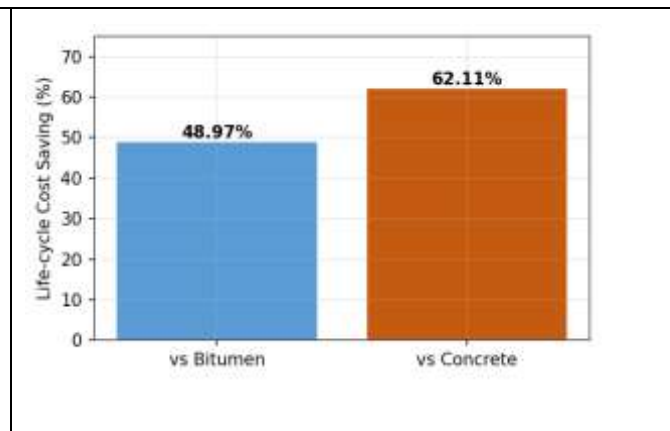


Fig. 17. % cost saving of GSB road.

Table 9. Cost saving of GSB road relative to alternatives.

Comparison	Cost Saving (Rs. lakh)	Saving (%)
GSB vs Bitumen	93.87	48.97
GSB vs Concrete	160.35	62.11

E. Overall Technical Discussion

Single-material demolition waste cannot automatically replace conventional GSB: BW-GSB alone gives only 24.8% soaked CBR owing to porosity, recycled mortar and moisture sensitivity. Blending with Conventional GSB (S1-C3: 36.5% soaked CBR, 0.52 MPa UCS) is a practical pathway for immediate field adoption. Grade II mixes perform slightly below Grade I, confirming the value of coarser gradation for interlock, yet S2-C3 (34.1% soaked CBR) still suits light-to-medium traffic. The strongest sustainability outcome is S3-C3, where CTW offsets the porosity of RBA and BW-GSB to deliver 40.1% soaked CBR and 0.68 MPa UCS. ANN predictions remain consistent with experiments, but the study deliberately separates predicted from measured results, treating ANN-GA optimisation as a future direction rather than a design basis.

V. CONCLUSION

Building demolition waste can be converted into technically acceptable GSB material when blended with suitable aggregate fractions. BW-GSB alone satisfied most physical requirements but its 24.8% soaked CBR was below the desired threshold, so direct unblended use is not recommended for structural GSB. The 50:50 S1-C3 mix achieved 36.5% soaked CBR, 1.948 g/cc MDD and 0.52 MPa UCS, making it a balanced Grade I option. The multi-material S3-C3 mix (50% BW-GSB, 10% Conventional GSB, 20% RBA, 20% CTW) achieved 40.1% soaked CBR and the highest UCS of 0.68 MPa—the best sustainable experimental mix. ANN predictions agreed strongly with experiments ($R^2 = 0.932$ for soaked CBR, 0.983 for MDD), supporting data-driven preliminary screening. In pavement design, S3-C3 required only 325 mm GSB thickness versus 300 mm for conventional GSB, and life-cycle cost analysis showed the GSB road to be the lowest-cost option, saving 48.97% over bitumen and 62.11% over concrete. Overall, demolition-waste GSB can support sustainable, cost-effective and structurally reliable flexible-pavement construction.

Future work should include repeated-load triaxial testing for resilient modulus and permanent deformation, field trial sections, leachate and geo-environmental assessment of CTW and mixed waste, larger datasets for ANN and hybrid optimisation, expanded life-cycle assessment covering embodied carbon and transport sensitivity, and performance-based specifications for demolition-waste GSB under Indian conditions.

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