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Research Article

Comparative engineering performance of reclaimed asphalt pavement and construction and demolition waste in low- and high-plasticity clay subgrades

Gnana Rahul B [*,a], Hanumantharao Ch [b]

Department of Civil Engineering, Koneru Lakshmaiah Educational Foundation, India

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Abstract

The generation of reclaimed asphalt pavement (RAP) and construction and demolition (C&D) waste provides an opportunity for reuse in pavement subgrades. This study evaluates RAP and C&D waste as recycled amendments for low-plasticity clay (CL) and high-plasticity clay (CH) at replacement levels of 0%, 10%, 20%, 30%, and 40%, comprising eighteen experimental conditions. Atterberg limits, standard Proctor compaction, and soaked California Bearing Ratio (CBR) tests were conducted for mixtures, while direct shear tests were performed on selected mixtures. Increasing recycled-material content reduced the plasticity index and increased maximum dry density. The soaked CBR of C&D-modified soils increased up to 40% replacement, reaching 12.4%, whereas RAP-modified soils reached their maximum CBR at 30% replacement, with values of 9.1% for CL and 6.3% for CH, followed by a decrease at 40% replacement. Direct shear tests indicated increases of 10.0–13.0° in friction angle relative to the corresponding untreated soils, with C&D mixtures showing the greater increase. Factorial ANOVA identified significant effects of soil classification, recycled-material type, and replacement level on soaked CBR, together with significant interaction effects ($p < 0.001$), while the reported replicate variability remained low (CV = 0.8–4.6%). Economic assessment indicated reductions in costs, particularly for C&D waste at higher replacement levels and haul distances. RAP replacement of 20–30% and C&D waste replacement of 30–40% provided optimal engineering performance, with C&D waste proving particularly effective.

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1. Introduction

The subgrade is the base material of all flexible and rigid pavement structures and the stiffness and bearing capacity of the subgrade dictates the thickness, cost and serviceability of the overlying pavement layers [1]. Among the most problematic subgrade materials are fine-grained soils with low soaked bearing capacity, namely low-plasticity (CL) and high-plasticity (CH) clays. Fine-grained subgrade soils can exhibit moisture sensitivity and changes in volume with variations in water content. The extent of shrink–swell behavior depends on factors including mineralogy, soil structure, initial moisture condition and stress history; therefore, plasticity classification alone is insufficient to quantify the swelling potential of a soil [19,20]. Chemical stabilizers like cement and lime are commonly used by engineers to work with such soils, and both materials are energy and carbon intensive to produce; but more broadly, both materials have a history of being used on large scales, and are not sitting well with the low-carbon goals of infrastructure construction.

At the same time, two waste streams have increased in magnitude and are now comparable to the traditional demand for aggregates in many areas. Both reclaimed asphalt pavement (RAP) and

*Corresponding author: gnanarahul@gmail.com
[a]orcid.org/0000-0001-8441-4849; [b]orcid.org/0000-0003-4335-4143
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construction and demolition (C&D) waste are generated by the hundreds of millions of tons globally each year (millions annually worldwide) from the existing asphalt roads and the renovation and demolition of buildings and infrastructure, respectively. Both materials are being used more and more as an amendment within pavement structures, particularly in granular base and sub-base layers [4,5,7] but in recent years comparatively few and largely independent studies have been undertaken to determine the effectiveness of using both materials as a direct amendment to the fine-grained subgrade soil and not as a separate layer within pavement structure; that is, replacing a portion of the subgrade soil itself. How well a recycled material performs when added to a soil matrix is not a characteristic of the recycled material alone, but the result of how the recycled material interacts with the plasticity, fines content and moisture-holding capacity of the host soil and the gradation, angularity, absorption and (for RAP) residual binder content of the recycled material. The replacement level can vary from soil to soil based on the dominance of the fines fraction and its moisture sensitivity in a high-plasticity soil which can behave differently than a low-plasticity soil. Given that most of the existing literature focuses on RAP or C&D behavior in one host soil, and typically at one specific, study-specific set of replacement levels, it is difficult to draw general or transferable conclusions about the preference of a given RAP or C&D, based on a specific study, for a particular clay classification. The comparison of controlled RAP and C&D waste in a similar experimental program in a head-to-head manner is seldom reported.

Comparative data for the two soil classifications (CL and CH) tested under similar conditions are scarce. Studies often have different replacement levels or compaction procedures across the different materials, making it difficult to compare the materials. Unlike the CBR, shear-strength characterization (cohesion and friction angle) is reported much less frequently, although it is directly related to slope and embankment stability next to the pavement corridor. Replication, variability and significance testing of observed differences (known as statistical validation) are sometimes reported in recycled-subgrade literature. This research study is to quantify and compare, within one controlled experiment, the engineering performance of RAP and C&D waste as partial replacement materials for CL and CH clay subgrades, and determine the range of replacement that provides the best engineering gain for each type of recycled material and soil. Characterize the physical and index properties of the parent CL soil, CH soil, RAP and C&D waste materials. Measure the effect of addition of RAP and C&D replacement on plasticity characteristics (LL, PL, PI) of both soils. Evaluate the effect of replacement on standard Proctor compaction behavior (MDD and OMC). Determine the influence of replacement on soaked CBR for 5 replacement levels (0–40%). Use direct shear testing to determine the cohesion (c) and friction angle (φ) of selected, representative mixtures. Statistically compare the effects of soil type, recycled-material type and replacement level on measured performance. Determine the desirable-performing range of replacement materials and soils. Evaluate engineering and indicative economic consequences of the results for practical subgrade improvement.

The novelty of this study is that two different host soils were examined (CL and CH), two recycled materials with different particle character (RAP and C&D waste) were used, a common replacement range (0–40%) was used and a common testing program (Proctor and CBR) was applied to all eighteen conditions (with the same test levels); a formal statistical validation was applied to the observed trends; a resource-efficient, targeted direct-shear program was applied only to the best-performing mixtures; a transparent, sensitivity-tested economic comparison was carried out. This combination enables a like-for-like comparison of the relative merits of RAP and C&D waste over the entire range of clay plasticity, the major deficiency noted in the literature.

2. Materials and Experimental Program

2.1 Materials

2.1.1 CL Soil

The low-plasticity clay (CL) was obtained from a natural clay borrow. The soil had a liquid limit (LL) of 43%, a plastic limit (PL) of 20%, and a plasticity index (PI) of 23%. Approximately 60% of the material passed the 0.075 mm sieve, indicating that it was predominantly fine-grained. Under

the Unified Soil Classification System (USCS)[13], the soil was classified as CL based on its liquid limit below 50% and its plasticity index plotting above the A-line on the plasticity chart. Its specific gravity was 2.71. The measured index properties and particle-size distribution are reported in Tables 1 and 2, respectively and the resulting grading data were used to construct the particle-size distribution curve presented in Fig. 2.

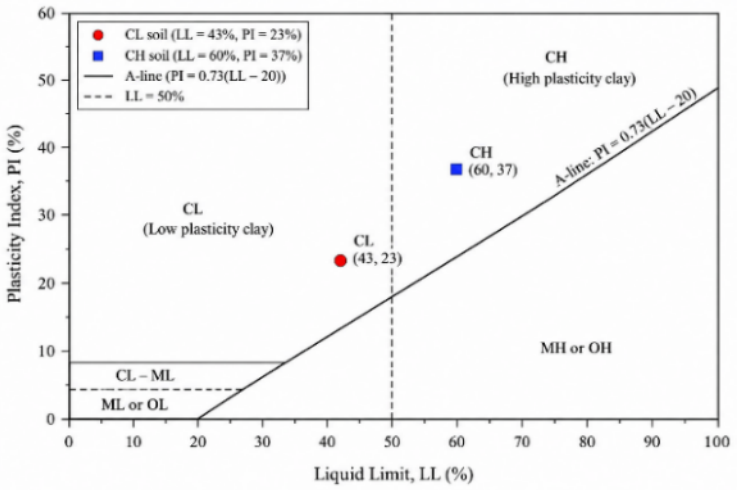

Fig. 1. USCS plasticity chart showing the measured liquid limit and plasticity index of the CL and CH soils

Note: The USCS classification of the CL and CH soils was assessed using their measured liquid limits and plasticity indices. Figure 1 presents the positions of the two soils relative to the A-line and the liquid-limit boundary of 50%.

2.1.2 CH Soil

The high-plasticity clay (CH) was obtained from a natural deposit. It had a liquid limit (LL) of 60%, a plastic limit (PL) of 23%, and a plasticity index (PI) of 37%. Approximately 73% of the material passed the 0.075 mm sieve, confirming that it was predominantly fine-grained. Under the USCS, the soil was classified as CH because its liquid limit was greater than 50% and its plasticity index plotted above the A-line on the plasticity chart. The specific gravity was 2.73. The measured index properties and particle-size distribution are reported in Tables 1 and 2, respectively. The particle-size distribution of the CH soil was determined over the coarse- and fine-particle ranges, and the resulting grading data were used to construct the particle-size distribution curve presented in Fig. 2.

2.1.3 The Reclaimed Asphalt Pavement (RAP)

RAP was obtained from an existing asphalt pavement and processed by milling and crushing before use. The reclaimed asphalt pavement (RAP) used in this study was collected from existing road pavements in Vijayawada, Andhra Pradesh, India, in the form of milled asphalt material. Based on the available source information, the pavement was estimated to be approximately five years old; however, documentary records confirming its construction year were unavailable. The collected milled RAP was screened to obtain a maximum particle size of 19.0 mm before being used as a partial replacement material in the clay subgrade mixtures. The processed material was screened to a maximum particle size of 19.0 mm, representing the particle-size range of the recycled material intended for subgrade modification. The processed RAP had a specific gravity of 2.45 and a water absorption of 1.8%. The particle-size distribution indicated that 86% and 63% of the material passed the 4.75 mm and 2.36 mm sieves, respectively, while 7% passed the 0.075 mm sieve. The asphalt/binder content was 5.0%. The complete particle-size distribution of the RAP is presented in Table 1 and Fig. 2. [9]. The characteristic particle sizes D10,D30,D60 were obtained from the particle-size distribution curves. The coefficient of uniformity Cu and coefficient of curvature Cc were calculated using Eqs. (1) and (2), respectively, in accordance with the soil-classification definitions provided in ASTM D2487.

Table 1. Particle-size distribution of the constituent materials

Sieve / particle size	CL – % passing	CH – % passing	RAP – % passing	C&D – % passing
19.0 mm	100	100	100	100
9.50 mm	100	100	96	97
4.75 mm	100	100	86	89
2.36 mm	95	97	63	68
1.18 mm	88	92	43	50
0.600 mm	80	87	29	36
0.300 mm	72	82	18	25
0.150 mm	65	78	11	16
0.075 mm	60	73	7	10
0.038 mm	52	65	—	—
0.020 mm	43	55	—	—
0.010 mm	34	45	—	—
0.005 mm	25	35	—	—
0.002 mm	18	27	—	—
0.001 mm	8	15	—	—
0.0005 mm	3	8	—	—

Note: The fine-particle distribution of the CL and CH soils below 0.075 mm was obtained from the sedimentation/hydrometer portion of the particle-size analysis, whereas the RAP and C&D distributions were characterized within their applicable granular size range.

Table 2. Characteristic particle-size parameters of the constituent materials

Material	D10 (mm)	D30 (mm)	D60 (mm)	Cu	Cc
CL	0.00115	0.00735	0.0750	65.3	0.63
CH	0.00061	0.00282	0.0276	45.2	0.47
RAP	0.126	0.630	2.127	16.9	1.48
C&D	0.075	0.411	1.734	23.1	1.30

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

$$C_c = \frac{D_{30}^2}{D_{10} D_{60}} \tag{2}$$

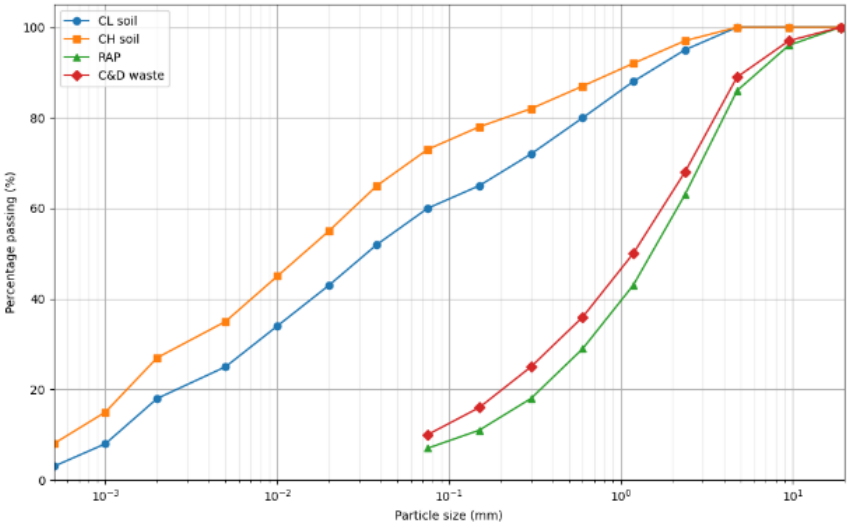

Fig. 2. Particle-size distribution curves of CL soil, CH soil, reclaimed asphalt pavement (RAP), and construction and demolition (C&D) waste

2.1.4 The Construction and Demolition Waste

The construction and demolition (C&D) waste was obtained from a mixed demolition-waste stockpile and processed by to obtain a maximum particle size of 19.0 mm. The processed material had a specific gravity of 2.45, water absorption of 6.0%, and 10% passing the 0.075 mm sieve. Its particle-size distribution is presented in Table 1 and Fig. 2.

Table 3. Physical and index properties of the CL soil, CH soil, RAP and C&D waste

Property	CL soil	CH soil	RAP	C&D waste
USCS classification	CL	CH	—	—
Specific gravity, Gs	2.71	2.73	2.4	2.45
Liquid limit, LL (%)	43	60	—	—
Plastic limit, PL (%)	20	23	—	—
Plasticity index, PI (%)	23	37	—	—
Passing 75 μm (%)	60	73	7	10
Natural moisture content (%)	11.9	15.1	3.0	5.0
Maximum particle size (mm)	4.75	4.75	19.0	19.0
Water absorption (%)	—	—	1.8	6.0
Asphalt/binder content (%)	—	—	5.0	—

Note: Water absorption of the RAP and C&D materials was determined in accordance with IS 2386 (Part 3):1963. The asphalt binder content of RAP was determined by solvent extraction in accordance with ASTM D2172/D2172M.



(a) Demolition of building structure



(b) Generation of construction and demolition (C&D) waste



(c) C&D waste at the demolition site



(d) Prepared C&D waste sample



(e) Milled reclaimed asphalt pavement (RAP) sample



(f) Laboratory pulverizer used for sample preparation

Fig. 3. Sources and representative samples of recycled materials used in the experimental investigation

The material was reported to consist of approximately 50% concrete-derived material, 20% mortar, 25% brick/masonry particles, and 5% other materials by mass (Table 4). The detailed composition of the remaining constituents should be reported where supported by material-sorting records. The particle-size distribution of the processed C&D material showed 89%, 68%, 50%, 36%, 25%, 16% and 10% passing the 4.75, 2.36, 1.18, 0.600, 0.300, 0.150 and 0.075 mm

sieves, respectively. The processed C&D material was subsequently used as the recycled replacement material in the soil mixtures [10].

Table 4. Constituent composition of the C&D waste

Constituent	Percentage by mass (%)
Concrete-derived material	50
Mortar	20
Brick/masonry	25
Other materials	5
Total	100

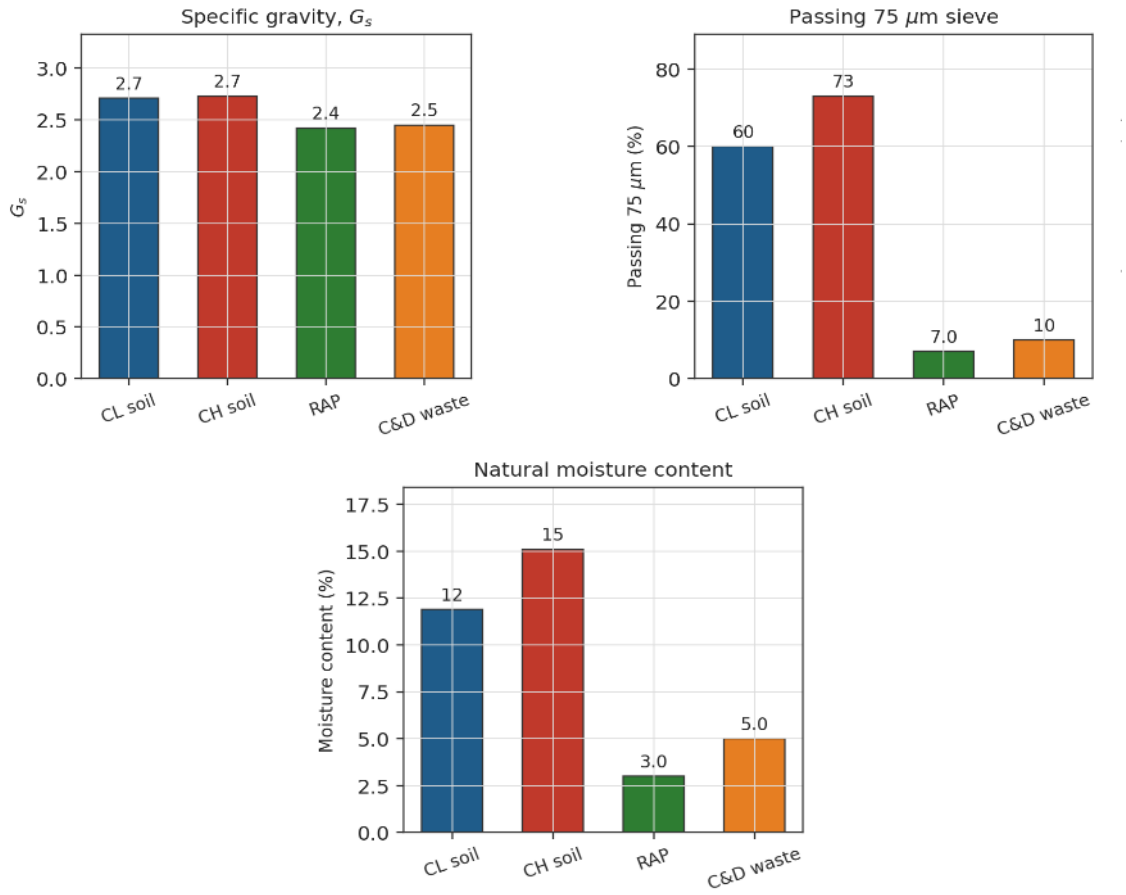

Fig. 4. Comparative physical and index properties of CL, CH, RAP and C&D waste

2.2 Experimental Matrix

Four series of mixtures were prepared consisting of CL + RAP, CL + C&D waste, CH + RAP and CH + C&D waste at replacement levels of 0, 10, 20, 30 and 40% on a dry-mass basis. For each replacement level, the specified dry mass fraction of the host soil was replaced by an equal dry mass fraction of RAP or C&D waste, while maintaining a constant total dry mass of the soil–recycled-material blend.

Accordingly, the replacement percentage was defined as the mass fraction of recycled material in the final dry blend and was calculated as

$$R = M_r/(M_s + M_r) \times 100 \quad (3)$$

where $M_r$is the dry mass of recycled material and $M_s$is the dry mass of host soil. Thus, for a normalized 100 kg dry blend, a 10% replacement consists of 90 kg of dry host soil and 10 kg of dry recycled material, while a 40% replacement consists of 60 kg of dry host soil and 40 kg of dry recycled material.

The adopted replacement basis was intentionally mass-based rather than volume-based. Because the specific gravities of the host soils and recycled materials were different, equal dry-mass replacement percentages do not correspond to equal volumetric replacement fractions. No volumetric correction was therefore applied. The mass-based approach was maintained consistently for all mixtures to provide a common basis for comparison of RAP and C&D waste across the CL and CH soils.

Table 5. Experimental mixture matrix (18 unique conditions).

Series	Host soil	Recycled material	Replacement levels tested (%)	No. of conditions
1	CL	RAP	0, 10, 20, 30, 40	5
2	CL	C&D waste	10, 20, 30, 40 (0% shared with Series 1)	4
3	CH	RAP	0, 10, 20, 30, 40	5
4	CH	C&D waste	10, 20, 30, 40 (0% shared with Series 3)	4

Note*: Total unique mixture conditions: 18 (2 controls + 8 CL blends + 8 CH blends).*

2.3 Material Preparation and Mixing

The soils (CL and CH) were air-dried, ground and sieved before mixing. Oven drying was performed at a low temperature for RAP (60 ± 5 °C) so as not to soften the residual binder, and at ambient temperature or 60 °C for C&D waste, prior to screening to the target maximum particle size of 19.0 mm. For each mixture, the required dry masses of host soil and recycled material were weighed separately according to the specified dry-mass replacement level. The dry constituents were then thoroughly blended to obtain a uniform mixture before water was progressively added to achieve the target moisture condition established from the Standard Proctor test. The mixture was thoroughly homogenized after water addition and sealed in polyethylene bags for 24 h to allow moisture equilibration before compaction.

2.4 Specimen Preparation and Quality Control

The samples were compacted in the standard Proctor mold with standard compactive effort (101.6 mm diameter) in three layers of 25 blows per layer using a standard rammer. The results of the strength and index tests were obtained from three replicate specimens (n = 3 for each mixture condition) to enable within-condition variability to be assessed. Moisture content was checked for each batch, and batches exceeding ±1% of the target moisture content were discarded and remixed. Individual test results exceeding 10% from the corresponding batch mean were flagged for review under the adopted quality-control criterion. The reported dataset retained three replicate observations for each mixture condition. During the experimental program, no specimens were rejected because of the ±1% moisture-content criterion, and no test results were excluded following application of the 10% deviation criterion.

2.5 Laboratory Testing

2.5.1 Atterberg Limits

The host soils and all CL and CH mixtures were tested for liquid limit, plastic limit and plasticity index [14]. Since the majority of the RAP and C&D waste materials are granular and not plastic, they were not tested separately for Atterberg limits.

2.5.2 Standard Proctor

The standard Proctor compaction procedure [16] was used to determine the maximum dry density (MDD) and optimum moisture content (OMC) for all eighteen mixture conditions.

2.5.3 Soaked CBR

The laboratory California Bearing Ratio (CBR) test was conducted with reference to IS 2720 (Part 16):1987. The CL and CH soil mixtures incorporating reclaimed asphalt pavement (RAP) and construction and demolition (C&D) waste were prepared at the corresponding optimum moisture

content (OMC) and maximum dry density (MDD) determined from the Standard Proctor test. The specimens were soaked for the duration recorded in the experimental programme and subjected to the surcharge used during testing. Following soaking, penetration testing was conducted, and CBR values were evaluated at penetrations of 2.5 mm and 5.0 mm in accordance with the standard. When the CBR value at 5.0 mm penetration exceeded that at 2.5 mm, the repeat-test requirement specified in the standard was applicable. The final reported value must be selected according to the standard's reporting procedure and supported by the laboratory records [17].

2.5.4 Direct Shear

Direct shear testing was applied selectively to the untreated controls and to the mixtures determined to provide the best-performing replacement level for each RAP and C&D series, namely 30% RAP and 40% C&D waste for the CL and CH soils. Direct shear specimens were prepared using a 60 mm × 60 mm × 25 mm shear box at the corresponding maximum dry density (MDD) and optimum moisture content (OMC) obtained from the Standard Proctor test. The tests were conducted under consolidated-drained conditions at normal stresses of 50, 100 and 150 kPa[18]. For the clayey mixtures, the shearing rate was maintained at 0.01 mm/min in accordance with the consolidated-drained procedure specified in IS 2720 (Part 13):1986. The shear-stress-at-failure data were plotted according to the Mohr–Coulomb failure criterion to determine cohesion (c) and friction angle (φ).

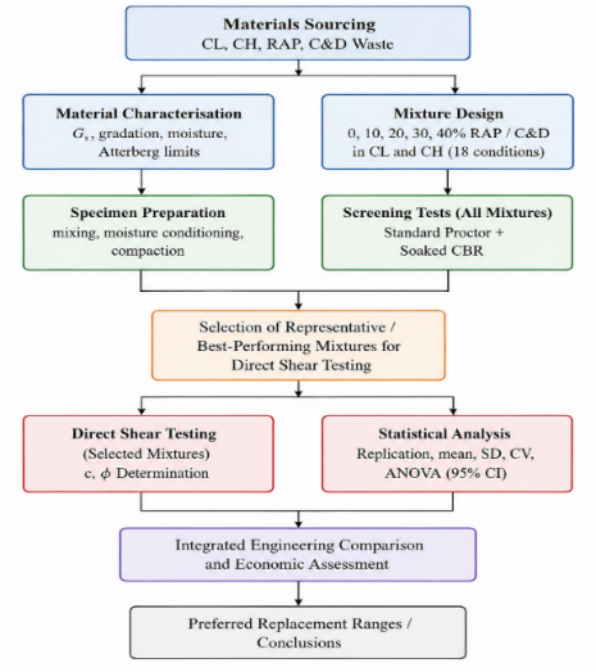

Fig. 5. Overall experimental framework adopted in this study

2.5.5 Statistical Analysis

Triplicate soaked CBR measurements were summarized using the mean, standard deviation (SD), and coefficient of variation (CV). For inferential analysis, the non-zero replacement levels (10%, 20%, 30%, and 40%) were analyzed using a three-factor fixed-effects general linear model (factorial ANOVA), with soil classification (CL and CH), recycled-material type (RAP and C&D waste), and replacement level (10%, 20%, 30%, and 40%) treated as categorical fixed factors. All two-way and three-way interaction effects were included. The 0% mixtures represented the common untreated reference soils and were therefore not duplicated as separate RAP and C&D treatments in the factorial model. They were retained as reference conditions for comparison with the corresponding treated mixtures. The analysis was based on the replicate CBR values reported in Table 11.

Type II sums of squares were used for the factorial ANOVA because the experimental design was balanced and the model contained interaction terms. The results were reported using F-statistics,

degrees of freedom (df), p-values, and partial eta-squared (ηp^2) effect sizes. Tukey's honestly significant difference (HSD) procedure was used for post-hoc comparison of replacement levels within the individual soil–material series where significant effects were identified. Model assumptions were evaluated using residual diagnostics and Levene's test for homogeneity of variance. Because the replicate values in Table 11 are reported to one decimal place, the statistical analysis represents the reported rounded dataset and the resulting residual variance is interpreted with consideration of this reporting precision [21].

2.5.6 Economic Assessment

An indicative project-level cost comparison was conducted on the basis of 1 ton of treated subgrade, considering the cost of virgin borrow soil, recycled material procurement, processing, transportation, and, where applicable, an avoided-disposal credit. For a replacement level r the unit cost of the recycled-material alternative was calculated as:

$$C_r = (1 - r)C_v + r\left(C_m + C_p\right) + C_t - rC_d \tag{4}$$

where C_r is the cost of 1 tonne of treated subgrade (₹/t), C_v is the unit cost of virgin borrow material (₹/t), C_m is the recycled-material cost (₹/t), C_p is the processing cost (₹/t), C_t is the transportation cost (₹/t), C_d is the avoided disposal cost (₹/t), and r is the replacement fraction by mass. Transportation cost was calculated as:

$$C_t = D \times C_{tr} \tag{5}$$

where D is the one-way haul distance (km) and C_{tr} is the transportation rate [₹/(t·km)]. The virgin-soil reference case was calculated as:

$$C_{virgin} = C_v + C_t \tag{6}$$

The economic comparison was restricted to the material procurement/processing and haulage stage, with no allowance for construction labor, equipment operating costs, pavement maintenance, user costs, taxes or financing. The base-case haul distance was 25 km. The reference year for the indicative cost assumptions was 2025–26, with the geographical basis taken as the Andhra Pradesh construction-material market. The adopted rates should therefore be regarded as indicative rather than universal project rates and should be replaced by project-specific quotations or applicable local Schedule of Rates during implementation.

The avoided-disposal term was treated as conditional credit rather than an intrinsic property of recycled material. The credit is applicable only where diversion of the same quantity of RAP or C&D waste from disposal generates an actual disposal-cost saving for the project owner or waste generator. If the disposal cost has already been incorporated into the supplier's recycled-material price, or if the project owner does not otherwise incur the disposal cost, the credit is excluded to avoid double counting. Both credited and uncredited cases are therefore distinguished in the economic interpretation.

3. Results and Discussion

3.1 Initial Material Characteristics

The CH soil had a much higher plasticity (LL = 60 and PI = 37), and also a higher fines content (73% passing 75 μm) than the CL soil (LL = 43, PI = 23 and 60% passing 75 μm), as would be expected when the soils are compared and a meaningful range of clay plasticity has been bracketed (Table 1, Fig. 1). Both RAP and C&D waste were coarse, low-fines materials (7% and 10% passing the 75 μm sieve, respectively) with lower specific gravities (2.42 and 2.45, respectively) than the clay soils (2.71 for CL and 2.73 for CH). Compared with RAP, the water absorption of C&D waste (6.0%) is higher, due to the presence of the porosities associated with mortar and brick in the mix and is an important control on the compaction and moisture-retention behavior discussed in Section 3.3.

Table 6. Dry-mass mixture proportions and target moisture conditions

Mixture	Host soil	Recycled material	Repl. (%)	Dry host soil* (kg)	Dry recycled material* (kg)	Total dry blend* (kg)	Target OMC (%)	Target water at OMC* (kg)
CL control	CL	—	0	100	0	100	19.0	19.0
CL + RAP10	CL	RAP	10	90	10	100	17.4	17.4
CL + RAP20	CL	RAP	20	80	20	100	16.1	16.1
CL + RAP30	CL	RAP	30	70	30	100	15.0	15.0
CL + RAP40	CL	RAP	40	60	40	100	14.2	14.2
CL + C&D10	CL	C&D waste	10	90	10	100	18.1	18.1
CL + C&D20	CL	C&D waste	20	80	20	100	17.2	17.2
CL + C&D30	CL	C&D waste	30	70	30	100	16.4	16.4
CL + C&D40	CL	C&D waste	40	60	40	100	15.7	15.7
CH control	CH	—	0	100	0	100	22.0	22.0
CH + RAP10	CH	RAP	10	90	10	100	20.7	20.7
CH + RAP20	CH	RAP	20	80	20	100	19.5	19.5
CH + RAP30	CH	RAP	30	70	30	100	18.4	18.4
CH + RAP40	CH	RAP	40	60	40	100	17.6	17.6
CH + C&D10	CH	C&D waste	10	90	10	100	20.8	20.8
CH + C&D20	CH	C&D waste	20	80	20	100	19.7	19.7
CH + C&D30	CH	C&D waste	30	70	30	100	18.6	18.6
CH + C&D40	CH	C&D waste	40	60	40	100	17.8	17.8

Dry constituent masses and corresponding target water quantities are presented on a normalized 100 kg total dry-blend basis for clarity. The target water quantity was calculated as;

$$M_w = (OMC/100)M_T \tag{7}$$

where M_T is the total dry blend mass. Actual batch masses were scaled proportionally according to the quantity required for specimen preparation.

Table 7. Atterberg-limit results for CL and CH mixtures with RAP and C&D waste

Mixture	Replacement (%)	LL (%)	PL (%)	PI (%)
CL control	0	43.0	20.0	23.0
CL + RAP	10	40.8	20.0	20.8
CL + RAP	20	38.5	19.8	18.7
CL + RAP	30	36.2	19.5	16.7
CL + RAP	40	34.0	19.2	14.8
CL + C&D	10	40.5	20.5	20.0
CL + C&D	20	38.0	20.5	17.5
CL + C&D	30	35.5	20.0	15.5
CL + C&D	40	33.0	19.5	13.5
CH control	0	60.0	23.0	37.0
CH + RAP	10	56.5	23.0	33.5
CH + RAP	20	53.0	22.8	30.2
CH + RAP	30	49.5	22.5	27.0
CH + RAP	40	46.0	22.2	23.8
CH + C&D	10	55.5	23.5	32.0
CH + C&D	20	51.0	23.5	27.5
CH + C&D	30	47.0	23.0	24.0
CH + C&D	40	43.0	22.5	20.5

3.2 Effect on Plasticity

The reduction in liquid limit and plasticity index with increasing RAP and C&D waste content indicates a change in the measured plasticity characteristics of the mixtures. This trend may be

associated with the increasing proportion of relatively non-plastic recycled material and the corresponding reduction in the relative contribution of the plastic clay fraction. However, the present results do not independently establish chemical alteration of the clay minerals. The observed changes are therefore interpreted primarily in terms of mixture composition, rather than a demonstrated chemical mechanism [5]. A decrease in liquid limit and plasticity index was observed with increasing RAP and C&D waste content in both soil types (Table 3 and Fig. 4). The reduction in plasticity index was mainly associated with the decrease in liquid limit, whereas the plastic limit changed only slightly. At comparable replacement levels, the C&D mixtures generally exhibited a greater reduction in PI than the RAP mixtures. This difference may be associated with differences in particle characteristics, fines content and interactions between the recycled materials and the clay fraction [2]. However, these mechanisms were not directly investigated in the present study. In particular, the potential influence of residual bitumen coating on RAP particles cannot be confirmed from the Atterberg-limit results alone. Therefore, the observed differences are interpreted as the measured response of the mixtures rather than evidence of a specific physical or chemical mechanism.

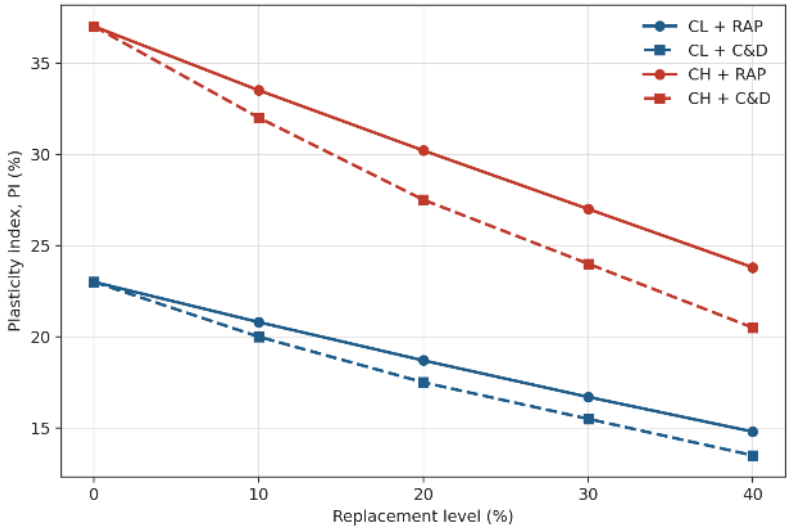

Fig. 6. Variation of plasticity index with replacement level for CL and CH mixtures

3.3 Compaction Behavior

These trends may be associated with differences in particle-size distribution, specific gravity and water absorption between the clay soils and the recycled materials. (Table 1, Fig. 4) [6, 9] However, the individual contributions of particle packing and moisture redistribution were not directly evaluated in this study. The values of MDD showed a rise and final peak at 30% RAP in the CL soil and a gradual rise in the C&D series till 40% replacement. Similarly, in the CH soil, the peak MDD of 1.77 Mg/m^3 was obtained with RAP at 30% replacement rate while the C&D increased monotonically up to 1.77 Mg/m^3 at 40%. OMC decreased steadily with replacement in every series, from 19.0% to 14.2% (CL + 40% RAP) and 15.7% (CL + 40% C&D), and from 22.0% to 17.6% (CH + 40% RAP) and 17.8% (CH + 40% C&D).

The difference between 30% RAP replacement and the results for recycled materials is attributed to the lower absorption capacity and bitumen coated surface texture of RAP particles, which will start to interfere with efficient particle packing when they account for a high percentage of the coarse fraction of the mix, which has been observed elsewhere for RAP modified subgrade mixes [3]. The C&D waste, which was more angular and slightly more absorptive, produced a continued increase in maximum dry density up to the highest replacement level tested. These trends are consistent with the overall finding that incorporating coarser well-graded recycled aggregate into a fine-grained soil increases the dry density that can be achieved, and reduces the water requirement for compaction [6].

Table 8. Maximum dry density (MDD, Mg/m^3) and optimum moisture content (OMC, %) results

Soil	Material	0%	10%	20%	30%	40%
CL	RAP – MDD	1.74	1.78	1.82	1.85	1.83
CL	RAP – OMC	19.0	17.4	16.1	15.0	14.2
CL	C&D – MDD	1.74	1.76	1.79	1.82	1.84
CL	C&D – OMC	19.0	18.1	17.2	16.4	15.7
CH	RAP – MDD	1.66	1.70	1.74	1.77	1.75
CH	RAP – OMC	22.0	20.7	19.5	18.4	17.6
CH	C&D – MDD	1.66	1.69	1.72	1.75	1.77
CH	C&D – OMC	22.0	20.8	19.7	18.6	17.8

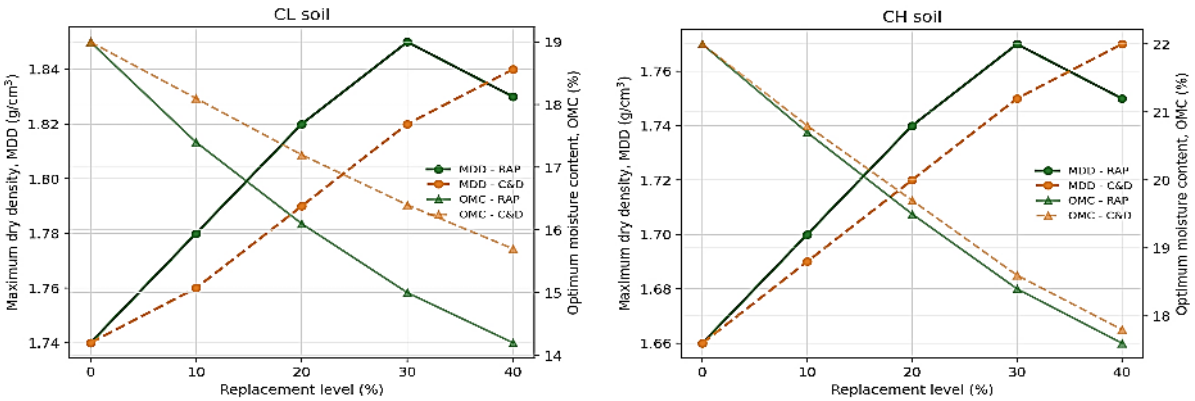

Fig. 7. Effect of replacement level on compaction characteristics (MDD and OMC) for CL and CH mixtures

3.4 Soaked CBR Performance

In all series, soaked CBR tended to increase with the replacement level, but the two recycled materials showed a significant difference in replacement levels beyond 30% (Table 9, Fig. 8). For the CL soil, CBR was raised monotonically from 3.8% (control) to 9.1% at 30% RAP, and decreased to 8.5% at 40% RAP. For the C&D waste, CBR increased monotonically from 3.8% for the control to 12.4% at 40% replacement, which was the highest value recorded within the replacement range investigated. In the CH soil, the RAP increased to a maximum of 6.3% (30%) and then declined to 6.0% (40%), and the C&D waste CBR increased monotonically to 8.0% at 40% replacement, the highest tested replacement level. When comparing the soils, the replacement of RAP by both C&D waste showed a materially greater maximum CBR gain, and outperformed RAP at all replacement levels tested (20% and above).

Table 9. Soaked CBR (%) results for CL and CH mixtures with RAP and C&D waste

Soil	Material	0%	10%	20%	30%	40%
CL	RAP	3.8	5.4	7.2	9.1	8.5
CL	C&D	3.8	5.5	7.8	10.2	12.4
CH	RAP	2.2	3.4	4.8	6.3	6.0
CH	C&D	2.2	3.5	5.1	6.8	8.0

The reduction in RAP-mixture CBR beyond 30% replacement correlates with the reduction in MDD over this range of RAP content (Section 3.3, Table 8), and is consistent with the concept that above the threshold RAP content, the RAP particles dominate the RAP-mixture skeleton but are not sufficiently supported by the reduced clay matrix, resulting in a structure that is less efficiently packed and slightly weaker in soaked conditions.

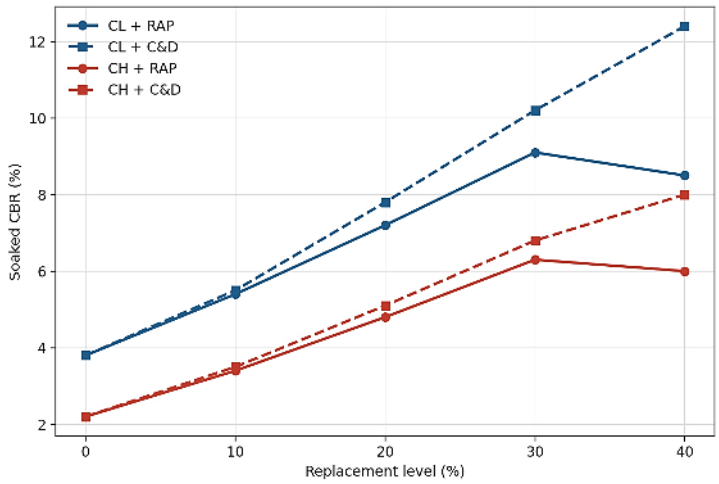

Fig. 8. Effect of replacement level on soaked CBR of CL and CH mixtures

The CBR response has been found to be similar with an increasing RAP content, namely peak then decline, for fine-grained subgrade soils with reclaimed asphalt material modification [3,4]. However, this reversal was not observed within the tested replacement range for C&D waste. The continued increase in CBR may be associated with differences in particle characteristics and mixture composition; however, the individual contributions of particle interlocking, moisture redistribution and other mechanisms were not directly measured in this study. These explanations should therefore be considered possible interpretations rather than experimentally confirmed mechanisms [4,6].

The original specimen-level penetration-load records were unavailable for independent verification during manuscript revision. Consequently, the individual CBR calculations at 2.5 mm and 5.0 mm penetration and the application of the repeat-test requirement could not be independently confirmed. This limitation should be considered when interpreting the reported summary CBR results.

3.5 Selection of Mixtures for Direct Shear

The screening data in Sections 3.3 and 3.4 showed a clear and consistent pattern: 30% RAP was the best-performing replacement level within the tested range in both soils, whereas 40% C&D waste, the highest replacement level investigated, gave the highest CBR and MDD values within the tested range. For this resource-based justification, the untreated CL and CH controls, along with CL + 30% RAP, CL + 40% C&D, CH + 30% RAP and CH + 40% C&D mixes were subjected to direct shear testing. This selective approach is not a statement of a global optimum, as the levels above 40% and/or smaller increments between the tested levels were not covered in this study.

3.6 Direct Shear Behavior

The Mohr–Coulomb failure envelopes for the six mixtures tested are shown in Fig. 9, and the calculated values of cohesion and the friction angle obtained for each of the mixtures are summarized in Table 10. The friction angle of both recycled materials was significantly higher than the control soil (18.0°), with 28.0° for the RAP and 31.0° for the construction and demolition waste (C&D waste). Cohesion was lower for both recycled materials than the control soil, 22.1 kPa for RAP and 14.1 kPa for construction and demolition waste (C&D waste). The same trend was observed in the CH soil, where friction angle rose from 14.0° (control) to 24.0° (30% RAP) and 26.2° (40% C&D), with cohesion falling from 28.1 kPa to 19.9 kPa and 19.5 kPa. This behavior, with a significant increase in friction angle and a lesser reduction in cohesion, is also noted as shear strength response to RAP and demolition-aggregate modification of fine-grained soils [2,10] and can be attributed to the introduction of coarser, more granular particles into a cohesive clay matrix. C&D waste also resulted in a slightly greater increase in friction angle than RAP in both soils (31.0° versus 28.0° for CL and 26.2° versus 24.0° for CH). However, the cohesion values of the C&D mixtures were slightly lower than those of the corresponding RAP mixtures, decreasing from 16.1 to 14.1 kPa for CL and from 19.9 to 19.5 kPa for CH.

Mohr–Coulomb envelopes of the failure data for shear stress at failure at 50, 100 and 150 kPa normal stress were found to fit well for all six mixtures (Fig. 9) and the slope of the envelopes (φ) for the treated mixtures appeared steeper than for the controls, as well as the intercept (c), in accordance with the general interpretation of direct shear failure envelopes for blended granular–clay systems.

Table 10. Direct shear results and Mohr–Coulomb shear-strength parameters

Mixture	Normal stress σn (kPa)	Shear stress at failure τf (kPa)
CL control	50	38.3
CL control	100	54.5
CL control	150	70.7
CL + 30% RAP	50	42.6
CL + 30% RAP	100	69.1
CL + 30% RAP	150	95.7
CL + 40% C&D	50	44.1
CL + 40% C&D	100	74.1
CL + 40% C&D	150	104.1
CH control	50	40.5
CH control	100	52.9
CH control	150	65.4
CH + 30% RAP	50	42.2
CH + 30% RAP	100	64.5
CH + 30% RAP	150	86.8
CH + 40% C&D	50	44.1
CH + 40% C&D	100	69.0
CH + 40% C&D	150	93.4
Mixture	Cohesion, c (kPa)	Friction angle, φ (°)
CL control	22.1	18.0
CL + 30% RAP	16.1	28.0
CL + 40% C&D	14.1	31.0
CH control	28.1	14.0
CH + 30% RAP	19.9	24.0
CH + 40% C&D	19.5	26.2

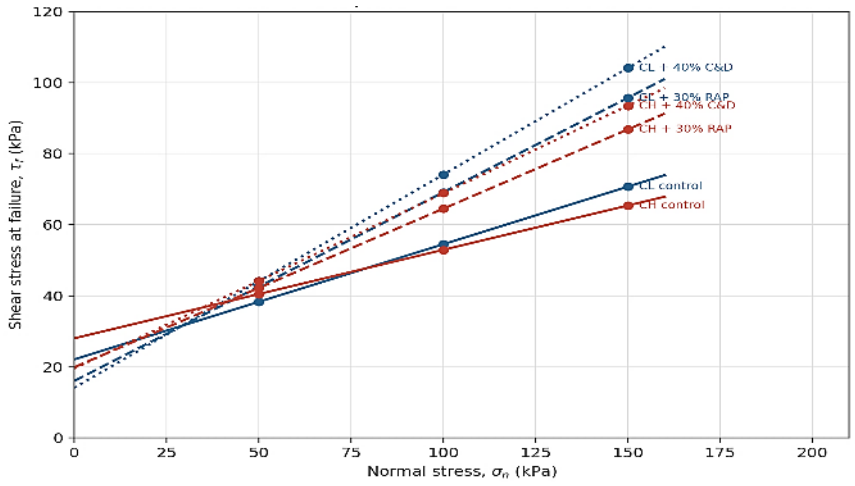

Fig. 9. Mohr–Coulomb failure envelopes for control and selected RAP/C&D mixtures

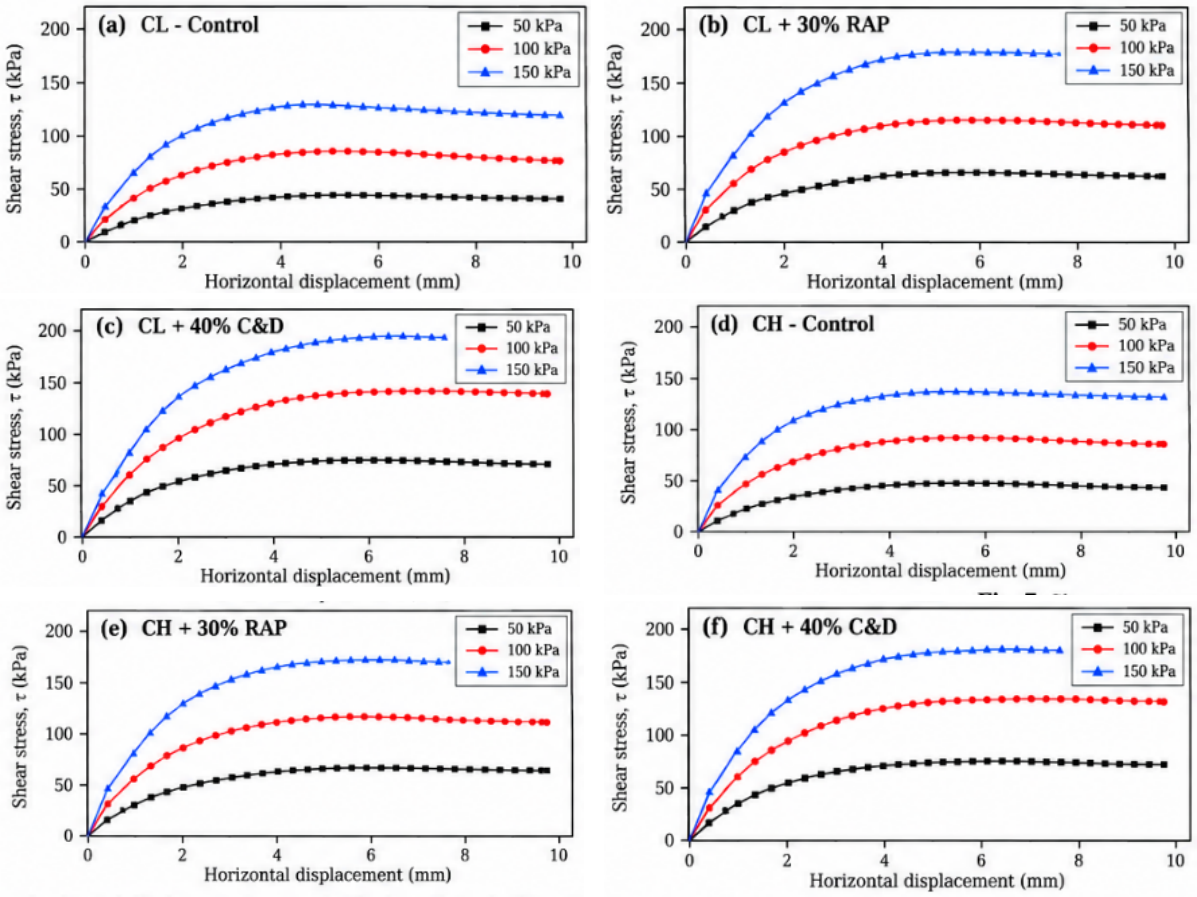

Fig. 10. Shear stress versus horizontal displacement for the six investigated mixtures at normal stresses of 50, 100 and 150 kPa

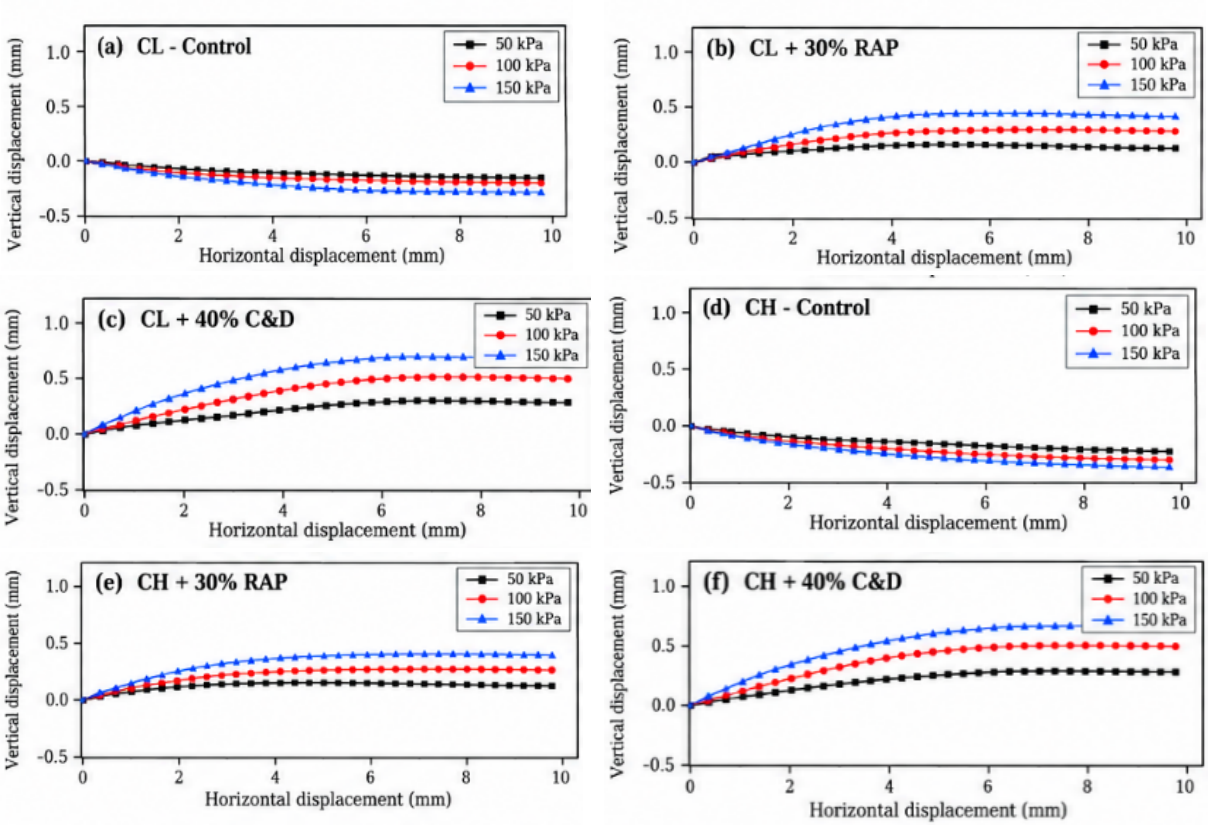

Fig. 11. Vertical displacement versus horizontal displacement for the six investigated mixtures at normal stresses of 50, 100 and 150 kPa

3.7 Statistical Validation

The coefficient of variation of the replicate soaked-CBR results (three tests per condition) ranged from 0.8% for CL + 40% C&D waste to 4.6% for the CH control (Table 11), indicating low reported within-condition variability. Because the experimental program involved three factors soil classification, recycled-material type, and replacement level, the statistical analysis was conducted using a three-factor factorial general linear model rather than a conventional one-way ANOVA.

Table 11. Replicate soaked-CBR results and variability statistics (n = 3 per mixture)

Mixture	Rep. 1 (%)	Rep. 2 (%)	Rep. 3 (%)	Mean (%)	SD (%)	CV (%)
CL control	3.7	3.8	3.9	3.80	0.10	2.63
CL + 10% RAP	5.3	5.4	5.5	5.40	0.10	1.85
CL + 20% RAP	7.1	7.2	7.3	7.20	0.10	1.39
CL + 30% RAP	9.0	9.1	9.2	9.10	0.10	1.10
CL + 40% RAP	8.4	8.5	8.6	8.50	0.10	1.18
CL + 10% C&D	5.4	5.5	5.6	5.50	0.10	1.82
CL + 20% C&D	7.7	7.8	7.9	7.80	0.10	1.28
CL + 30% C&D	10.1	10.2	10.3	10.20	0.10	0.98
CL + 40% C&D	12.3	12.4	12.5	12.40	0.10	0.81
CH control	2.1	2.2	2.3	2.20	0.10	4.55
CH + 10% RAP	3.3	3.4	3.5	3.40	0.10	2.94
CH + 20% RAP	4.7	4.8	4.9	4.80	0.10	2.08
CH + 30% RAP	6.2	6.3	6.4	6.30	0.10	1.59
CH + 40% RAP	5.9	6.0	6.1	6.00	0.10	1.67
CH + 10% C&D	3.4	3.5	3.6	3.50	0.10	2.86
CH + 20% C&D	5.0	5.1	5.2	5.10	0.10	1.96
CH + 30% C&D	6.7	6.8	6.9	6.80	0.10	1.47
CH + 40% C&D	7.9	8.0	8.1	8.00	0.10	1.25

Note: The original specimen-level CBR records, including unrounded penetration loads, individual moisture contents, achieved dry densities and swell measurements, were unavailable for independent verification during manuscript revision. Therefore, the origin and precision of the individual replicate values in Table 11, as well as the reported standard deviations (SD) and coefficients of variation (CV), could not be independently verified. The reported replicate statistics should not be interpreted as independently validated experimental variability until the original laboratory records have been checked.

The untreated 0% control was treated as a shared reference condition for the RAP and C&D waste series within each soil classification. Accordingly, the CL control and CH control were each represented only once and were not duplicated under both recycled-material categories in the factorial statistical model. The factorial analysis of the replacement mixtures considered soil classification (CL and CH), recycled-material type (RAP and C&D waste), and replacement level (10%, 20%, 30%, and 40%). The shared 0% controls were excluded from this factorial model because recycled-material type is not applicable to untreated soil. They were retained as reference conditions for descriptive comparison with the treated mixtures. This approach avoids counting the same control observations twice and preserves the distinction between the untreated reference soils and the recycled-material treatment groups.

The Type II factorial ANOVA identified significant main effects of soil classification, recycled-material type, and replacement level on soaked CBR. Significant soil × material, soil × replacement, material × replacement, and soil × material × replacement interaction effects were also identified. The complete statistical results are presented in Table 12. Because significant interaction effects were identified, post-hoc comparisons were conducted within the individual soil–material series using Tukey's HSD procedure at $\alpha = 0.05$. All replacement levels differed significantly within each soil–material series. For CL + RAP, the 30% replacement level produced a significantly higher CBR than 40% RAP (Tukey-adjusted $p < 0.001$), confirming the reduction beyond 30%. For CH + RAP, the corresponding 30% versus 40% comparison remained significant (Tukey-adjusted $p = 0.026$). In contrast, C&D waste showed a significant progressive increase in CBR through 40% replacement

in both CL and CH soils ($p < 0.001$ for the pairwise comparisons). These results statistically support the observed peak response of RAP at 30% and the continuing improvement of C&D waste up to the highest tested replacement level of 40%.

Table 12. Type II factorial ANOVA results for soaked CBR

Effect	df	SS	MS	F	p-value	Partial η^2
Soil classification	1	92.4075	92.4075	9240.75	<0.001	0.997
Recycled-material type	1	13.8675	13.8675	1386.75	<0.001	0.977
Replacement level	3	134.7150	44.9050	4490.50	<0.001	0.998
Soil × Material	1	1.4700	1.4700	147.00	<0.001	0.821
Soil × Replacement	3	3.6375	1.2125	121.25	<0.001	0.919
Material × Replacement	3	14.7975	4.9325	493.25	<0.001	0.979
Soil × Material × Replacement	3	1.5750	0.5250	52.50	<0.001	0.831
Error	32	0.3200	0.0100	—	—	—

Note: The factorial ANOVA was calculated using the 48 replicate observations corresponding to the 10–40% replacement levels reported in Table 12. The common 0% controls were not duplicated in the factorial model. Type II sums of squares were used. Partial η^2 represents the effect size for each model term relative to that effect and the residual error.

Model diagnostics showed no evidence of heteroscedasticity based on Levene's test ($F \approx 0.00$, $p = 1.000$). The Shapiro–Wilk test of the model residuals yielded $W = 0.794$ ($p < 0.001$). However, the residual distribution was strongly constrained by the one-decimal reporting precision of the replicate CBR values, resulting in only three distinct residual values around the fitted cell means. Therefore, the formal normality result was interpreted together with the residual structure and the reporting-precision limitation rather than as evidence of independently measured non-normal laboratory errors.

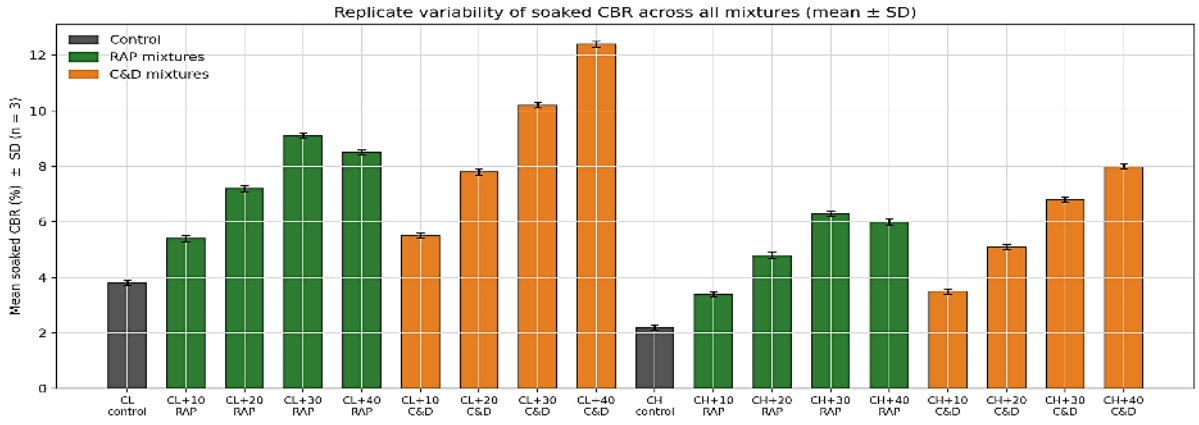

Fig. 12. Replicate mean soaked CBR with standard deviation across all eighteen mixture conditions

3.8 Integrated Engineering Comparison

The C&D waste yielded a reduction in plasticity index, a monotonic increase in dry density and CBR, and an increase in friction angle for both the CL and CH soils. The C&D mixtures therefore showed a consistent improvement in the measured index, compaction and bearing-capacity-related properties across the tested replacement range. RAP also improved the engineering performance of both soils, although its CBR and dry-density responses showed a decline at 40% replacement after reaching higher values at 30%.

The direct shear results further indicated that C&D waste produced slightly greater friction-angle gains than RAP in the selected mixtures, whereas the corresponding cohesion values were slightly lower than those of the RAP mixtures. Thus, the relative advantage of C&D was primarily associated with frictional resistance and the continued improvement in CBR and dry density up to the highest replacement level investigated, rather than superior cohesion retention.

Considering the combined trends observed in the present experimental program, replacement ranges of 20–30% for RAP and 30–40% for C&D waste can be considered promising within the tested conditions. However, these ranges should not be interpreted as universal optimum values because higher replacement levels, intermediate replacement increments, and RAP–C&D combined mixtures were not investigated. Further experimental work involving combined RAP–C&D blends is required before their performance can be assessed.

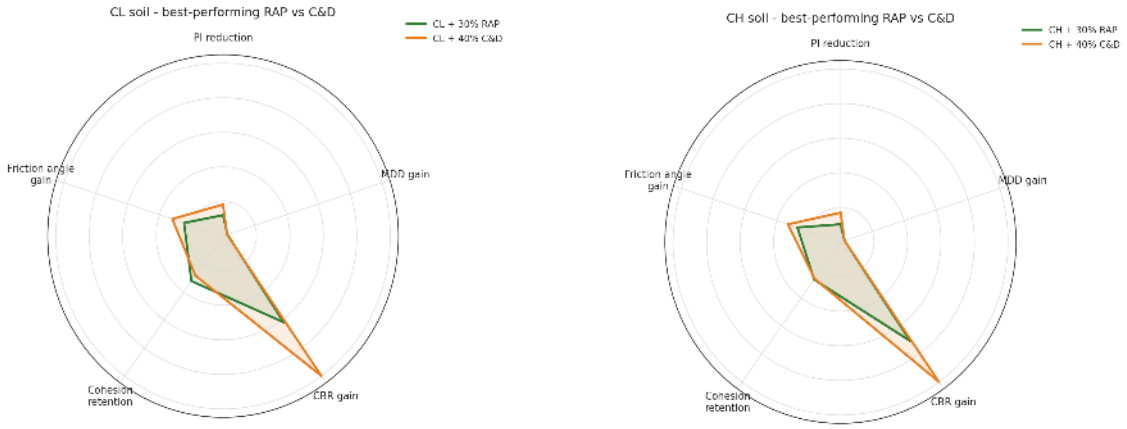

Fig. 13. Integrated comparison of 30% RAP and 40% C&D mixtures using normalized engineering-performance indices. Higher normalized values indicate better measured performance for the corresponding indicator

The engineering performance of the selected RAP and C&D mixtures was compared using five normalized indicators: plasticity-index (PI) reduction, maximum dry density (MDD) gain, soaked CBR gain, cohesion retention and friction-angle gain. The comparison was made separately for the CL and CH soils using the selected 30% RAP and 40% C&D mixtures. For the four improvement indicators, the absolute gain relative to the corresponding untreated soil was first calculated as:

$$\Delta PI = PI_0 - PI_m \tag{8}$$

$$\Delta MDD = MDD_m - MDD_0 \tag{9}$$

$$\Delta CBR = CBR_m - CBR_0 \tag{10}$$

$$\Delta\phi = \phi_m - \phi_0 \tag{11}$$

where the subscript 0 denotes the untreated soil and the subscript m denotes the recycled-material mixture. Cohesion retention was calculated as:

$$R_c = \frac{c_m}{c_0} \tag{12}$$

where $c_0$and $c_m$are the cohesion values of the untreated and treated soils, respectively. Thus, a higher value of $R_c$indicates greater retention of cohesion.

Because the five indicators have different units and numerical ranges, each indicator was converted to a dimensionless normalized score between 0 and 1 using the best-performing value among the two selected recycled-material mixtures for the same host soil:

$$I_i = \frac{X_i}{max(X_{RAP}, X_{C\&D})} \tag{13}$$

where $X_i$represents $\Delta PI, \Delta MDD, \Delta CBR, R_c, or\ \Delta\phi$Accordingly, the higher the normalized score, the better the measured engineering performance for that indicator. A score of 1.0 therefore represents the higher value between the selected RAP and C&D mixtures for that soil and indicator; it does not represent an absolute performance rating.

The resulting normalized indices are presented in Fig. 13. For the CL soil, the 30% RAP mixture produced normalized scores of 0.66, 1.00, 0.62, 1.00 and 0.77 for PI reduction, MDD gain, CBR gain, cohesion retention and friction-angle gain, respectively, whereas the corresponding 40% C&D mixture produced scores of 1.00, 0.91, 1.00, 0.88 and 1.00. For the CH soil, the corresponding normalized scores for 30% RAP were 0.61, 1.00, 0.71, 1.00 and 0.82, while those for 40% C&D were 1.00, 1.00, 1.00, 0.98 and 1.00, respectively. These indices are intended only as a comparative visualization of the measured laboratory results and should not be interpreted as a universal performance ranking.

3.9 Economic Assessment

The economic comparison was expressed as the cost per ton of treated subgrade. The base-case assumptions were ₹500/t for virgin borrow material, ₹250/t for RAP, ₹350/t for processed C&D material, ₹150/t for RAP processing, ₹300/t for C&D processing, a transportation rate of ₹2.80/(t·km), a haul distance of 25 km, and an avoided-disposal cost of ₹300/t. These values were treated as indicative regional assumptions for the Andhra Pradesh market for the 2025–26 reference period rather than as universal market prices.

At the base-case haul distance, the transportation component was:

- $C_t = 25 \times 2.80 = ₹70/t$

Thus, the virgin-soil reference cost was:

- $C_{virgin} = 500 + 70 = ₹570/\text{t}$

For the 30% RAP mixture:

- $C_{RAP,30} = 0.70(500) + 0.30(250 + 150) + 70 - 0.30(300)$

$$= 350 + 120 + 70 - 90 = ₹450/\text{t}$$

For the 40% C&D mixture:

- $C_{C\&D,40} = 0.60(500) + 0.40(350 + 300) + 70 - 0.40(300)$

$$= 300 + 260 + 70 - 120 = ₹510/\text{t}$$

Therefore, relative to the virgin-soil reference of ₹570/t, the base-case saving was ₹120/t (21.1%) for 30% RAP and ₹60/t (10.5%) for 40% C&D waste when the conditional avoided-disposal credit was included.

To demonstrate the effect of the disposal-credit assumption, the corresponding costs without the disposal credit were ₹540/t for 30% RAP and ₹630/t for 40% C&D waste. This distinction is important because the disposal credit is applicable only when the same waste stream would otherwise generate a real disposal expenditure for the project owner or waste generator. It should not be counted when disposal costs are already embedded in the recycled-material purchase price.

The avoided-disposal credit requires careful interpretation. From the project-owner or waste-generator perspective, the credit represents a cost that would have been incurred if the RAP or C&D waste had been transported to and disposed of at an authorized disposal facility but is avoided when the material is beneficially reused in the subgrade. It is therefore a conditional avoided-cost benefit, not a negative purchase price for the recycled material.

Table 13. Base-case cost comparison of virgin borrow soil, RAP, and C&D waste with and without avoided-disposal credit

Alternative	Replacement	Cost with disposal credit	Cost without disposal credit
Virgin borrow	0%	₹570/t	₹570/t
RAP	30%	₹450/t	₹540/t
C&D waste	40%	₹510/t	₹630/t

Table 14. Economic assumptions and sensitivity ranges

Parameter	Base-case value	Sensitivity range	Unit
Virgin soil/borrow material	500	400–600	₹/t
RAP material	250	150–350	₹/t
C&D recycled material	350	250–450	₹/t
RAP processing	150	100–200	₹/t
C&D processing	300	230–400	₹/t
Transportation distance	25	15–50	km
Transportation cost	2.80	2.0–4.0	₹/(t·km)
Landfill/disposal cost avoided	300	200–500	₹/t
RAP replacement	0–40	—	%
C&D replacement	0–40	—	%
Cost sensitivity	±20	−20 to +20	%

Note: *The listed rates are indicative assumptions for the 2025–26 Andhra Pradesh construction-material market, not verified quotations for every project location. The cost comparison covers material procurement, recycled-material processing and transport. Loading/unloading, stockpiling, handling, quality control, construction equipment, labor, taxes and other excluded costs must be identified separately where they are not included in the adopted rates.*

Table 15. Sensitivity scenarios for economic performance

Scenario	Material cost	Haul distance	Virgin soil (₹/t)	30% RAP (₹/t)	40% C&D (₹/t)
S1 – Base case	Base	25 km	570	450	510
S2 – Low material cost	−20%	25 km	470	356	398
S3 – High material cost	+20%	25 km	670	544	622
S4 – Short haul	Base	15 km	542	422	482
S5 – Long haul	Base	50 km	640	520	580
S6 – Best case	−20%	15 km	442	328	370
S7 – Worst case	+20%	50 km	740	614	692

Note: For S2 and S3, the ±20% material-cost adjustment was applied to the virgin/recycled material and processing components, while the avoided-disposal credit was retained at the base value. Transportation cost was varied according to the specified haul distance. The calculated values represent indicative project-level costs rather than quoted market prices.

The credit should be applied only once. In particular, it should not be simultaneously included in the recycled-material purchase price and deducted again as an avoided-disposal cost. Where the recycled material is purchased from an external supplier and the quoted price already reflects the supplier's collection, processing and disposal economics, the disposal credit should be omitted from the project-owner calculation.

4. Engineering Implications and Limitations

4.1 Engineering Implications

At the recommended replacement percentages, both RAP and C&D waste significantly improved the soaked CBR of the CL subgrade. The CBR increased from 3.8% for the untreated CL soil to 9.1% with 30% RAP and 12.4% with 40% C&D waste. For the CH subgrade, the soaked CBR increased from 2.2% for the untreated soil to 6.3% with 30% RAP and 8.0% with 40% C&D waste. The gains in absolute CBR are also smaller for CH subgrades, but the relative improvement is similar, and the corresponding decrease in plasticity index (up to 44% at 40% C&D) is also of independent engineering value in reducing shrink–swell related pavement distress. For the cases where the design consideration is maximum bearing capacity and reduction of plasticity, both C&D waste and RAP are suitable amendments, with C&D waste being the preferred amendment in both soils, and RAP being the most effective amendment at 20–30% replacement for these soils, and often the

more economical one where only moderate improvement is required, or water absorption and processing cost is minimized. The CBR, compaction and shear-strength evidence converge and suggest that 20-30% of RAP and 30-40% of C&D waste replacement is appropriate for a similar subgrade clay type, pending field-scale confirmation.

From a resource-conservation perspective, incorporating suitable RAP and C&D waste into clay subgrades may reduce demand for virgin borrow materials and divert waste from disposal. These potential benefits were not quantified through a life-cycle assessment or carbon-footprint analysis in the present study. Consequently, the findings do not establish that the investigated mixtures have lower greenhouse-gas emissions or lower overall environmental impacts than cement- or lime-stabilized alternatives. Such comparisons would require consistent system boundaries and consideration of processing, transportation, construction, service life, and end-of-life management.

4.2 Limitations

- Results are from a single RAP source and a single C&D waste source and may not be directly applicable to RAP or C&D waste of other compositions or gradings, or different content of RAP binder/mortar.
- Intermediate and organic fine-grained soils were ignored and only two soil classifications (CL and CH) were investigated.
- All testing was done at laboratory scale for standard compactive effort, field compaction, curing and traffic loading conditions may result in different absolute performance.
- Since direct shear testing was only done for the screened and best performing mixtures and not for the entire replacement range, the shear-strength response between the tested points has not been measured directly.
- No independent microstructural characterizations (SEM, XRD) were performed to confirm the particle-interaction mechanisms proposed.
- No long term or field scale validation such as trial pavement sections, repeated freeze–thaw cycles or wet–dry cycles were carried out.
- The economic assessment is derived from indicative cost assumptions for the region and should be reviewed and compared with the actual cost in the region and the project location prior to use in decision making.

The findings are based on laboratory testing of two soil classifications (CL and CH), one RAP source, and one construction and demolition (C&D) waste source under the adopted laboratory compaction effort and soaking conditions. The results should therefore be interpreted within the limits of these materials and test conditions and should not be directly generalized to other material sources or field conditions. Field performance may also depend on drainage, climate, traffic loading, in-situ moisture conditions, construction quality, and compliance with the governing pavement design method and local specifications. Field trials and additional evaluation of parameters such as resilient modulus are required before project-specific design recommendations can be established.

No environmental life-cycle assessment, greenhouse-gas accounting, energy-consumption analysis, or leachability testing was conducted. Accordingly, the environmental implications are limited to the potential conservation of virgin materials and diversion of suitable waste from disposal. RAP and C&D waste can exhibit source-dependent variability and may contain contaminants or undesirable constituents. Depending on their origin, relevant concerns may include sulphate and chloride content, gypsum, organic matter, and the potential release of contaminants under site-specific conditions. Before field use, materials should undergo appropriate source screening, physical and chemical characterization, contamination assessment, and quality control in accordance with applicable environmental regulations and project specifications. The present results do not establish the environmental safety of the tested materials beyond the properties and tests actually investigated.

5. Conclusions

Based on a controlled laboratory comparison of RAP and C&D waste used as partial replacement materials in CL and CH clay subgrades, at five replacement levels, and test procedures, the following conclusions are drawn.

- For CL soil, both recycled materials lowered the plasticity index and the dry density increased as the quantity of recycled material was increased, and the highest CBR value for the C&D waste was recorded in the study at 40% recycled material (12.4%).
- A similar improvement trend was observed for CH soil, although its higher initial plasticity and fines content resulted in lower absolute CBR values than those obtained for CL soil. The maximum CBR for CH was 8.0% at 40% C&D waste.
- RAP modified mixtures performed well up to 30% replacement in both soils but lost apparent and measurable dry density and CBR at 40% replacement suggesting a practical limit for the beneficial RAP content within the tested range.
- C&D waste showed a consistently higher soaked CBR than RAP at replacement levels of 20% and above and maintained an increasing CBR response up to the highest tested replacement level of 40%.
- Direct shear testing of the selected mixtures showed friction-angle increases of 10.0–13.0° relative to the corresponding untreated soils. C&D waste produced slightly greater friction-angle gains than RAP, while the corresponding cohesion values were slightly lower.
- The factorial statistical analysis identified significant main effects of soil classification, recycled-material type, and replacement level on soaked CBR ($p < 0.001$). Significant two-way and three-way interaction effects were also observed, demonstrating that the influence of replacement level depended on both the host-soil classification and recycled-material type. The reported replicate coefficients of variation ranged from 0.8% to 4.6%; however, interpretation of the statistical variance is subject to the one-decimal reporting precision of the replicate CBR measurements.
- For CL subgrades, it is recommended that the preferred-performing replacement range be 20–30% for RAP and 30–40% for C&D waste within the scope of this study. For CH subgrades, the preferred-performing replacement range is 20–30% RAP and 30–40% C&D waste within the scope of this study.
- The indicative economic assessment showed that the calculated cost of the 30% RAP blend was ₹540/t without an avoided-disposal credit and ₹450/t with the conditional credit. For the 40% C&D waste blend, the corresponding costs were ₹630/t and ₹510/t, respectively. These values compare with ₹570/t for virgin borrow soil under the adopted assumptions. RAP therefore had the lower calculated unit cost, whereas C&D waste produced larger soaked-CBR gains at the selected replacement levels. Longer haul distances increase transportation costs under the adopted assumptions and generally reduce the economic attractiveness of recycled materials. These findings are indicative and require validation using project-specific prices and confirmed disposal-credit eligibility.
- There is a recommended field-scale trials that will include construction-scale compaction, seasonal moisture cycling, and, if applicable, additional RAP and C&D sources, to validate the results of the laboratory-scale trials prior to wider use in subgrade design practice.

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