

Performance Evaluation of Full Depth Reclamation Mixes Stabilized with Bitumen Emulsion

Ayila Srinivasa Arjun

National Institute of Technology Warangal

Jithin Kurian Andrews

`jithin.ka@saintgits.org`

Saintgits College of Engineering (Autonomous)

Vishnu Radhakrishnan

National Institute of Technology Warangal

Research Article

Keywords: Full-depth reclamation, Bitumen-stabilized material, Reclaimed asphalt pavement, Low-volume roads, Pavement design catalogue

Posted Date: October 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10992304/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Performance Evaluation of Full Depth Reclamation Mixes Stabilized with Bitumen Emulsion

Abstract

Full-depth reclamation (FDR) stabilized with bitumen emulsion offers a flexible alternative to cement-treated bases and, unlike cementitious stabilization, does not require a crack-relief layer. Indian practice, however, has no standardized mix-design or thickness-design procedure for it. Material recovered from a distressed low-volume road was therefore stabilized with bitumen emulsion and 1% cement as active filler, at 100% reclamation without virgin aggregate. Three slow-setting emulsions, two anionic and one cationic, were evaluated using particle charge, residue, viscosity, cement-mixing stability, coating and dynamic shear rheometer tests. Mix design proceeded sequentially through total fluid content, emulsion-to-water ratio and filler content, with acceptance based on dry and wet indirect tensile strength (ITS) and tensile strength ratio (TSR). Only the anionic emulsion with 63.78% residue satisfied all criteria, at an optimum emulsion content of 5.02% (3.20% residual binder) within a total fluid content of 9.5%, giving a dry ITS of 231 kPa, a wet ITS of 118 kPa and a TSR of 51.1%. Emulsion suitability could therefore not be inferred from mineral composition alone. The accepted mix exhibited resilient moduli of 693–1,399 MPa, with a coefficient of variation of 20.6% and a 15th-percentile value of 867 MPa, and permanent strains of 3.03%, 4.01% and 6.21% at deviator stresses of 200, 400 and 600 kPa. Linear elastic layered analysis using a subgrade rutting criterion at 80% reliability produced thickness catalogues for traffic categories T5–T9 and California Bearing Ratio (CBR) values of 5–10%, requiring FDR thicknesses of 150–205 mm beneath 30 mm of bituminous concrete.

Keywords Full-depth reclamation · Bitumen-stabilized material · Reclaimed asphalt pavement · Low-volume roads · Pavement design catalogue

1 Introduction

A large proportion of the Indian road network comprises pavements that have reached or exceeded their intended service life. Declining availability of good-quality virgin aggregate and increasing haulage distances have made rehabilitation strategies that reuse existing pavement materials increasingly attractive. Full-depth reclamation (FDR) is one such strategy in which the bituminous surfacing, underlying granular base and where required, part of the subgrade, are pulverized in place, blended with a stabilizing agent and recompacted to form a new base beneath a thin bituminous surfacing. Since the process is carried out in situ, material import and disposal are minimized, and the treatment depth can be matched to the depth of

distress. Treatment depths typically range from 100 to 300 mm [1], and bitumen-stabilized materials (BSM) are now established as a rehabilitation option in several national design systems [2]. FDR stabilization may be achieved through mechanical stabilization with virgin aggregate, chemical stabilization with hydraulic binders such as cement, or bituminous stabilization using emulsion or foamed bitumen.

Cement remains the most commonly specified FDR stabilizer in India because of its availability, low cost, familiarity and ability to develop high early strength and stiffness. However, its rigid and brittle nature can result in shrinkage cracking, which may subsequently propagate through the surfacing as reflective cracking. Water entering these cracks can further weaken the crack edges and degrade load transfer. Crack-relief measures, such as aggregate interlayers, stress-absorbing membrane interlayers or geosynthetics, are therefore commonly required, adding material, cost and construction effort. Cement-treated layers are also sensitive to the mixing-to-compaction interval and to differential movement of the underlying layers. These considerations motivate the use of bituminous stabilization as a more flexible alternative. Bitumen-stabilized material retains much of the load-spreading behaviour of a granular skeleton while gaining cohesion and tensile strength through localized bitumen bonding. Unlike cement stabilization, it does not form a continuous rigid matrix and therefore avoids the hydration-shrinkage mechanism responsible for transverse cracking. This can reduce susceptibility to reflective cracking and may allow the surfacing to be placed directly over the stabilized base without a separate crack-relief layer.

Bitumen emulsion is particularly suitable for in-place recycling because it can be dispersed through damp reclaimed material without heating. Bitumen emulsions typically contain 40–75% bitumen, 0.1–2.5% emulsifier and 25–60% water, with droplets carrying either a positive or negative charge depending on the emulsifier chemistry [3]. Lesueur and Potti [4] emphasized that rational cold-mix design should therefore consider both emulsion characteristics and their interaction with the mineral surface. Emulsion selection is commonly related to the charge of the aggregate surface, with cationic emulsions conventionally associated with siliceous materials and anionic emulsions with carbonate materials. However, this relationship is not universal. Ignatavicius et al. [5] reported higher average coating for cationic emulsions, while also showing that performance ranking can reverse for individual mineralogy. Kong et al. [6, 7] demonstrated that emulsifier chemistry influences adsorption on SiO_2 and CaCO_3 , while Yuan et al. [8] showed that divalent cations can affect the stability of anionic emulsions. Therefore, emulsion selection for reclaimed material cannot be based on

mineral composition or ionic charge alone, particularly when particle surfaces may already be coated with aged binder. Mechanically, emulsion-treated layers exhibit stress-dependent behaviour closer to that of granular materials than continuously bound layers. Hornych et al. [9] demonstrated nonlinear resilient behaviour in gravel-emulsion mixtures, while Barbod and Shalaby [10] showed that fine particles may be fully coated whereas coarse particles remain only partially coated. Early-age strength evolution is also important, with Quick and Guthrie [11] reporting strength loss during the initial two weeks in field sections. Small quantities of cement or hydrated lime are therefore commonly used as active filler to accelerate emulsion breaking, consume free water and improve moisture resistance [12]. Baghini et al. [13] reported improved performance of cement–emulsion mixtures under wetting and drying, dynamic creep and wheel tracking, while Kumar et al. [2] identified approximately 2–3% bitumen with about 1% cement as a commonly effective BSM composition. Excessive cement can increase brittleness and undermine the flexibility sought through bituminous stabilization.

Research on RAP-containing emulsion-treated bases is relevant to FDR because reclaimed FDR material represents a site-blended reclaimed feedstock. Alkam et al. [14] identified moisture susceptibility and feedstock variability as important limitations in cold-recycled materials, while Saha et al. [15] showed that stiffness development depends on the interaction between binder and active filler. Coelho et al. [16] confirmed the stress-dependent resilient response of reclaimed asphalt emulsified granular mixtures. Fedrigo et al. [17] demonstrated substantial variability in tensile strength and its implications for reliability. Kumar et al. [18] reported nonlinear interaction between stabilized-layer modulus, thickness and subgrade strain. Andrews et al. [19] found that a mixture containing 75% RAP, 3% emulsion and 1% cement satisfied an ITS requirement when virgin aggregate was used to achieve the target grading, whereas higher RAP contents without gradation correction reduced rut resistance and resilient modulus. The limiting case of genuine in-place FDR using 100% reclaimed material without virgin aggregate correction has received considerably less attention.

A corresponding gap exists in structural design. Sahoo and Reddy [20] developed rutting and roughness criteria for thin-surfaced low-volume roads from test sections, which could be used parallelly with the thickness selection of IRC:SP:72 [21]. However, the code provides no thickness catalogue for bitumen-emulsion-stabilized bases. Consequently, designers may treat these materials as unbound granular layers, thereby overlooking their developed cohesion, or depend on transfer functions from other pavement systems without local verification. Three needs therefore remain. First, a standardized mix-design approach is required for emulsion-

stabilized FDR using 100% reclaimed material. Second, the mechanical properties and variability of such materials need to be established for structural analysis. Third, thickness-design guidance is required for their application in low-volume Indian roads. Addressing these needs would provide a rational basis for selecting the emulsion, characterizing the resulting stabilized material and determining an appropriate treatment thickness, while retaining the principal material-reuse advantage of FDR.

2 Objectives and Scope

The objectives of this study are to evaluate the suitability of bitumen emulsions for FDR mixes through strength and moisture-resistance testing, and to establish an experimentally verifiable procedure for emulsion selection. The objectives are specifically aimed to characterize the selected mix in terms of resilient modulus and dynamic creep behaviour and to develop mechanistic thickness-design catalogues for emulsion-stabilized FDR bases covering the traffic categories and subgrade conditions relevant to low-volume roads. The study is limited to material recovered from a single distressed low-volume pavement and used at 100% reclamation without virgin aggregate correction. The reclaimed material was stabilized using slow-setting bitumen emulsions with ordinary Portland cement as active filler, and three candidate emulsions were evaluated. Thickness design was developed for traffic categories T5–T9 and subgrade CBR values of 5–10% using linear elastic layered analysis and the subgrade rutting criterion adopted for thin-surfaced low-volume roads. Long-term fatigue, ageing, durability under extended environmental exposure and field validation are beyond the scope of the present study.

3 Methodology

The experimental programme was conducted in two sequential phases, as illustrated in Fig. 1. The first phase involved characterization of the reclaimed material and candidate emulsions, followed by systematic mix design to identify the most suitable emulsion and mix composition. The selected mix was then subjected to resilient modulus and dynamic creep testing to characterize its structural and deformation behaviour. In the second phase, these findings were used to establish the material properties for linear-elastic analysis and develop mechanistic thickness-design catalogues for different traffic and subgrade conditions.

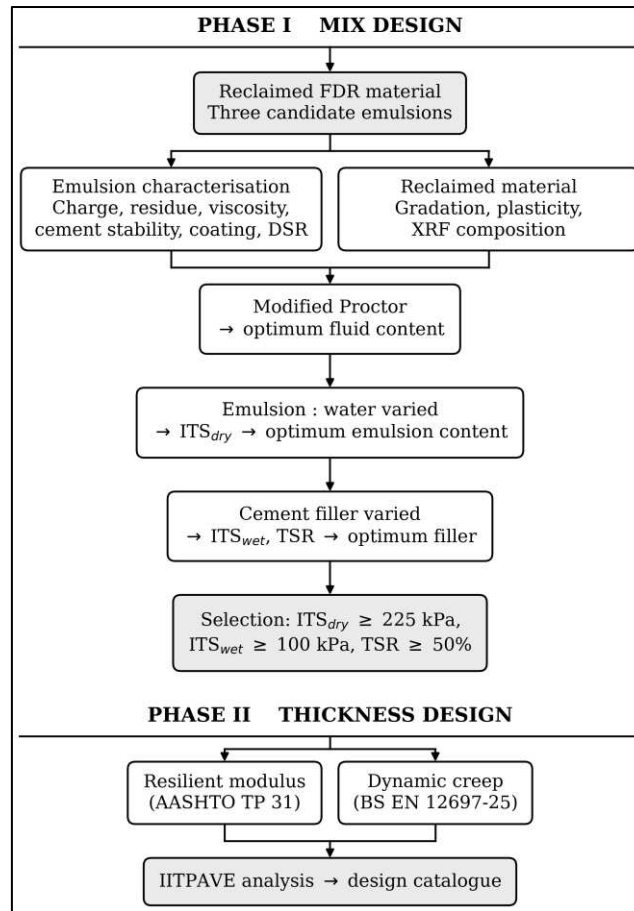


Fig. 1 Methodology adopted in the study

3.1 Materials

The reclaimed material was obtained from a distressed low-volume flexible pavement and comprised the pulverized bituminous surfacing, underlying granular base and a portion of the subgrade soil, retained in their in-situ proportions. No virgin aggregate was added, representing a 100% reclaimed FDR condition. The dry-sieved particle size distribution is compared in Fig. 2 with the base gradation limits of IRC:37-2012 [22], with the corresponding values presented in Table 1. The reclaimed material remained within the specified envelope over the full sieve range, indicating that pulverization produced a well-graded material without requiring gradation correction. The gradation was generally below the mid-band line, except in the finer fraction, reflecting the combined influence of partly agglomerated RAP particles and fines contributed by the granular and subgrade materials.

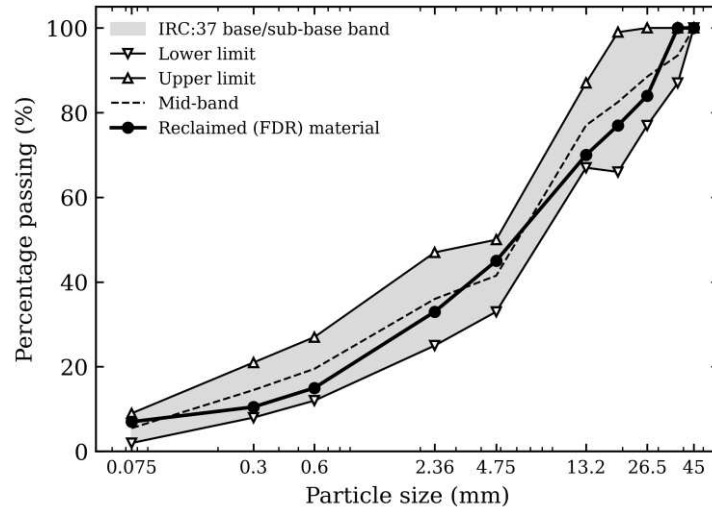


Fig. 2 Particle size distribution of the reclaimed FDR material compared with the IRC:37-2012 base and sub-base gradation band

Table 1 Gradation of the reclaimed FDR material compared with the IRC:37-2012 base and sub-base band

IS sieve size (mm)	IRC:37-2012 band, lower limit (% passing)	IRC:37-2012 band, upper limit (% passing)	Reclaimed FDR material (% passing)
45	100	100	100
37.5	87	100	100
26.5	77	100	84
19	66	99	77
13.2	67	87	70
4.75	33	50	45
2.36	25	47	33
0.60	12	27	15
0.075	2	9	7

The consistency limits of the fraction passing the 425 μm sieve are presented in Table 2. The reclaimed material had a liquid limit of 23% and a plastic limit of 17%, giving a plasticity index of 6%, which is below the conventional limit of 7% for materials intended for bitumen emulsion treatment. Excessive plasticity can increase moisture sensitivity and interfere with adhesion between the bitumen and mineral particles. Materials with a plasticity index above 10% may therefore require lime pre-treatment. The measured plasticity index confirms that the reclaimed material was suitable for emulsion stabilization without lime modification.

Table 2 Consistency limits of the fraction of the reclaimed material passing the 425 μm sieve

Property	Measured value	Requirement for bitumen emulsion treatment
Liquid limit, LL (%)	23	—
Plastic limit, PL (%)	17	—
Plasticity index, PI = LL – PL (%)	6	$PI \leq 7$

The chemical composition of the fines, determined by X-ray fluorescence spectrometry, is presented in Table 3. Ferric oxide was the predominant constituent (46.04%), followed by silica (30.85%) and alumina (10.68%), while calcium oxide, potassium oxide, phosphorus pentoxide and manganese oxide ranged from 0.14% to 3.90%. The predominance of iron and silicon oxides together with the relatively low calcium oxide content indicates an acidic, predominantly siliceous fines fraction associated with the lateritic soil and granular material in the original pavement. Based on the conventional charge-matching principle, this composition would suggest a cationic emulsion, as acidic siliceous surfaces are generally expected to develop a negative charge in an aqueous environment. However, the experimental results presented later show that the cationic emulsion was not the most suitable, suggesting that the aged binder coating the reclaimed particles may influence the interfacial behaviour more strongly than the mineral composition of the fines alone.

Table 3 Chemical composition of the FDR fines determined by X-ray fluorescence spectrometry

Compound	Content (%)	Compound	Content (%)
Fe_2O_3	46.039	K_2O	3.384
SiO_2	30.846	CaO	3.900
Al_2O_3	10.677	P_2O_5	0.596
MnO	0.139	Others	3.861

Three slow-setting bitumen emulsions were evaluated in the present study. This includes two anionic grades (designated as A-1 and A-2, and conforming to IS 3117:2004 [23]) and one cationic slow-setting SS-2 grade (designated C-1 and conforming to IS 8887:2004 [24]). Slow-setting emulsions were selected to provide sufficient working time for uniform distribution through the reclaimed material, which has a relatively high specific surface area, before breaking occurs. Ordinary Portland cement passing the 150 μm sieve was used as the active filler. The cement was intended to promote localized emulsion breaking, consume part

of the free water, accelerate early cohesion and improve moisture-related strength retention. Its content was therefore kept low and treated as a mix-design variable.

3.2 Emulsion Characterization

Six tests were conducted on each emulsion in accordance with IS 3117:2004 [23] for the anionic grades and IS 8887:2004 [24] for the cationic grade, with the test apparatus shown in Fig. 3. Particle charge was determined by electrolysis between stainless-steel plates at 12 V, maintaining a current above 4 mA for 30 minutes. Residue by evaporation was determined in triplicate using 50 ± 0.1 g of emulsion, heated at 163 ± 2.8 °C for two hours. Viscosity was measured as the efflux time of 60 mL through the standard orifice of a Saybolt Furol viscometer at 30 °C. Cement-mixing stability was evaluated by mixing 100 mL of emulsion, diluted to 50% water content, with 50 g of cement passing the 150 μ m sieve, followed by washing through a 1.40 mm sieve and drying to constant mass. The coagulation value was expressed as the retained mass relative to the binder present. For the coating test, 35 ± 0.1 g of emulsion was mixed with 465 ± 0.1 g of reclaimed material for three minutes, with at least 50% coating required after 30 minutes. Rheological characterization of the recovered residue was performed using a dynamic shear rheometer, with testing completed within two hours of specimen preparation to minimize steric hardening. After 8–16 conditioning cycles, frequency, phase angle and complex modulus were averaged over a further 8–16 cycles, and the rutting parameter was evaluated at 25, 35, 45, 55, 65 and 75 °C. The apparatus is shown in Fig. 3(b). Rheological testing was conducted only on the residue from the selected emulsion, as its purpose was to assess the high-temperature performance of the accepted binder rather than to rank the candidate emulsions, which was established through the coating and strength tests.



Fig. 3 Emulsion characterization test set-ups

3.3 Mix Design

The mix design followed the sequential procedure recommended in the Asphalt Academy guideline for bitumen-stabilized materials [12], adapted to the acceptance criteria of IRC:37-2012 [22]. The procedure comprised three successive optimization stages, with each stage fixing the selected variable before proceeding to the next.

3.3.1 Optimum Fluid Content

The total fluid content comprised the pre-mixing water, water contained in the emulsion and hygroscopic moisture present in the reclaimed material. Pre-mixing water was added to wet the fines, limit preferential absorption of the emulsion by the fine fraction, and facilitate compaction. The optimum fluid content was determined using modified Proctor compaction, with the added fluid supplied as a 50:50 mixture of pre-mixing water and emulsion. Twelve specimens were prepared for each emulsion at total fluid contents of 6.5–9.5% for the cationic emulsion and 7.5–10.5% for the anionic emulsions, while cement content was fixed at 1%. The specimens were cured at 40 °C for three days to remove the introduced water and allow the residual binder to develop cohesion. As shown in Fig. 4, curing changed the specimens from light brown to a darker, more cohesive material, indicating emulsion breaking and binder coalescence.



Fig. 4 Compacted specimens (a) before curing, and after curing at 40 °C for three days for (b) the anionic-stabilized mix and (c) the cationic-stabilized mix

3.3.2 Optimum Emulsion Content

With the total fluid content fixed, the proportion supplied as emulsion rather than pre-mixing water was varied at emulsion-to-water ratios of 60:40 and 75:25. Three specimens each were prepared at each ratio, compacted, cured and tested for indirect tensile strength (ITS) in the dry condition. Testing was performed in a Marshall loading frame on 100 mm diameter specimens at 25 °C, with the load applied along the vertical diameter through 12.7 mm curved loading strips at a rate of 50.8 mm/min. The indirect tensile strength was calculated as Eq. (1).

$$ITS = \frac{2000P}{\pi dh} \quad (1)$$

where P is the maximum load (N), d the specimen diameter (mm) and h the specimen height (mm). The emulsion content corresponding to an ITS-dry of 225 kPa was adopted as the optimum. The balance of the fluid content was calculated as the pre-mixing water requirement.

3.3.3 Optimum Filler Content

The cement content was varied from 1.0% in increments of 0.5%. Companion specimens prepared under identical conditions were tested in the dry state to determine ITS-dry and, after soaking in water at the test temperature for two hours, to determine ITS-wet. The tensile strength ratio (TSR) was calculated as the ratio of ITS-wet to ITS-dry, expressed as a percentage. The lowest cement content satisfying both acceptance criteria, $ITS\text{-wet} \geq 100$ kPa and $TSR \geq 50\%$, was adopted as the optimum cement content.

3.3.4 Emulsion Selection

An emulsion was accepted only when the resulting mix satisfied all three criteria simultaneously. This includes $ITS\text{-dry} \geq 225$ kPa, $ITS\text{-wet} \geq 100$ kPa, and $TSR \geq 50\%$. The

dry ITS criterion ensures adequate initial cohesive strength, while the wet ITS criterion confirms that a minimum level of strength is retained after saturation. The TSR criterion assesses the proportion of strength retained under moisture exposure and therefore provides an indication of the quality of the bitumen–mineral bond. The criteria are complementary rather than redundant, since a mix may achieve adequate dry strength while experiencing an unacceptable loss of strength after soaking.

3.4 Performance Testing

Resilient modulus testing was conducted in accordance with AASHTO TP 31-96 [25], using cylindrical specimens of 101.6 mm in diameter and 71.6–75.1 mm in height. Haversine load pulses of 0.1 s duration followed by a 0.9 s rest period were applied through curved loading strips using a closed-loop servo-pneumatic system. Recoverable deformation was monitored with linear variable differential transformers, as shown in Fig. 5. A minimum of 30 pulses was applied, and the recoverable deformation from the final five cycles was used to calculate the resilient modulus. Twelve specimens were tested under an applied load of 375 N. Permanent deformation was evaluated by uniaxial dynamic creep testing in accordance with Method A of BS EN 12697-25 [26]. Specimens were conditioned at 50 °C for two hours and subjected to repeated haversine loading through a platen smaller than the specimen diameter, providing partial confinement. Axial deformation was recorded for 1,800 cycles at deviator stresses of 200, 400 and 600 kPa.

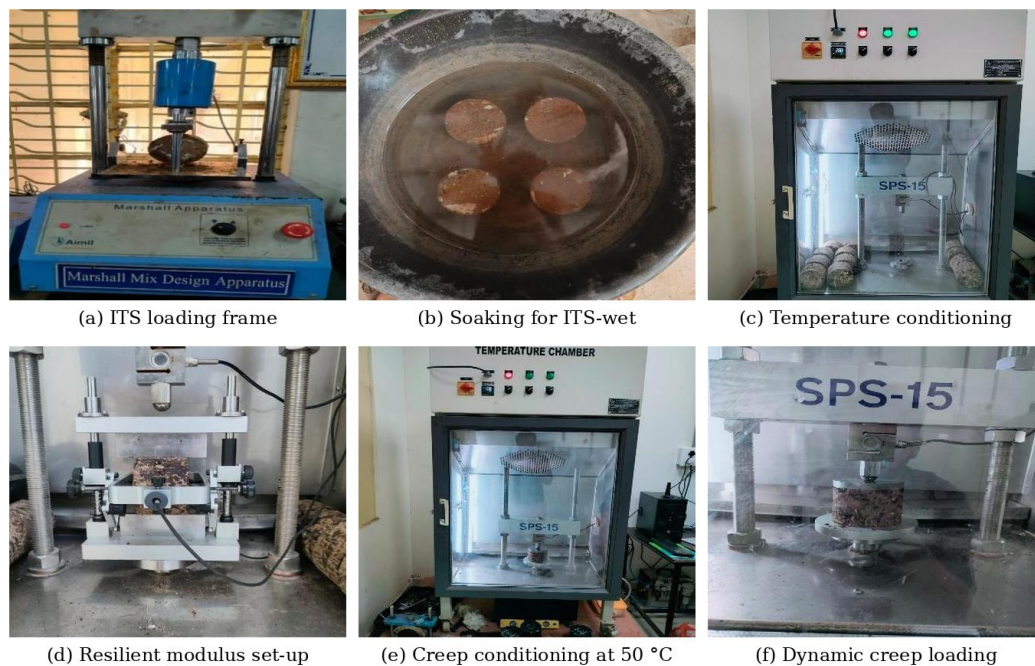


Fig. 5 Strength and performance test set-ups

3.5 Mechanistic Thickness Design

Thickness design was performed using IITPAVE, which evaluates stresses and strains in a linear-elastic layered system subjected to a uniformly distributed load over a circular contact area. As shown in Fig. 6, the pavement was modelled as three layers consisting of a 30 mm thick bituminous concrete wearing course conforming to MoRTH [27], an emulsion-stabilized FDR base, and a semi-infinite subgrade. The bituminous concrete was assigned an elastic modulus of 2,000 MPa, while the FDR base was assigned 800 MPa, consistent with the value recommended in IRC:37-2018 [28] for emulsion-stabilized mixes containing reclaimed asphalt pavement. This value is also conservative relative to the measured 15th-percentile modulus of 867 MPa, while retaining consistency with current Indian design practice and accounting for differences between laboratory-compacted specimens and field-placed material. A Poisson's ratio of 0.35 was adopted for all layers in accordance with IRC:37-2012 [22]. The 2,000 MPa surfacing modulus represents a thin dense bituminous layer under the pavement temperatures considered and remains conservative relative to the higher values reported for stiffer binder grades in IRC:37. Traffic loading was represented by a dual-wheel assembly with 20,000 N per wheel, a contact pressure of 0.56 MPa and a centre-to-centre spacing of 310 mm. Vertical compressive strain was calculated at the top of the subgrade beneath the centre of one wheel and midway between the wheels, with the larger value adopted as governing. These inputs fully define the layered-elastic analysis and permit reproduction of the thickness-design procedure.

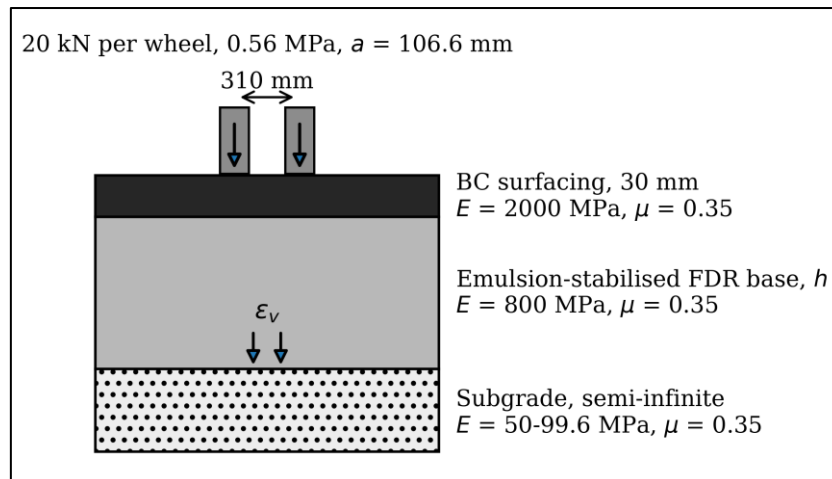


Fig. 6 Pavement cross section and layer properties adopted for the IITPAVE analysis

Table 4 presents the design procedure for three representative subgrade strengths, illustrating a sequence that can be reproduced for other combinations. For each case, the subgrade

modulus is first obtained from the CBR correlation, followed by determination of the cumulative standard axles corresponding to the upper limit of the traffic category. The permissible subgrade strain is then calculated from the adopted rutting model, and the three-layer pavement structure is analysed by progressively adjusting the FDR base thickness until the computed strain satisfies the criterion, subject to the minimum treatment thickness of 150 mm.

Table 4 Design template for traffic category T7 at three representative subgrade strengths

Design step	CBR 5%	CBR 7%	CBR 10%
Subgrade resilient modulus, Eq. (3) (MPa)	50.0	61.1	76.8
Cumulative standard axles, N	1,000,000	1,000,000	1,000,000
Permissible strain, Eq. (4) ($\mu\epsilon$)	1,119	1,119	1,119
Surfacing modulus / thickness	2,000 MPa / 30 mm	2,000 MPa / 30 mm	2,000 MPa / 30 mm
FDR base modulus	800 MPa	800 MPa	800 MPa
FDR base thickness adopted (mm)	180	165	150
Computed strain from IITPAVE ($\mu\epsilon$)	1,090	1,100	1,096
Check against Eq. (5)	Satisfied	Satisfied	Satisfied
Governing constraint	Strain	Strain	Minimum depth

Subgrade classes S₃, S₄ and S₅ of IRC:SP:72-2015 [21] correspond to CBR ranges of 5–6%, 7–9% and 10–15%, respectively, and the analysis considered CBR value from 5% to 10%. The subgrade resilient modulus was estimated using the CBR-based correlations specified in IRC:37, which express modulus solely as a function of CBR, as given in Eqs. (2) and (3). As noted by Lee et al. [29], subgrade modulus is inherently stress dependent and the adopted correlations should therefore be regarded as design simplifications rather than constitutive relationships.

$$M_R = 10 \text{ CBR} \quad (2)$$

$$M_R = 17.6 \text{ CBR}^{0.64} \quad (3)$$

where Eq. (2) applies for $\text{CBR} \leq 5$ and Eq. (3) for $\text{CBR} > 5$.

Design traffic was represented by categories T5 to T9 of IRC:SP:72-2015 [21], spanning cumulative applications of 0.2 to 2.0 million standard axles. The permissible vertical compressive strain at the top of the subgrade was taken from the rutting model of IRC:37-2018 [28] at 80% reliability, as given in Eq. (4).

$$N_R = 4.1656 \times 10^{-8} \frac{1}{\varepsilon_v}^{4.5337} \quad (4)$$

IRC:SP:20 [30] identifies the subgrade rutting equation corresponding to 80% as the appropriate reliability level for pavements carrying less than 2 million standard axles. This criterion was preferred to the thin-surfaced low-volume road models of Sahoo and Reddy [20], which were calibrated using unbound granular sections without a bound base and are therefore not directly representative of a bituminous surfacing over a bitumen-stabilized layer. Since no criterion has been developed specifically for emulsion-stabilized FDR, the IRC:37 relationship was adopted as the available design basis. The upper limit of each traffic category was used to ensure that the resulting design remains adequate throughout the category. For each combination of traffic category and subgrade CBR, the FDR base thickness was iteratively adjusted until the computed subgrade strain satisfied the adopted criterion, given in Eq. (5).

$$\varepsilon_v \leq \varepsilon_{v,allowable} \quad (5)$$

The thickness obtained from the analysis was rounded upward to the nearest 5 mm. A minimum stabilized base thickness of 150 mm was additionally imposed, since the section carries no granular sub-base and the reclaimed layer must therefore provide the whole of the load spreading beneath the surfacing as well as a constructible treatment depth for the reclaimer.

4 Results

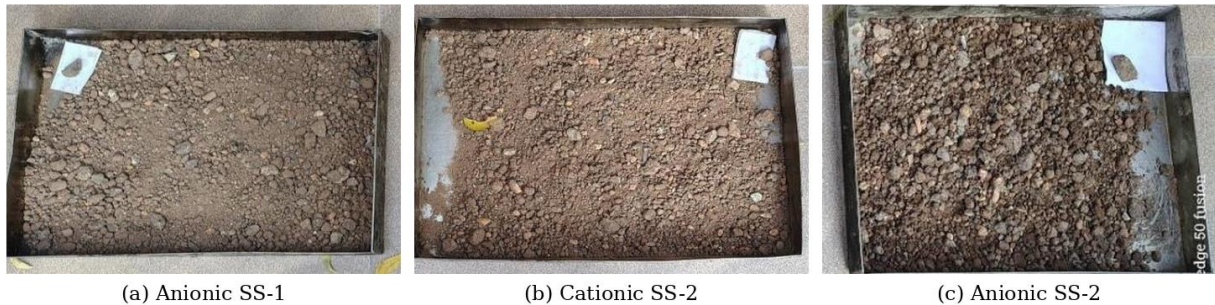
4.1 Emulsion Characterization

The results of the six characterization tests are compared with the requirements of IS 3117 [23] and IS 8887 [24] in Table 5. The particle charge test confirmed the ionic classification of the three emulsions. Residue by evaporation was 58.56% for A-1, 63.39% for C-1 and 63.78% for A-2, exceeding the specified minimums of 57% for anionic and 60% for cationic grades. Saybolt Furol viscosities at 30 °C were 30, 68 and 50 s, respectively, all within the specified ranges. Coagulation values were 2.00%, 1.50% and 2.00%, respectively, satisfying the maximum allowable value of 2%.

Table 5 Physical characterization of the three candidate bitumen emulsions

Property	Emulsion A-1 (anionic)	Emulsion C-1 (cationic)	Emulsion A-2 (anionic)	Requirement	Test standard
Particle charge	Deposits on anode	Deposits on cathode	Deposits on anode	—	IS 3117 / IS 8887
Residue by evaporation (%)	58.56	63.39	63.78	≥ 57 (anionic); ≥ 60 (cationic)	IS 3117 / IS 8887
Saybolt Furol viscosity at 30 °C (s)	30	68	50	20–100 (anionic); 30–150 (cationic)	IS 3117 / IS 8887
Coagulation value, stability to mixing with cement (%)	2.00	1.50	2.00	≤ 2	IS 3117 / IS 8887
Coating after 30 min	Slight darkening	No change	More than 50% coating	More than 50% coating	IS 3117 / IS 8887

The coating test produced the first clear differentiation between the emulsions, as shown in Fig. 7. Emulsion C-1 produced no visible change after 30 minutes, indicating that it had not broken within the working period. A-1 produced only slight darkening and A-2 produced coating of more than 50% of the surface, satisfying the acceptance requirement.

**Fig. 7** Coating test after 30 minutes for (a) emulsion A-1, (b) emulsion C-1 and (c) emulsion A-2

The rutting parameter of the recovered residue from A-2, the only emulsion advanced to rheological characterization, is presented in Table 6. The parameter decreased from 335,000 Pa at 25 °C to 1,580 Pa at 75 °C, representing a reduction of more than two orders of magnitude, with an approximately linear trend on the logarithmic scale. The residue remained above the 1.0 kPa criterion for unaged binder throughout the tested temperature range, including 75 °C, indicating a high-temperature performance grade of at least PG 70.

Table 6 Rutting parameter of the residue recovered from emulsion A-2

Temperature (°C)	$ G^* /\sin \delta$ (Pa)	Ratio to value at 25 °C
25	335,000	1.00
35	111,000	0.331
45	32,100	0.096
55	10,200	0.030
65	3,790	0.011
75	1,580	0.005

4.2 Mix Design and Emulsion Selection

The compaction curves are shown in Fig. 8. The cationic emulsion C-1 gave an optimum fluid content of 8.5% at a maximum dry density of 1.82 g/cm³, and the anionic emulsions an optimum of 9.5% at 1.80 g/cm³. The anionic compaction curve falls away more steeply beyond the optimum, indicating greater sensitivity to over-wetting.

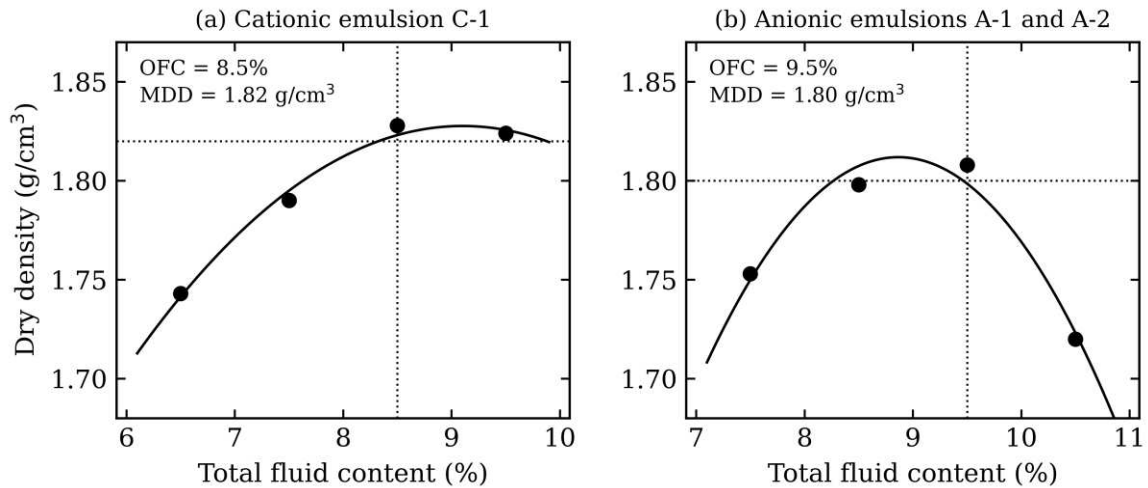


Fig. 8 Dry density against total fluid content at a 50:50 emulsion-to-water ratio for (a) the cationic emulsion and (b) the anionic emulsions

Fig. 9 shows the relationship between emulsion content and ITS-dry for emulsion A-2, which was strongly linear over the range investigated, as given in Eq. (6).

$$ITS_{dry} = 74.83 E_c - 150.76 \quad (6)$$

with a coefficient of determination R^2 of 0.9879. The high coefficient of determination indicates that within this range the mix had not reached the binder content at which further addition reduces strength through over-lubrication of the aggregate skeleton. The emulsion content corresponding to 225 kPa was 5.02%, within a total fluid content of 9.5%. This

corresponds to a division of approximately 53% emulsion and 47% pre-mixing water. Applying the measured residue content of 63.78%, this delivers a residual binder content of 3.20% by mass of dry reclaimed material.

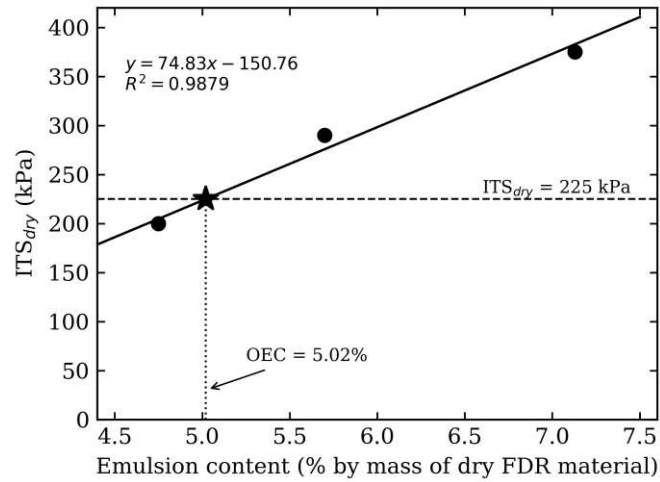


Fig. 9 Indirect tensile strength in the dry state against emulsion content for emulsion A-2

The complete mix-design matrix is presented in Table 7. The programme was conducted sequentially rather than as a full factorial, with emulsions A-1 and C-1 first evaluated across the investigated emulsion-to-water ratios and filler contents to determine whether either could satisfy the acceptance criteria. Both were subsequently rejected. Emulsion C-1 achieved a dry ITS of 231 kPa only at an emulsion-to-water ratio of 75:25 with 2.5% cement. Although its wet ITS of 110 kPa met the minimum requirement, the resulting TSR of 47% was below the acceptance limit. Emulsion A-1 produced the highest dry ITS of 348 kPa, but its wet ITS remained below 84 kPa for all combinations tested and therefore failed the wet-strength criterion. Emulsion A-2 satisfied all three criteria at the lowest filler content investigated, 1% cement, with a dry ITS of 231 kPa, wet ITS of 118 kPa and TSR of 51.1%. The selected mix comprised 100% reclaimed material, 5.02% anionic emulsion A-2, 4.48% pre-mixing water and 1% cement, corresponding to a residual binder content of 3.20%.

Table 7 Mix design matrix and emulsion selection

Emulsion	Residue (%)	OFC (%)	Emulsion : water	Filler (%)	ITS-dry (kPa)	ITS-wet (kPa)	TSR (%)	OEC (%)	Outcome
C-1 (cationic)	63.39	8.5	60 : 40	1.0	168	—	—	6.1	Rejected: TSR below 50%
				1.5	176	—	—		
				2.0	184	—	—		
				2.5	192	—	—		
			75 : 25	1.0	210	—	—		
				1.5	217	—	—		
				2.0	224	—	—		
				2.5	231	110	47.6		
A-1 (anionic)	58.56	9.5	60 : 40	1.0	230	86	37.4	5.58	Rejected: TSR below 50%
				1.5	250	96	38.4		
				2.0	270	108	40.0		
				2.5	290	122	42.1		
			75 : 25	1.0	288	98	34.0		
				1.5	328	104	31.7		
				2.0	332	115	34.6		
				2.5	340	135	39.7		
A-2 (anionic)	63.78	9.5	60 : 40	1.0	231	118	51.1	5.02	Selected
				1.5	254	133	52.4		
				2.0	291	160	55.0		
				2.5	320	179	56.0		
			75 : 25	1.0	280	146	52.1		
				1.5	321	158	49.2		
				2.0	344	187	54.4		
				2.5	349	194	55.6		

OFC optimum fluid content, OEC optimum emulsion content, ITS indirect tensile strength, TSR tensile strength ratio. Values in bold denote the selected mix.

4.3 Resilient Modulus

Twelve specimens were tested and the results are given in Table 8 and presented in Fig. 10. Three results lay above the main body of the data and were excluded as outliers. The statistics below are therefore for the nine retained specimens. Values ranged from 693 to 1,399 MPa with a mean of 1,046 MPa, a standard deviation of 216 MPa and a coefficient of variation of

20.6%. Seven of the nine fall within the 600 to 1,200 MPa range, indicated in IRC:37-2012 [22] for stabilized materials of this class.

Table 8 Resilient modulus of the selected emulsion-stabilized FDR mix

Specimen no.	Applied load (N)	Height (mm)	Diameter (mm)	Resilient modulus (MPa)
1	375	72.18	101.6	1,142
2	375	74.22	101.6	849
3	375	73.50	101.6	980
4	375	74.81	101.6	1,162
5	375	71.60	101.6	1,253
6	375	72.53	101.6	693
7	375	73.41	101.6	1,399
8	375	72.79	101.6	937
9	375	73.79	101.6	1,000
Mean	—	—	—	1,046
Standard deviation	—	—	—	216
Coefficient of variation	—	—	—	20.6%
15th percentile	—	—	—	867

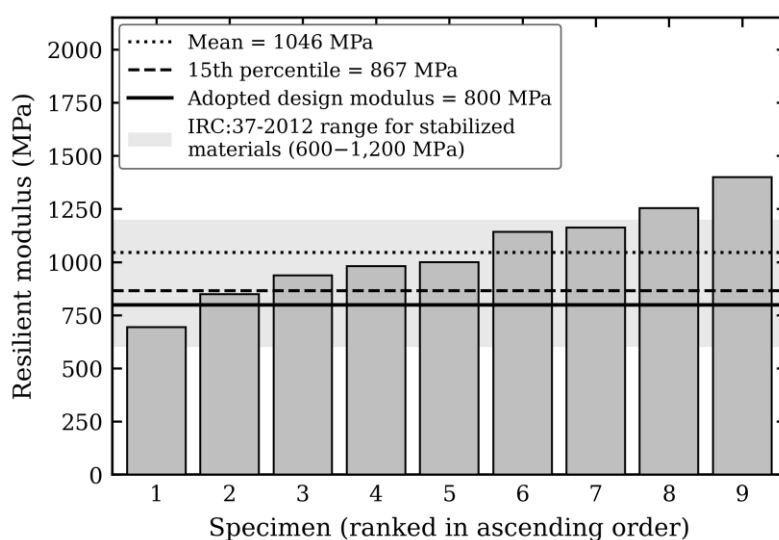


Fig. 10 Ranked resilient modulus of the nine retained specimens

The observed scatter is not unexpected for a material produced entirely from reclaimed feedstock. The reclaimed material combines pulverized surfacing, granular base and subgrade soil in proportions that may vary along the road. Hence individual specimens can represent slightly different material compositions. In addition, the discontinuous distribution of the

binder can produce local variations in the concentration of coated fines, while the stress-dependent nature of the resilient modulus makes the measured response sensitive to small differences in specimen seating and loading conditions [31]. From the present study 15th-percentile modulus was 867 MPa and, this value was adopted as the characteristic laboratory value. The design modulus was nevertheless taken as 800 MPa, consistent with the IRC:37-2018 [28] value specified for emulsion-stabilized mixes containing reclaimed asphalt. This represents approximately 92% of the characteristic laboratory value and provides a conservative design value relative to the measured modulus, while maintaining consistency with current Indian practice.

4.4 Permanent Deformation

The accumulation of permanent strain is shown in Fig. 11 and summarized in Table 9. Permanent strain reached 3.03%, 4.01% and 6.21% at deviator stresses of 200, 400 and 600 kPa, respectively. All three curves exhibited rapid initial densification followed by a secondary stage with a low and nearly constant strain rate [32]. At 200 and 400 kPa, the curves became essentially stable after about 500 cycles, whereas the 600 kPa curve retained an upward trend throughout the 1,800 cycles, indicating a lower degree of stabilization, although tertiary deformation was not reached. Increasing the deviator stress from 200 to 600 kPa increased the accumulated strain by a factor of 2.05. Out of the total increase, 31% occurred between 200 and 400 kPa, while the remaining 69% occurred between 400 and 600 kPa, indicating a substantially stronger sensitivity to stress at the higher loading level.

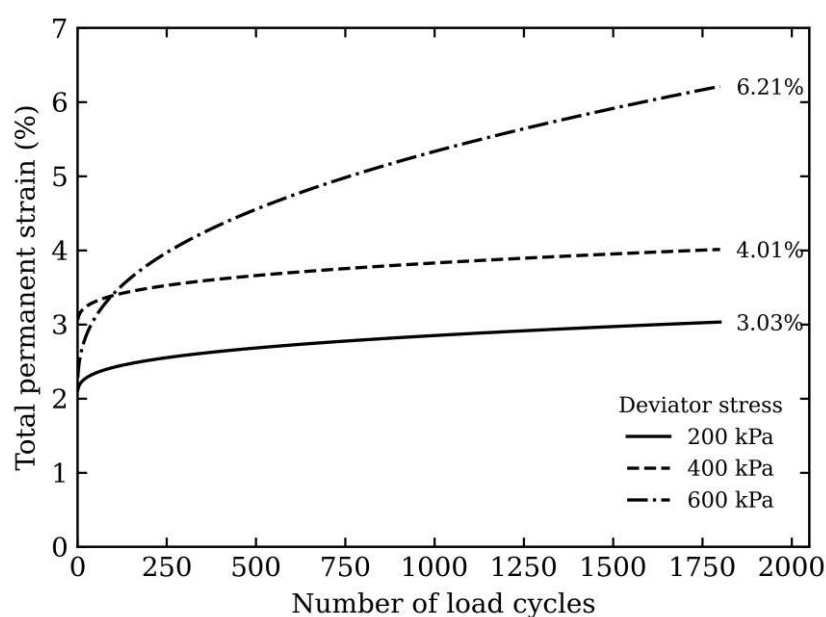


Fig. 11 Accumulation of total permanent strain with load cycles at deviator stresses

Table 9 Total permanent strain at 1,800 loading cycles

Deviator stress (kPa)	Total permanent strain at 1,800 cycles (%)	Increase relative to 200 kPa (%)
200	3.03	—
400	4.01	32.3
600	6.21	105.0

4.5 Thickness Design Catalogues

Subgrade moduli are given in Table 10 for five representative CBR values, ranging from 50.0 MPa at CBR 5% to 99.6 MPa at CBR 15%. Permissible strains from the IRC:37 rutting model at 80% reliability are given in Table 11, falling from 1,459 $\mu\epsilon$ at traffic category T5 to 960 $\mu\epsilon$ at T9.

Table 10 Subgrade classification and resilient modulus for representative CBR values

Subgrade class (IRC:SP:72-2015)	CBR (%)	Resilient modulus (MPa)
S ₃ (fair)	5	50.0
S ₄ (good)	7	61.1
S ₄ (good)	9	71.8
S ₅ (very good)	12	86.3
S ₅ (very good)	15	99.6

Table 11 Traffic categories and permissible vertical compressive strain from the IRC:37 rutting model at 80% reliability

Traffic category	Cumulative standard axles, <i>N</i> (upper limit)	Permissible strain ($\mu\epsilon$)	Design life basis
T5	300,000	1,459	Rutting, 80% reliability
T6	600,000	1,252	Rutting, 80% reliability
T7	1,000,000	1,119	Rutting, 80% reliability
T8	1,500,000	1,023	Rutting, 80% reliability
T9	2,000,000	960	Rutting, 80% reliability

Vertical compressive strains computed for the adopted thicknesses are given in Table 12, and every configuration satisfies its criterion. The margins are not uniform, and the reason is visible in the catalogue itself. In majority of the combinations, the mechanistic requirement

falls below the 150 mm minimum treatment depth. So, the adopted section is thicker than the strain criterion demands and hence the computed strain sits well inside the limit.

Table 12 Vertical compressive strains computed by IITPAVE for the adopted catalogue thicknesses

Traffic category	Vertical compressive strain at top of subgrade ($\mu\epsilon$) for subgrade CBR of											Permissible ($\mu\epsilon$)
	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%	
T5	1343	1281	1223	1174	1132	1096	1063	1034	1007	983	961	1,459
T6	1249	1235	1223	1174	1132	1096	1063	1034	1007	983	961	1,252
T7	1090	1076	1100	1094	1093	1096	1063	1034	1007	983	961	1,119
T8	990	1008	996	989	987	987	992	998	1007	983	961	1,023
T9	930	946	934	957	955	924	928	932	940	950	928	960

Table 13 Design thickness catalogue for emulsion-stabilized full-depth reclamation bases

Subgrade CBR (%)	Subgrade class	BC surfacing (mm)	Emulsion-stabilized FDR base thickness (mm) for traffic category				
			T5	T6	T7	T8	T9
5	S ₃ (fair)	30	150	160	180	195	205
6	S ₃ (fair)	30	150	155	175	185	195
7	S ₄ (good)	30	150	150	165	180	190
8	S ₄ (good)	30	150	150	160	175	180
9	S ₄ (good)	30	150	150	155	170	175
10	S ₅ (very good)	30	150	150	150	165	175

Values in bold are governed by the subgrade strain criterion; the remaining values are governed by the 150 mm minimum treatment depth.

The catalogue is presented in Table 13, with design templates for three representative subgrades in Fig. 12. Values printed in bold are governed by the strain criterion. The remaining values sit at the 150 mm minimum treatment depth. Required thickness of the emulsion-stabilized base ranges from 150 mm to 205 mm beneath a 30 mm bituminous concrete surfacing. Traffic categories T5 and T6 are at the minimum depth for every subgrade above CBR 6%, T7 from CBR 10% upward, and only T8 and T9 on the weaker subgrades are governed by strain throughout.

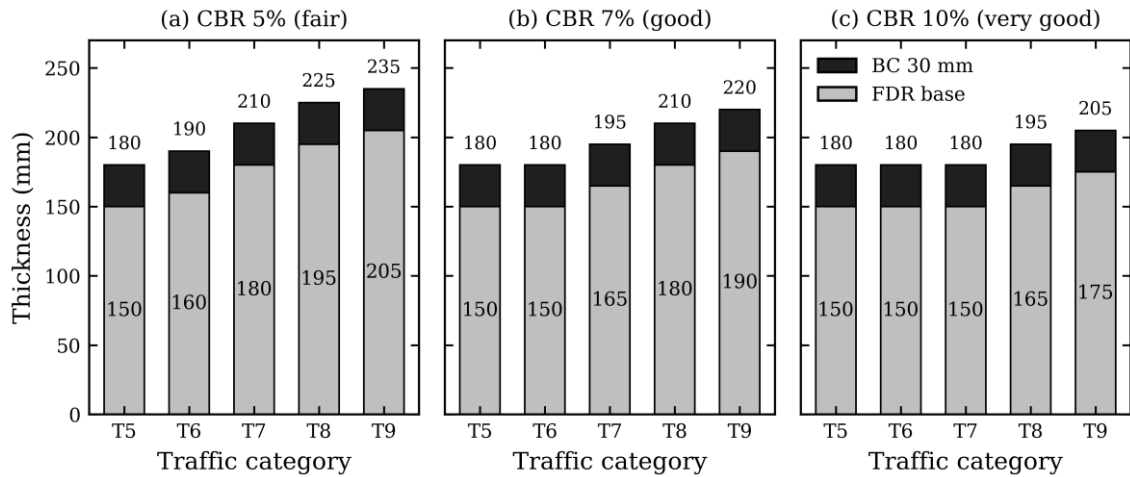


Fig. 12 Design templates for subgrade CBR of 5%, 7% and 10%

5 Practical Application and Scope for Future Research

The practical value of this work lies less in the specific numerical values than in the procedure used to obtain them, since reclaimed material will vary between sites. Several implications follow for designers considering emulsion-stabilized FDR, with the catalogue subject to the stated assumptions.

- Emulsion selection should be tested rather than predicted. Conventional charge-matching rules may be unreliable for reclaimed material because particle surfaces can already be coated with aged binder, making the mineral composition of the fines an imperfect indicator of the effective surface condition. A practical sequence is to use the coating test as an initial screen, followed by acceptance against all three strength criteria simultaneously.
- Design should account for material variability. The coefficient of variation reflects the inherent heterogeneity of material recovered from an existing pavement. Designing on the mean modulus could therefore overestimate the stiffness available in a substantial proportion of the layer. Construction specifications should consequently emphasize uniform pulverization, thorough mixing and consistent blending along the treatment length rather than relying on average material properties.
- The stress reaching the stabilized layer should be controlled. The creep results indicate a change in deformation behaviour between 400 and 600 kPa, with stresses near the top of the base approaching 400–500 kPa under the adopted 0.56 MPa contact pressure. This supports retaining a bituminous surfacing rather than relying on a surface dressing alone for the higher traffic categories.

- Constructability, rather than strain, governs much of the catalogue. With a realistic surfacing modulus and the IRC:37 subgrade criterion, the required thickness for an 800 MPa stabilized base is below 150 mm for more than half of the combinations. Since no granular sub-base is provided, 150 mm represents a practical minimum. Thus, T5 and T6 above CBR 6%, and T7 above CBR 10%, can generally be accommodated at this thickness. Only T8 and T9 on weaker subgrades require additional thickness, reaching a maximum of 205 mm. For much of the low-volume road range, structural analysis primarily confirms a constructability-driven treatment depth.
- The catalogue remains conditional on two key assumptions: a 30 mm bituminous concrete surfacing with a modulus of at least 2,000 MPa and an FDR modulus of 800 MPa. The latter is the IRC:37-2018 value for emulsion-stabilized mixes containing reclaimed asphalt and is below the characteristic laboratory modulus measured here. Consequently, the catalogue does not depend on reproducing the full laboratory stiffness in the field. A softer surfacing, particularly under higher pavement temperatures, would reduce this reserve most noticeably for heavy traffic on weak subgrades.

Several aspects warrant further investigation. Field validation using instrumented sections is the most important because the catalogue is based on laboratory-cured specimens and a linear-elastic idealization. Early-age strength development also requires consideration before trafficking. Long-term wetting–drying, ageing and fatigue behaviour remain unaddressed, while the narrow TSR margin indicates that moisture durability deserves particular attention. Testing reclaimed materials with different mineralogy would establish whether the proposed emulsion-selection procedure is transferable, and further work should quantify the balance between active-filler content, moisture resistance and the flexibility that motivates bituminous stabilization.

6 Conclusions

This study developed an experimentally based mix-design and mechanistic thickness-design framework for FDR using 100% reclaimed material stabilized with bitumen emulsion and 1% cement. The results demonstrate the feasibility of emulsion-stabilized FDR for low-volume road rehabilitation and provide a practical route from emulsion selection to structural thickness design. The principal conclusions are:

- The reclaimed material was suitable for direct stabilization without gradation correction or lime pretreatment. Its plasticity index was 6% and its gradation fell within the IRC:37-

2012 base envelope. Of the three slow-setting emulsions, only the anionic emulsion with 63.78% residue satisfied all three acceptance criteria including ITS-dry ≥ 225 kPa, ITS-wet ≥ 100 kPa and TSR $\geq 50\%$. Hence the optimum was selected at 5.02% emulsion, 4.48% pre-mixing water and 1% cement, giving 3.20% residual binder.

- Emulsion suitability could not be predicted from mineral composition or ionic charge alone. Although the siliceous fines conventionally suggested a cationic emulsion, it was rejected because its TSR was less than 50%. The result indicates that aged binder coatings on reclaimed particles can substantially influence the effective emulsion–particle interface.
- Dry strength alone is insufficient for emulsion selection. The rejected anionic emulsion produced the high dry ITS, but its wet ITS remained below 50% of dry strength. TSR should therefore be considered together.
- The selected mix showed moderate stiffness variability and stress-dependent permanent deformation. Resilient modulus ranged from 693 to 1,399 MPa, with a coefficient of variation of 20.6% and a 15th-percentile value of 867 MPa. Permanent strains were 3.03%, 4.01% and 6.21% at 200, 400 and 600 kPa, respectively, with 69% of the additional strain above the 200 kPa level occurring between 400 and 600 kPa.
- The thickness catalogue provides practical designs for T5–T9 traffic and CBR values of 5–10%. Required FDR thicknesses ranged from 150 to 205 mm beneath 30 mm of bituminous concrete, based on IITPAVE analysis using the IRC:37 subgrade rutting criterion and an 800 MPa FDR modulus. In majority of the combinations, the mechanistic requirement was below the adopted 150 mm minimum, indicating that constructability governs much of the catalogue. All sections can be constructed within a single reclaimer pass.
- The study provides a design route for emulsion-stabilized FDR for which Indian practice currently has limited guidance, linking emulsion selection, sequential mix design, material characterization and mechanistic thickness design.

Overall, the findings support 100% reclaimed emulsion-stabilized FDR as a viable rehabilitation option for low-volume roads. However, the results are based on material from a single distressed pavement. Field validation and longer-term studies of moisture durability, ageing, fatigue and early-age performance are needed before broader application of the catalogue.

References

1. Mallick, R. B., Teto, M. R., Kandhal, P. S., Brown, E. R., Bradbury, R. L., & Kearney, E. J. (2002). Laboratory study of full-depth reclamation mixes. *Transportation Research Record*, 1813(1), 103–110. <https://doi.org/10.3141/1813-13>
2. Kumar, R., Anupam, B. R., Chandrappa, A. K., Kar, S. S., & Sahoo, U. C. (2025). Bitumen stabilised materials for sustainable pavements: A review. *Road Materials and Pavement Design*, 26(9), 2139–2171. <https://doi.org/10.1080/14680629.2024.2436957>
3. Transportation Research Board. (2006). *Asphalt emulsion technology* (Transportation Research Circular E-C102). National Academies.
4. Lesueur, D., & Potti, J. J. (2004). Cold mix design: A rational approach based on the current understanding of the breaking of bituminous emulsions. *Road Materials and Pavement Design*, 5(sup1), 65–87. <https://doi.org/10.1080/14680629.2004.9689988>
5. Ignatavicius, S., Kavanagh, A., Brennan, M. J., Colleran, D., Sheahan, J., & Newell, S. (2021). Experimental investigation of optimum adhesion properties for anionic emulsions in road maintenance applications. *Construction and Building Materials*, 304, 124678. <https://doi.org/10.1016/j.conbuildmat.2021.124678>
6. Kong, L., Zhu, S., Chen, Y., Peng, Y., Zhao, P., Ouyang, J., & Feng, B. (2024). Quantifying the influence of lipophilic carbon chain length on adhesion between emulsified asphalt and acidic aggregates. *International Journal of Pavement Engineering*, 25(1), 2376219. <https://doi.org/10.1080/10298436.2024.2376219>
7. Kong, L., Zhu, S., Peng, Y., Zhao, P., Ouyang, J., Shao, Q., & Wang, W. (2024). Effect of phenyl functional groups on the adsorption behaviour of dodecyl anionic emulsifiers on oxides on the aggregate surface. *International Journal of Pavement Engineering*, 25(1), 2303662. <https://doi.org/10.1080/10298436.2024.2303662>
8. Yuan, Y., Chen, H., Wang, Y., Xu, S., Xue, B., Zou, G., & Wang, B. (2023). How calcium and magnesium ions affect the stability of asphalt with anionic emulsifiers: A molecular dynamics study. *Construction and Building Materials*, 400, 132770. <https://doi.org/10.1016/j.conbuildmat.2023.132770>
9. Horny, P., Gaudefroy, V., Geffard, J. L., & Goyer, S. (2009). Study of the mechanical behaviour of gravel-emulsions using triaxial tests. In A. Loizos, M. N. Partl, T. Scarpas, & I. L. Al-Qadi (Eds.), *Advanced testing and characterization of bituminous materials* (pp. 639–650). CRC Press. <https://doi.org/10.1201/9780203092989>
10. Barbod, B., & Shalaby, A. (2014). Laboratory performance of asphalt emulsion treated base for cold regions applications. In *Proceedings of the 2014 Conference of the Transportation Association of Canada*. Transportation Association of Canada.
11. Quick, T., & Guthrie, W. S. (2011). Early-age structural properties of base material treated with asphalt emulsion. *Transportation Research Record*, 2253(1), 40–50. <https://doi.org/10.3141/2253-05>
12. Asphalt Academy. (2009). *Technical guideline 2 (TG2): Bitumen stabilised materials — A guideline for the design and construction of bitumen emulsion and foamed bitumen stabilised materials* (2nd ed.). Asphalt Academy.

13. Baghini, M. S., Ismail, A., & Karim, M. R. B. (2015). Evaluation of cement-treated mixtures with slow setting bitumen emulsion as base course material for road pavements. *Construction and Building Materials*, 94, 323–336. <https://doi.org/10.1016/j.conbuildmat.2015.07.057>
14. Alkam, R. B., Airey, G. D., Thom, N., & Tajudin, A. N. (2025). Reclaimed asphalt pavement (RAP) in cold recycled bituminous mixtures: A systematic review. *Road Materials and Pavement Design*, 1–46. <https://doi.org/10.1080/14680629.2025.2595213>
15. Saha, S., Kumar, R., Behera, A., & Sahoo, U. C. (2026). Influence of constituents on the evolutionary response of bitumen-stabilized material. *Journal of Materials in Civil Engineering*, 38(2), 04025560. <https://doi.org/10.1061/JMCEE7.MTENG-21486>
16. Coelho, L. M., Guimarães, A. C. R., de Azevedo, A. R. G., & Monteiro, S. N. (2024). Sustainable reclaimed asphalt emulsified granular mixture for pavement base stabilization: Prediction of mechanical behavior based on repeated load triaxial tests. *Sustainability*, 16(13), 5335. <https://doi.org/10.3390/su16135335>
17. Fedrigo, W., Kleinert, T. R., Schreinert, G. G., Brito, L. A. T., & Núñez, W. P. (2025). Statistical analysis of the tensile strength of cold recycled cement-treated materials and its influence on pavement design. *Infrastructures*, 10(11), 284. <https://doi.org/10.3390/infrastructures10110284>
18. Kumar, A., Gupta, A., Anupam, K., Singh, A., & Premarathna, S. (2025). Mechanistic empirical studies of emulsion stabilized bases using finite element method. *Mechanics Based Design of Structures and Machines*, 53(10), 6863–6890. <https://doi.org/10.1080/15397734.2025.2491033>
19. Andrews, J. K., Radhakrishnan, V., & Koshy, R. Z. (2023). Laboratory evaluation of emulsion-treated base layer mixes incorporating reclaimed asphalt pavement materials. *Journal of Materials in Civil Engineering*, 35(7), 04023198. <https://doi.org/10.1061/JMCEE7.MTENG-15695>
20. Sahoo, U. C., & Reddy, K. S. (2011). Performance criterion for thin-surface low-volume roads. *Transportation Research Record*, 2203(1), 178–185. <https://doi.org/10.3141/2203-22>
21. Indian Roads Congress. (2015). *Guidelines for the design of flexible pavements for low volume rural roads* (IRC:SP:72-2015). Indian Roads Congress.
22. Indian Roads Congress. (2012). *Guidelines for the design of flexible pavements* (IRC:37-2012). Indian Roads Congress.
23. Bureau of Indian Standards. (2004a). *Bitumen emulsion for roads (anionic type) — Specification* (IS 3117:2004). Bureau of Indian Standards.
24. Bureau of Indian Standards. (2004b). *Bitumen emulsion for roads (cationic type) — Specification* (IS 8887:2004). Bureau of Indian Standards.
25. American Association of State Highway and Transportation Officials. (1996). *Standard test method for determining the resilient modulus of bituminous mixtures by indirect tension* (AASHTO TP 31-96). AASHTO.
26. British Standards Institution. (2005). *Bituminous mixtures — Test methods for hot mix asphalt — Part 25: Cyclic compression test* (BS EN 12697-25:2005). British Standards Institution.
27. Ministry of Road Transport and Highways. (2013). *Specifications for road and bridge works* (5th rev.). Indian Roads Congress.
28. Indian Roads Congress. (2018). *Guidelines for the design of flexible pavements* (IRC:37-2018). Indian Roads Congress.

29. Lee, J., Kim, J., & Kang, B. (2009). Normalized resilient modulus model for subbase and subgrade based on stress-dependent modulus degradation. *Journal of Transportation Engineering*, 135(9), 600–610. [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000019](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000019)
30. Indian Roads Congress. (2002). *Rural roads manual* (IRC:SP:20-2002). Indian Roads Congress.
31. Li, P., & Liu, J. (2014). Predictive model for nonlinear resilient modulus of emulsified asphalt treated base. In *Pavement materials, structures, and performance* (pp. 383–394). ASCE. <https://doi.org/10.1061/9780784413418.038>
32. Roy, N., Veeraragavan, A., & Krishnan, J. M. (2016). Influence of confinement pressure and air voids on the repeated creep and recovery of asphalt concrete mixtures. *International Journal of Pavement Engineering*, 17(2), 133–147. <https://doi.org/10.1080/10298436.2014.925622>