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# Field investigation of material layer properties for emulsion-treated base layer application in low-volume roads

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**ABSTRACT**

The study presents the determination of pavement design input parameters-structural layer coefficients and back-calculated layer moduli for Emulsion-Treated Base (ETB) layer materials in a Low-Volume Road (LVR) application. Seven test sections were constructed on a stretch of LVR with varying emulsion contents and 50% Recycled Asphalt Pavement (RAP) aggregate incorporation in ETB mixes. Structural performance of the test sections was periodically observed using a Benkelman Beam Deflectometer (BBD) and the data was used for the estimation of the structural layer coefficient of ETB, based on the effective structural number of the pavement. The deflection bowl data of the test sections were also captured using a Falling Weight Deflectometer (FWD) and the modulus of ETB layer was back-calculated using a back-calculation software. The study proposes a structural layer coefficient of 0.23–0.29 and back-calculated moduli of 578–919 MPa for ETB mixes characterised by Indirect Tensile Strength (ITS) values ranging between 140 kPa and 245 kPa. Traffic level-based ETB mix specifications are also proposed in the study, which enables a mix designer to proportion the mix for a selected design traffic level. For a design traffic level of 1 million standard axles, the target dry ITS specification was found to be 188 MPa.

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**KEYWORDS**
Low-volume road; emulsion-treated base; structural layer coefficient; back-calculated moduli; indirect tensile strength

## 1. Introduction

ETB is a cold mix application where the granular aggregate base layer materials are either modified (residual bitumen content < 1.5%) or stabilised (residual bitumen content ≥ 1.5%) with bituminous emulsions (Grobler *et al.* 1994). For incorporating ETB in LVRs, it is necessary to have appropriate material layer properties that are relevant to the pavement design philosophy adopted. For designing LVRs, some road agencies adopt Mechanistic-Empirical (M-E) pavement design, whereas others adopt the empirical AASHTO (1993) pavement design. For M-E pavement design, layer modulus is required, whereas for AASHTO (1993) pavement design, structural layer coefficients of pavement materials are required. Although ETB comes under the category of bitumen-treated bases, the structural layer coefficients provided in AASHTO (1993) pavement design guide for bitumen-treated bases cannot be reliably used. The layer coefficients in AASHTO (1993) were developed for a hot mix base layer, which was stabilised using 5.2%, 85/100 penetration grade bitumen and had a Marshall stability value in the range of 1600 lb (Elliot and Arif 1995). For an indicative resilient modulus value of ETB mixes given in IRC 37 (2018) (800 MPa for ETB with 4% bituminous emulsion and 1% cement), the structural layer coefficient read from the nomograph in AASHTO (1993) is 0.14, which is close to the typical layer coefficient value obtained for unbound granular base layer materials. Pavement designs carried out based on the above-selected layer coefficient would result in higher thickness requirements for ETB mixes, thereby increasing the cost of construction. Hence, it is necessary to evaluate the structural layer coefficients of ETB mixes for their future inclusion in LVRs if road agencies continuing to adopt AASHTO's (1993) pavement design philosophy. Apart from structural layer coefficients, the study also evaluates the back-calculated layer moduli for ETB mixes constructed in a test road project with different emulsion dosages and also incorporating Recycled Asphalt Pavement (RAP) materials. Instead of providing a single indicative structural layer coefficient/layer modulus, the study presents a relationship between laboratory-evaluated strength values and field mobilised layer properties.

Although most of road agencies appreciate the necessity of migrating from empirical pavement design to M-E-based pavement design, the lack of performance data collected in a systematic manner remains a challenge (Sahoo and Reddy 2011). Hence, AASHTO's (1993) pavement design continues to be used by several road agencies across the globe. For designing LVRs in India, the AASHTO (1993) pavement design philosophy is followed (IRC SP 72 2015). IRC SP 72 (2015) defines LVRs as roads, which cater traffic volume of less than 450 commercial vehicles per day and those having design traffic of up to 2 million standard axles (msa) load repetitions. For a given traffic volume and subgrade condition and for a selected reliability level, AASHTO (1993) pavement design estimates the structural number of the pavement to

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be provided above the compacted subgrade. Layer coefficients express the empirical relationship between structural number and thickness of different layers of material, and represent the relative ability of materials to function as structural components in pavement systems (Diaz-Snchez *et al.* 2017, Farrar and Ksaibati 1996). The layer coefficients initially proposed for different pavement materials in the AASHTO (1993) design guidelines were based on the AASHO road test, which was performed during 1958–1960 near Ottowa, Illinois, in the U.S.A. (Elliot and Arif 1995). The AASHTO (1993) pavement design guideline has proposed nomographs and equations for the determination of layer coefficients for asphalt concrete, unbound aggregate base and sub-base materials, bituminous-treated bases, and cement-treated base materials as a function of laboratory-determined strength parameters. The layer coefficients initially proposed by AASHTO (1993) for these different pavement materials have undergone changes, and several road agencies have recalibrated the layer coefficients based on observed pavement performance (Timm *et al*. 2014).

The actual method of determination of structural layer coefficients for pavement materials requires field performance data. As this takes several years, many researchers have attempted accelerated methods to determine layer coefficients. Hwang and Hiltunen (2020) identified four accelerated methods found in the literature to evaluate the structural layer coefficients: (a) using empirical equations/nomographs provided in AASHTO (1993), from laboratory-evaluated material properties; (b) by evaluating the effective structural number of the pavement; (c) by layer equivalency concept; and (d) by comparing the structural number of paired sections (one with known layer coefficient and pavement thickness, and the other with unknown layer coefficient and known pavement thickness) for reaching the same threshold level of performance. Farrar and Ksaibati (1996) evaluated the effect of emulsion content on the resilient modulus and layer coefficient of emulsion-treated aggregate mixes. Resilient modulus tests were conducted under laboratory conditions and the observed values were used to evaluate the layer coefficient, using the AASHTO (1993) equation for granular base layers. The study proposed a layer coefficient of ETB mixes with 1-3% emulsion in the range of 0.15–0.17. However, this value would depend on the curing condition of the ETB specimen at the time of testing. Quick and Guthrie (2011) made an attempt to evaluate the layer coefficient of RAP-modified ETB, treated with 4% emulsion. Test sections were constructed and the moduli values were back-calculated at regular time intervals. A maximum modulus value of 350 ksi (2413 MPa) was observed after 3 months of construction, and a correspondingly layer coefficient of 0.3 was assigned based on AASHTO's (1993) recommended design charts for bitumen-treated bases. The study concluded that the back-calculated moduli value of ETB mixes would increase up to three months and thereafter it starts to decrease, due to changes in behaviour of the material. Diaz-Snchez *et al.* (2017) used the data collected from two test sections at the National Centre for Asphalt Technology (NCAT) test track for assessing the layer coefficient of base layers with 100% RAP and 2% foamed asphalt. No significant distresses were observed during the two-year period of accelerated traffic loading in which 10 msa load repetitions were applied. Hence, layer coefficients were evaluated based on back-calculated moduli and were found to be in the range of 0.36–0.39. Marquis *et al.* (2003) evaluated the equivalent thickness and layer coefficient of foam-treated base using laboratory-evaluated moduli of core samples collected from the field and back-calculated moduli from Falling Weight Deflectometer (FWD) deflection data. Based on the deflection data observed from the four test sections, the layer coefficients of foam-treated bases were found to vary in the range of 0.22–0.35. Thus, it can be found that most of the researchers who proposed layer coefficients for ETB mixes have developed these values based on the empirical relation given in AASHTO (1993), relating laboratory resilient moduli and layer coefficient for granular material. Limited studies have been performed to evaluate structural layer coefficients from the observed long-term field performance of ETB mixes.

Material inputs for the M-E pavement design approach relies heavily on the back-calculated moduli evaluated using deflection bowl data, for the design and rehabilitation of pavements. For the design of high-volume roads in India, the Indian Roads Congress (IRC) guideline (IRC 37 2018) follows the M-E design approach. Indicative resilient modulus values of 600 and 800 MPa are recommended for ETB mixes with 3% and 4% emulsion content, respectively (IRC 37 2012; IRC 37 2018). Kumar *et al.* (2008) evaluated the back-calculated moduli of a cold-in-place recycled layer on the National Highway (NH 6) in India using FWD and recommended a moduli value of 1100 MPa for the design of cold recycled layers with 3.5% emulsion and 2% cement. South African guidelines (TG-2 2020) recommend minimum moduli values of 500 and 700 MPa for bitumen-stabilised materials with a granular supporting layer, for low-volume road and high-volume road applications, respectively. However, the guidelines recommend slightly higher moduli values for bitumen-stabilised material with a cemented supporting layer, indicating that the behaviour of bitumen-stabilised materials will depend on the position of the layer within the pavement system. Australian guidelines (AUSTROADS 2019) recommend minimum moduli values of 500 and 700 MPa for foamed bitumen-stabilised material for application in pavements with average daily traffic less than 100 Equivalent Single Axle Load (ESAL) and greater than 100 ESAL, respectively. Although few agencies and researchers have recommended indicative moduli values and layer coefficients for the design of ETB layer (for selected mix proportions), there exists a need to establish a relationship between laboratory-evaluated strength and field mobilised material property. For BSM mix design, TG-2 (2009) recommends a minimum Indirect Tensile Strength (ITS) requirement of 225 kPa, for design traffic greater than 6 msa, 175–225 kPa, for design traffic in the range of 1–6 msa; and 125–175 kPa, for a design traffic less than 1 msa. IRC 37 (2012), irrespective of the design traffic level, has adopted the minimum ETB mix specification of 225 kPa ($ITS_{dry}$) and 100 kPa ($ITS_{wet}$), for mixes incorporating RAP. For the wide adoption of ETB mixes in LVRs in India, it is necessary to develop traffic level-based ETB mix specifications, wherein the designer can deviate from the indicative specifications that are mentioned. Traffic level-based specification thereby would promote ETB mixes over a wide range of mix constituents. Considering the above aspects, this study presents the determination of pavement design input parameters, structural layer coefficients and back-calculated layer moduli for Emulsion-Treated Base (ETB) layer materials in Low-Volume Road (LVR) applications.

## 2. Objectives and scope of study

The specific objectives of the study were identified as follows.

- Estimate the structural layer coefficient and back-calculated moduli of ETB mixes using field performance data.
- Establish a relationship between laboratory strength, structural layer coefficient and the back-calculated modulus of ETB mixes.
- Develop traffic level-based mix specifications for ETB mixes.

## 3. Research methodology

### 3.1. Materials and field test section properties

The objectives listed above were evaluated using the field performance data collected from test sections. Seven test sections were constructed one after the other in a LVR in the state of Kerala, India. The test sections in the study primarily differed in the base course layer constructed above the existing granular layer. The control section (S1) incorporated an unbound granular base course, and the six sections (S2 to S7) following the control section incorporated ETB mixes. Sections S2 to S4 had virgin aggregates in the ETB mixes, whereas sections S5 to S7 incorporated 50% RAP in the ETB mix. The thickness of the base layer (150 mm) for all the sections (S1 to S7) was maintained constant. The Wet Mix Macadam (WMM) aggregate gradation given by the Ministry of Rural Development (MoRD 2014) was used for the unbound granular base course of the control section. For ETB sections, the aggregate gradation given in IRC 37 (2012) was adopted. Slow-setting bituminous emulsion (SS-2), complying with IS 8887 (2018) was used for constructing the ETB layers. Table 1 shows the summary of the base layer composition used in the seven test sections.

Before starting the paving operation, a laboratory mix design was carried out using the materials supplied from the project site. The physical properties of aggregates and bituminous emulsions used in this study are presented in Tables 2 and 3, respectively. Laboratory mix design for ETB mixes was determined by the procedure outlined in IRC 37 (2012) in Annexure IX. The Optimum Fluid Content (OFC) for ETB mixes incorporating virgin aggregates was found to be 7%, and for mixes with 50% virgin and 50% RAP aggregates, it was found to be 6.5%. The Optimum Emulsion Content (OEC) for both mixes was found to be 3% by weight of dry aggregates. The OEC of the mixes was determined corresponding to the emulsion content in the compacted mix, which resulted in a minimum dry ITS value of 225 kPa. OFC will be equal to the sum of OEC and pre-wetting water content. In order to evaluate the effect of emulsion content, sections S2, S3 and S4 were prepared with OEC-1%, OEC and OEC + 1% (2%, 3% and 4% by weight of dry aggregates) emulsion contents, respectively. Similarly, for sections incorporating RAP (sections S5, S6 and S7), emulsion dosage was varied in the same manner. RAP aggregates were obtained from the hot mix recycling project, which was in progress at a nearby location (the HMA recycling project of NH-66, between Cherthala and Aroor stretch, in Alappuzha, Kerala). From the bitumen extraction test conducted on the RAP material, it was inferred that the residual binder content was 4%. An active filler of 1% cement (Ordinary Portland Cement) by weight of aggregates was used in all ETB sections.

Aggregate blending exercises were carried out on the site, in order to achieve the target aggregate gradations. The aggregate gradation obtained for WMM (used in Section S1) is presented in Figure 1 and was well within the gradation envelope given by the MoRD (2014). The aggregate gradation of dry aggregate blends achieved in the field for ETB mixes is presented in Figure 2. The blended ETB gradation incorporating only virgin aggregate was found to be coarser and was close to the lower envelope of the gradation band for ETB mixes given by IRC 37 (2012). The ETB gradation incorporating 50% RAP aggregate was found to incorporate less fines and was within the gradation envelope.

**Table 1.** Details of base layer composition.

| Section ID | Base layer properties |
|---|---|
| S1 | 150 mm WMM |
| S2 | 150 mm ETB with 2% emulsion |
| S3 | 150 mm ETB with 3% emulsion |
| S4 | 150 mm ETB with 4% emulsion |
| S5 | 150 mm ETB with 2% emulsion and 50% RAP |
| S6 | 150 mm ETB with 3% emulsion and 50% RAP |
| S7 | 150 mm ETB with 4% emulsion and 50% RAP |

**Table 2.** Physical properties of aggregates used in test sections.

| Sl. No. | Property | Result | Specification as per MoRD (2014) | Test method |
|---|---|---|---|---|
| 1 | Specific gravity | 2.71 | – | BIS 2386 – Part 3 |
| 2 | Angularity number | 9 | – | BIS 2386 – Part 1 |
| 3 | Flakiness index | 19% | Maximum 25% | BIS 2386 – Part 1 |
| 4 | Los Angeles abrasion value | 28% | – | BIS 2386 – Part 4 |
| 5 | Impact value | 24% | Maximum 40% | BIS 2386 – Part 4 |

**Table 3.** Properties of cationic slow-setting emulsion (SS-2) used in test sections.

| Sl. No. | Property | Result | Specification as per IRC SP 100 (2014) | Test method |
|---|---|---|---|---|
| 1 | Residue on 600-micron sieve | 0.02% | Maximum 0.05% | IS 8887 (2018) |
| 2 | Storage Stability after 24 h | 0.40% | Maximum 2% | |
| 3 | Residual bitumen | 62% | Minimum 60% | |
| 4 | Miscibility with water | No coagulation | No coagulation | |
| 5 | Stability to mix with cement (percentage coagulation) | 1.84% | Maximum 2% | |
| 6 | Particle Charge | Positive | Positive | |
| 7 | Penetration of residual bitumen (25°C, 100 g, 5 s) | 71 | 60–120 | |

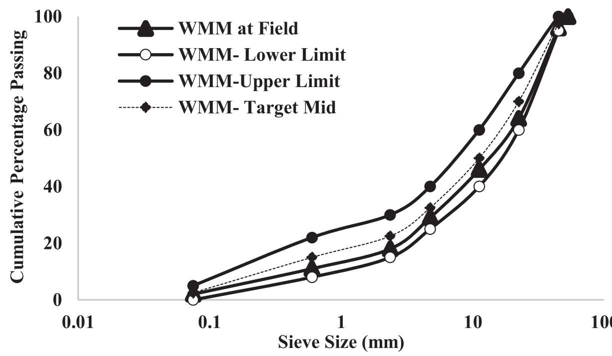


**Figure 1.** WMM gradation of control section.

### 3.2. Construction and evaluation of test sections

As mentioned earlier, the objectives of the present study were achieved by evaluating the field performance data of test sections constructed in a LVR. The test sections were located on the Kallapuram–Kannaadikavala road, in Muhama Grama Panchayath of Alappuzha district of Kerala, India. Each test section was 50 m long, and 3.75 m wide. These test sections were constructed as part of a strengthening proposal for the above-mentioned road. The cross-section of the road before strengthening consisted of 150 mm of granular material placed above the compacted subgrade. A thin bituminous surfacing of 20 mm of Open Graded Premix Carpet (OGPC) was originally present before the rehabilitation. Before constructing the test sections, the design traffic of the road was estimated by conducting a 3-day 24-hour traffic survey using manual counting. The vehicle damage factors provided in IRC SP 72 (2015) were used for converting the number of commercial vehicles to an equivalent number of standard axles. Based on the traffic data collected from the proposed test section route, the design traffic for 10 years was found to be 1 msa. Three test pits were taken along the length of these test sections, and subgrade strength was assessed in terms of California Bearing Ratio (CBR) and was found to be 7%.

Before constructing the test sections, the distressed bituminous surface was scarified and the granular layer beneath was levelled and compacted. The existing granular material was corrected for aggregate gradation and was converted to a 150 mm-thick Granular Sub-Base (GSB) layer for all the test sections. The ETB mixes placed at the site were compacted using an 8 T static roller and were done in two lifts of 100 mm until each lift reached a compacted thickness of 75 mm. The field densities immediately after the construction of the test sections were evaluated using the sand replacement method (IS 2720 Part 28, 1974) and were found to be 93–95% of the laboratory densities of the respective mixes. Light and medium traffic were allowed to move on the test sections after 24 h of construction. The surface course of the test sections was placed one week after the construction of the base layers. The surface course of the test sections included 20 mm OGPC and a 6 mm-thick seal coat. OGPC and seal coat are recipe mixes whose mix constituents were proportioned based on the guidelines given in MoRD (2014) specifications. Prior to surfacing, ETB mixes were found to cure by 60–70% with respect to the initial condition of the mix. The field density of the all base layer mixes (S1 to S7) was assessed again and was found to have achieved 96–98% of their maximum laboratory density. Table 4 presents a comparison of laboratory densities and the field densities of various test sections. Figures 3 and 4 present photographs of the ETB sections (S2–S7) after compaction. The construction of test sections was completed in October 2020.

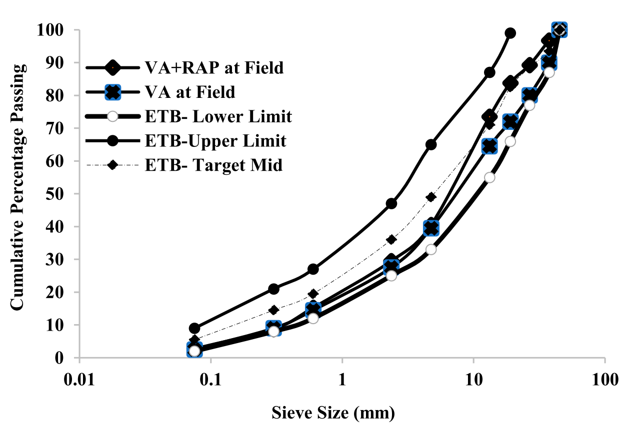


**Figure 2.** Gradation of ETB mixes.

### 3.3. Evaluation of structural layer coefficient

In order to evaluate the structural layer coefficient of ETB mixes, it was necessary to conduct periodic performance evaluations of the test sections. Performance evaluation of the test sections was conducted in terms of the progression in surface deflection after 1 week, 1, 3, 6, 9 and 12 months of construction. The surface deflection was measured using a Benkelman Beam Deflectometer (BBD), following the Canadian Good Roads Association (CGRA) method outlined in IRC 81 (1997). As deflection measurements were carried out on pavement sections having thin bituminous surfaces, temperature correction was not made. The deflection studies were carried out during the early morning hours, when the pavement temperature was close to 35°C, so as to minimise the chance of error due to the temperature effect. Pavement temperature at the time of testing was measured by creating a 40 mm-deep drill hole filled with glycerine and dipping a digital thermometer. It was observed that the pavement temperature was in the range of 34–37°C during the time of testing. Since deflection data was measured at different time periods of the year, a moisture correction was applied to the observed deflection data. Moisture correction factors outlined in IRC 81

**Table 4.** Density achieved by ETB layer at the field condition.

| | | Immediately after compaction | | After 7 days curing | |
|---|---|---|---|---|---|
| Section | Laboratory density (g/cc) | Density (g/cc) | Relative density | Density (g/cc) | Relative density |
| S1 | 2.201 | 2.049 | 93.1% | 2.122 | 96.4% |
| S2 | 2.236 | 2.098 | 93.8% | 2.155 | 96.4% |
| S3 | 2.244 | 2.119 | 94.4% | 2.156 | 96.1% |
| S4 | 2.250 | 2.154 | 95.7% | 2.189 | 97.3% |
| S5 | 2.229 | 2.075 | 93.1% | 2.154 | 96.6% |
| S6 | 2.238 | 2.118 | 94.6% | 2.177 | 97.3% |
| S7 | 2.242 | 2.110 | 94.1% | 2.198 | 98.0% |

**Figure 3.** Section S2, S3 and S4 – ETB mixes with virgin aggregates.

(1997) for sandy/gravelly subgrades with annual rainfall more than 1300 mm were used in this process.

Table 5 presents the corrected deflection data observed at different time periods of the year for different test sections. ETB mixes generally require several days to complete the curing process. Since these mixes are densely graded, the water particles require sufficient time to escape from the base layer. The time taken for evaporation may be further delayed after the application of the thin surface course. Due to the presence of water particles within the ETB mix, they require sufficient time to complete the strength gain process. This results in reduced stiffness and higher surface deflections during the initial days after construction. From the deflection data observed during the subsequent evaluations, it can be inferred that the deflection values in the test sections with higher emulsion dosages are comparatively lower. Since the pavement composition varies only in terms of the base layer combination, the lower deflection values can be attributed to the improved stiffness of the ETB layers. It can also be observed that for every pavement section, the deflection value initially decreased, attained a minimum value and further started to increase. The decreasing trend of deflection values can be attributed to the strength gain in ETB with respect to time. Deflection values were found to decrease continuously for 9 months, indicating that the ETB layers require sufficient time to attain their maximum stiffness. Reddy and Veeraragavan (1997) indicated this time period during which the pavement deflection reduces after construction as 'stabilisation period'. The stabilisation period depends on the secondary compaction characteristics of the layers under traffic loading, the thickness of the layers and the traffic loading rate. The time at which deflection starts increasing can be considered as an initiation of structural deterioration of the pavement stretch. The minimum deflection value achieved at the end of the stabilisation period was considered as a characteristic measure of pavement strength and is referred to as initial deflection ($DEF_i$) in this paper. Initial deflection values for the seven stretches considered in this study were found to

**Figure 4.** Section S5, S6 and S7 – ETB mixes incorporating 50% RAP.

**Table 5.** Pavement deflection from BBD test data (in mm).

| Section | S1 | S2 | S3 | S4 | S5 | S6 | S7 |
|---|---|---|---|---|---|---|---|
| 1 Week | 0.850 | 1.144 | 1.220 | 1.234 | 1.212 | 1.158 | 1.146 |
| 1 Month | 0.790 | 0.802 | 0.822 | 0.820 | 0.914 | 0.860 | 0.882 |
| 3 Month | 0.704 | 0.688 | 0.672 | 0.680 | 0.680 | 0.680 | 0.646 |
| 6 Month | 0.672 | 0.644 | 0.600 | 0.598 | 0.592 | 0.578 | 0.536 |
| 9 Month | 0.714 | 0.642 | 0.582 | 0.554 | 0.606 | 0.562 | 0.540 |
| 1 Year | 0.718 | 0.660 | 0.646 | 0.578 | 0.612 | 0.574 | 0.574 |

occur after 6–9 months of construction. These initial deflection values were used in the present study for evaluating the effective structural number of the pavement sections and the structural layer coefficient of ETB. Since the actual method of structural number determination may take several years to complete, AASHTO (1993) has proposed a simple method to estimate the effective structural number of the pavement as a function of the effective pavement modulus and the thickness of the pavement above subgrade.

$$SN_{eff} = 0.0045 * D * (Ep)^{\left(\frac{1}{3}\right)} \tag{1}$$

In equation (1), '$SN_{eff}$' represents the effective structural number of the pavement, '$Ep$' represents the effective modulus of the pavement layers above the subgrade in psi and '$D$' represents the thickness of the pavement in inches. For estimating the effective modulus of pavement layers above the subgrade, the surface deflection was the mechanistic parameter used for comparing the pavement response of a selected multi-layer system and an 'equivalent' layer considered above the subgrade. For converting a multi-layer system to its equivalent single-layer system, previous researchers have used the concept of equivalency in terms of stiffness, stress, strain and surface deflections. Since surface deflection was the known parameter in this study, the present study uses the concept of equivalent surface deflection for converting the multi-layer system to its equivalent single-layer system. The analysis was done using a linear elastic layer programme, IITPAVE software, which was developed for the analysis of flexible pavements (IRC 37 2018). The actual pavement system consists of a thin bituminous surface layer, base and sub-base layers above compacted subgrade. For the purpose of analysis, three layers above the subgrade were modelled as a single-layer, above the subgrade. In the IITPAVE software, the modulus value of this layer was iterated until the calculated surface deflection beneath the loading, matched with the observed deflection under BBD loading. The loading condition used for the analysis was 40 kN wheel load and 0.56 MPa tyre pressure, which is similar to that of the load applied during the BBD test. Equation (2) shows the correlation used for estimating the modulus of subgrade based on the CBR value. In equation (2), $M_{R\ subgrade}$ represents the modulus of subgrade and CBR represents the CBR of the subgrade in percentage. Accordingly, the subgrade was assigned with a modulus value of 61 MPa, which corresponds to 7% CBR, and Poisson's ratio was assumed as 0.35. Once the effective modulus was determined, the structural number of the pavement was determined using Equation 1. The design life corresponding to the obtained structural number and subgrade condition was calculated using the performance equation of AASHTO (1993).

$$M_R subgrade = 17.6X\ CBR^{-0.64} \tag{2}$$

$$\begin{aligned} Log_{10}(W_{18}) = {} & ZrxSo + 9.36log10\,(SN + 1) - 0.20 \\ & + \frac{(\log\,(\Delta PSI/(4.2 - 1.5))}{(0.40 + (1094/(SN + 1)^{5.19})} \\ & + 2.32xlog10\,(Mr) - 8.07 \end{aligned} \tag{3}$$

In equation (3), $\Delta PSI$ represents the drop-in pavement serviceability index and was taken as a value of 2. The allowable drop-in PSI for the design of LVR is taken as 2 in IRC SP 72 (2015). '$W_{18}$' represents design life in terms of standard 18-kip (80 kN) wheel load repetitions (referred to in terms of equivalent standard axle load repetitions), '$Z_r$' represents standard normal deviation and '$S_o$' represents standard deviation. For the design of low-volume roads in India, IRC SP 72 (2015) has recommended a reliability level of 50%. The recommended value of $Z_r$ corresponding to a reliability of 50% is zero, and hence the first term in equation 3 becomes insensitive. 'SN' represents the structural number of the pavement and '$M_r$' represents the effective road bed modulus in psi. Once the structural number of the pavement, layer thickness and structural layer coefficient of materials used in other layers are known, the structural layer coefficient of ETB is estimated using the generalised equation for structural number given in Equation 4. For Equations (2)–(4), the units of different terms are considered to be British Imperial units.

$$SN = a_1 D_1 + a_2 D_2 \tag{4}$$

For the present study, '$a_1$' and '$a_2$' in Equation (4) represent the layer coefficients of the ETB layer and granular sub-base layer, respectively. Similarly, '$D_1$' and '$D_2$' represent the thicknesses (in inches) of the ETB layer and the granular sub-base layer, respectively. IRC 37 (2018) recommends that thin bituminous layers such as the OGPC shall not be considered as part of the bituminous layer for the analysis of pavements. Hence, a thin bituminous surface was considered as part of the base layer. $D_1$ was taken as 6.8 in. and $D_2$ was taken as 6 in. CBR of the granular sub-base layer was found to be 80%, and accordingly, the layer coefficient of the granular sub-base layer ($a_2$) was taken as 0.14 from the AASHTO (1993) recommended design charts.

### 3.4. Evaluation of back-calculated moduli

For evaluating the back-calculated moduli of the ETB test sections, a deflection study was performed using FWD. FWD studies ideally need to be conducted during the period following the monsoon season, when the pavement is under the weakest condition. From the periodic performance evaluation data, it was evident that all the test sections had completed the stabilisation period after 9 months of construction. Hence, it was decided to conduct the FWD study in October 2021, which was after 1 year of construction of the test sections. The deflection bowl data was captured using FWD, and the moduli values were back-calculated using KGPBACK software, following the guidelines outlined in IRC 115 (2014). Figures 5 and 6, respectively, show the loading unit and the geophones attached to the FWD. A load of 200 kg was dropped from a pre-determined height onto a loading plate of 300 mm diameter so as to develop a load of 40 kN force. The deflections produced at radial distances were captured using geophones. The deflection data was further used for back-calculating the moduli of each individual layer. For the present study, deflection data collected at radial distances of 0, 200, 300, 450, 600, 900 and 1500 mm were used for the back-calculation process (Table 6).

### 3.5. Evaluation of the laboratory strength of ETB

In order to evaluate the laboratory strength of the ETB mixes mobilised at the site, blended dry aggregates were collected from the construction site and transported to the laboratory, where they were mixed with an active filler, pre-wetting water and bituminous emulsion. The samples were compacted by applying the design compaction effort of 50 blows on both sides of the specimen (Figure 7). The compacted specimens were placed in the mould for 24 h, and after extraction, the specimens were cured in a forced draft oven for 72 h at 40°C. For each mix, two sets of specimens with three replicates were prepared. Indirect Tensile Strength (ITS) test was carried out on both the set of specimens (ASTM D 6931-2017) at 25 ºC. One set was tested at dry conditions and another set was tested at moisture-saturated conditions. Moisture-saturated specimens were conditioned at 60°C for 24 h, followed by 2 h conditioning at 25°C, before conducting the test. Tensile Strength Ratio (TSR) was evaluated for different mix combinations as the ratio of the ITS strength of wet to dry specimens. Since ITS is the strength parameter used by the majority of the road agencies for designing ETB mixes, the present study developed a relationship between layer coefficient, back-calculated moduli and the laboratory-evaluated dry ITS values of the samples prepared at the emulsion content and gradation achieved in the field. For developing traffic level-based mix design criteria, the pavement life estimated using the effective structural number for different ETB sections, and the corresponding laboratory dry ITS value of field-delivered mixes (compacted by applying 50 blows of Marshall compaction on both sides) were correlated. The relationship will serve as a performance specification for ETB mixes for LVR applications in terms of ITS value.

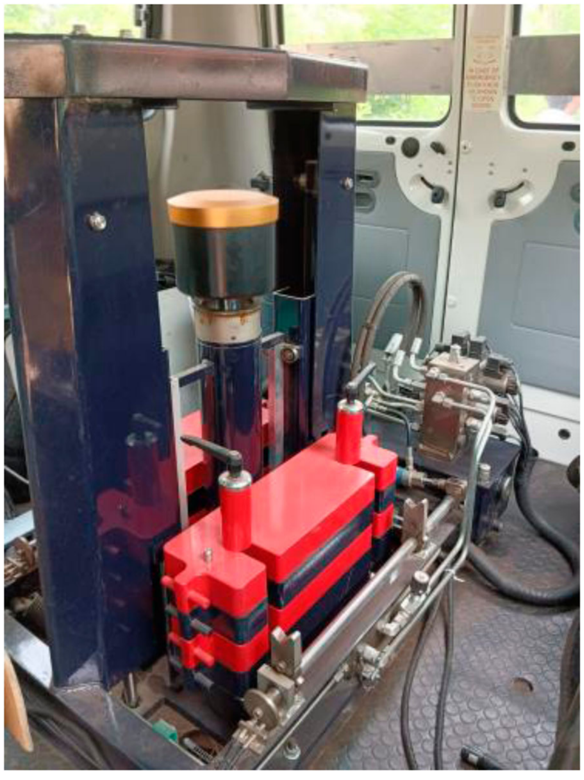

**Figure 5.** FWD loading unit.

## 4. Results and discussion

### 4.1. Structural layer coefficient of ETB

The structural layer coefficient of ETB corresponding to the six combinations considered in the present study was evaluated using the effective structural number of the test sections. Table 7 shows the values of initial deflection, effective pavement modulus, effective structural number and structural layer coefficient of ETB corresponding to each test section. In Table 7, a1 represents the structural layer coefficient of ETB, calculated based on the number of equivalent standard axle load repetitions obtained corresponding to the effective structural number of the test sections. It can be inferred that the layer coefficients determined using the effective structural number approach were found to be sensitive to variations in ETB mix compositions. Layer coefficient varied from 0.23 to 0.29, as the emulsion content varied from 2% to 4%. The observed layer coefficients were in comparison to the layer coefficient values proposed by researchers who evaluated them based on field performance data (Table 8). It was also observed that the layer coefficient of ETB with 50% RAP incorporation was slightly higher than the ETB with 100% virgin aggregates. This indicates the contribution of the RAP binder to the cohesive and adhesive strength of the ETB mix. The softening agents in the emulsion have the potential to rejuvenate the aged binder in RAP, thereby improving the binding property of ETB (IRC SP 100 2014). The presence of RAP in ETB is thus expected to increase the cohesive and adhesive properties of ETB, resulting in improved structural performance and an associated increase in the value of the structural layer coefficient.

### 4.2. Back-calculated moduli of ETB

In order to back-calculate the moduli using KGPBACK software, the pavement was considered as a 3-layer system, and the material properties (layer thickness and seed moduli range) were substituted accordingly. For the present study, a 20 mm-thick surface layer and a 150 mm base layer were combined together as the top-most layer, a 150 mm granular subbase layer was considered as the middle layer, and a subgrade was considered as the bottom most layer. According to the recommendations of IRC 37 (2018), a representative value of 0.35

**Figure 6.** Loading plate and geophones.

was assumed as the Poisson's ratio for all three layers. The modulus range recommended by IRC 115 (2014) for a thick bituminous layer was 750–3000 MPa. Since the top layer in this analysis is considered to be a combination of 20 mm OGPC and 150 mm stabilised base, 500–1000 MPa was assumed as the input moduli range for the top-most layer in most of the cases. Although the recommended range of granular layer moduli was 100–500 MPa, a slightly higher range of 400–800 MPa was used in most of the cases, since it was expected that the modulus of sub-base layer was more than 500 MPa. However, the range of input moduli values was suitably adjusted depending on the expected output moduli value. The CBR of subgrade in this case was 7%, and it was decided to select 50–200 MPa as the moduli range for subgrade. The average value of the back-calculated ETB layer moduli values obtained from the six test sections is shown in Figure 8.

From the back-calculation process, the modulus of the conventional base layer in the control section (S1) was found as 510 MPa. The observed value was found to be much higher than the expected moduli value for unbound granular base layers. The effect of the 20 mm bituminous surface layer, considered along with the base layer during the analysis, can be one of the reasons for this higher value. The back-calculated moduli of ETB mixes were found to be 1.5–2 times those of conventional base layers. The obtained ETB moduli values were found to be slightly higher than the moduli value recommended by the Indian Roads Congress for ETB mixes incorporating RAP aggregates (600 MPa for ETB with 3% emulsion and 800 MPa for ETB with 4% emulsion). Similar to the trend observed in the layer coefficient values, the back-calculated moduli of ETB were also sensitive to the mix composition. The back-calculated moduli varied from 578 to 919 MPa as the emulsion content varied from 2% to 4%. Back-calculated moduli values of ETB with 50% RAP were slightly higher than those observed in ETB with 100% virgin aggregates.

**Table 6.** Deflection data obtained from the test sections using FWD.

| | Radial distances (mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| Section | 0 | 200 | 300 | 450 | 600 | 900 | 1500 |
| S1-1 | 0.518 | 0.333 | 0.237 | 0.167 | 0.134 | 0.090 | 0.056 |
| S1-2 | 0.505 | 0.332 | 0.247 | 0.169 | 0.136 | 0.096 | 0.059 |
| S1-3 | 0.512 | 0.312 | 0.232 | 0.172 | 0.134 | 0.090 | 0.052 |
| S2-1 | 0.463 | 0.302 | 0.233 | 0.166 | 0.132 | 0.093 | 0.055 |
| S2-2 | 0.474 | 0.298 | 0.232 | 0.164 | 0.127 | 0.089 | 0.054 |
| S2-3 | 0.516 | 0.315 | 0.247 | 0.187 | 0.147 | 0.099 | 0.057 |
| S3-1 | 0.410 | 0.292 | 0.211 | 0.148 | 0.123 | 0.094 | 0.060 |
| S3-2 | 0.450 | 0.300 | 0.231 | 0.159 | 0.127 | 0.090 | 0.052 |
| S3-3 | 0.419 | 0.279 | 0.224 | 0.172 | 0.136 | 0.092 | 0.053 |
| S4-1 | 0.390 | 0.280 | 0.214 | 0.147 | 0.118 | 0.088 | 0.058 |
| S4-2 | 0.366 | 0.250 | 0.203 | 0.156 | 0.124 | 0.084 | 0.048 |
| S4-3 | 0.419 | 0.280 | 0.211 | 0.154 | 0.121 | 0.085 | 0.052 |
| S5-1 | 0.391 | 0.273 | 0.211 | 0.151 | 0.127 | 0.089 | 0.051 |
| S5-2 | 0.437 | 0.288 | 0.227 | 0.158 | 0.127 | 0.087 | 0.055 |
| S5-3 | 0.408 | 0.261 | 0.217 | 0.152 | 0.123 | 0.095 | 0.047 |
| S6-1 | 0.403 | 0.275 | 0.226 | 0.150 | 0.124 | 0.086 | 0.054 |
| S6-2 | 0.371 | 0.264 | 0.210 | 0.167 | 0.137 | 0.094 | 0.059 |
| S6-3 | 0.420 | 0.299 | 0.224 | 0.165 | 0.134 | 0.093 | 0.055 |
| S7-1 | 0.368 | 0.244 | 0.183 | 0.137 | 0.110 | 0.082 | 0.051 |
| S7-2 | 0.408 | 0.276 | 0.217 | 0.153 | 0.119 | 0.092 | 0.059 |
| S7-3 | 0.381 | 0.275 | 0.229 | 0.180 | 0.146 | 0.100 | 0.058 |

### *4.3. Laboratory strength of ETB*

The laboratory strength of ETB used in the present study was evaluated in terms of ITS and TSR. The majority of the guidelines consider ITS and TSR to characterise the ETB material. ITS is considered as a measure of the cohesive strength of the material, while TSR is considered as a measure of the moisture resistance of the ETB material. Table 9 shows the ITS and TSR values corresponding to the six mixes used in the test sections. It can be inferred that all the mixes satisfied the minimum TSR criteria of 50%. However, only mixes with 4% emulsion content satisfied the minimum dry ITS criteria of 225 kPa. It should be noted that the variation in field gradation from the actual target gradation was one of the major reasons for the lower ITS values of the ETB mixes.

### *4.4. Relationship between structural layer coefficient, back-calculated modulus and ITS*

In order to familiarise themselves with the incorporation of ETB, it is essential to develop a simple methodology using

**Figure 7.** Samples prepared for ITS test.

which the designers can select a layer coefficient or ETB layer modulus based on a laboratory-evaluated strength parameter. Since ITS is the strength parameter used by the majority of the road agencies for characterising ETB, the present study developed a relationship between layer coefficients, back-calculated moduli and the laboratory-evaluated dry ITS values of the samples prepared at the emulsion content and gradation achieved in the field (Table 10). Figure 9 shows the relationship between laboratory dry ITS layer coefficients of ETB obtained using the effective structural number approach and back-calculated moduli of the ETB layer. The goodness of fit corresponding to both the equations was evaluated using the coefficient of determination and was found to be more than 0.9, indicating that both the equations exhibit a good fit. The relationship given in Figure 9 can be reliably adopted for ITS values in the range of 140–245 kPa. It is observed that the ITS value increases from 140 to 245 kPa as the emulsion content increases from 2% to 4%, and accordingly, the layer coefficient increases from 0.23 to 0.29 and the ETB layer moduli increases from 578 to 919 MPa.

### *4.5. Traffic level-based mix specification for ETB mixes*

Based on the design life estimated using the effective structural number and dry ITS value of field-delivered mixes (compacted by applying 50 blows of Marshall compaction on both sides), an empirical relationship is presented in Figure 10. The relationship will serve as a performance specification for ETB mixes for low-volume road applications, in terms of ITS value. A designer can determine the target dry ITS value of ETB mixes, which have to be mobilised in the field for the selected design traffic level. This also enables the designer to utilise Figure 9, from where layer coefficients or moduli for ETB can be estimated. The mix designer can appropriately develop the mix design recipe by varying the aggregate gradation, emulsion content, residual binder type or incorporating RAP material to satisfy the required ITS strength for the intended traffic. For a design traffic of 1 msa, it can be found that the required dry ITS strength is 188 kPa. When compared with the dry ITS specification for Bitumen-Stabilised Mixes (BSM) given by TG-2 (2009), for BSM-2 mixes (intended for design traffic levels of 1 msa to 6 msa), the minimum ITS

**Table 7.** Calculation of effective structural number and layer coefficient.

| Section | $DEF_i$ (mm) | Ep (psi) | D (inches) | $SN_{eff}$ | ESAL | a1 |
|---|---|---|---|---|---|---|
| S1 | 0.672 | 67715 | 12.8 | 2.35 | 536646 | – |
| S2 | 0.642 | 75690 | 12.8 | 2.44 | 674043 | 0.23 |
| S3 | 0.582 | 95700 | 12.8 | 2.63 | 1092710 | 0.26 |
| S4 | 0.554 | 108750 | 12.8 | 2.75 | 1423789 | 0.28 |
| S5 | 0.592 | 92510 | 12.8 | 2.61 | 1018800 | 0.26 |
| S6 | 0.562 | 104255 | 12.8 | 2.71 | 1304513 | 0.28 |
| S7 | 0.536 | 118175 | 12.8 | 2.83 | 1691929 | 0.29 |

**Table 8.** Layer coefficient found in literature for bitumen-stabilised base layers.

| Author | ETB specification | Method adopted | Proposed layer coefficient |
|---|---|---|---|
| Farrar and Ksaibati (1996) | 1–3% emulsion | Correlated resilient modulus with layer coefficient using the equation proposed by AASHTO (1993) for granular base layers | 0.15–0.17 |
| Marquis *et al.* (2003) | Foam-treated base using reclaimed material | Calculated layer coefficient using the concept of effective structural number proposed by AASHTO (1993) | 0.22–0.35 |
| Quick and Guthrie (2011) | RAP-modified ETB, treated with 4% emulsion | Correlated field moduli observed after 3 months with equation proposed by AASHTO (1993) for bitumen-treated base layers | 0.2–0.3 |
| Diaz-Snchez *et al.* (2017) | 100% RAP and 2% foamed asphalt | Calculated using the concept of effective modulus and known value of layer coefficient of remaining layer | 0.36–0.39 |
| Present study | ETB characterised by ITS ranging from 140 to 245 kPa | Calculated layer coefficient using the concept of effective structural number proposed by AASHTO (1993) | 0.23–0.29 |

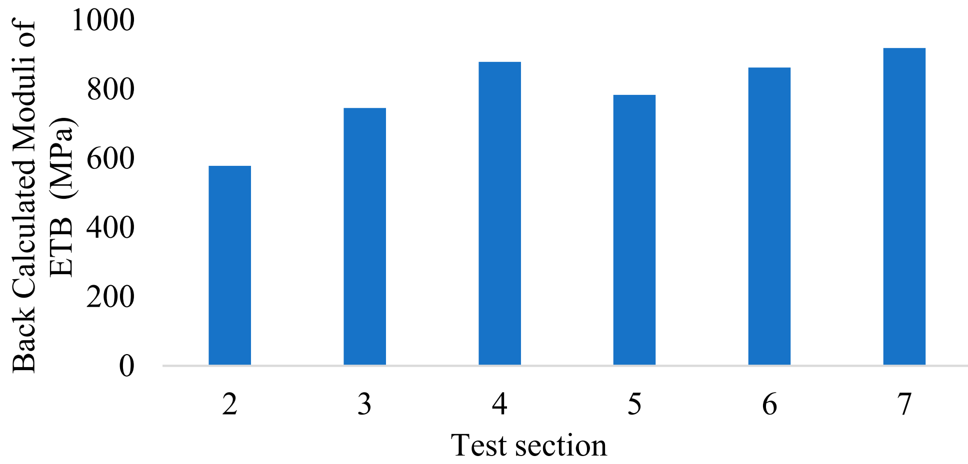


**Figure 8.** Back-calculated moduli of ETB.

**Table 9.** ITS and TSR of ETB samples prepared at field conditions.

| Section | Fluid content | Emulsion content | RAP content | Dry ITS (kPa) | Wet ITS (kPa) | TSR |
|---|---|---|---|---|---|---|
| S2 | 7% | 2% | 0% | 140 | 94 | 67% |
| S3 | 7% | 3% | 0% | 200 | 144 | 72% |
| S4 | 7% | 4% | 0% | 230 | 168 | 73% |
| S5 | 6.5% | 2% | 50% | 190 | 124 | 65% |
| S6 | 6.5% | 3% | 50% | 220 | 158 | 72% |
| S7 | 6.5% | 4% | 50% | 245 | 181 | 74% |

**Table 10.** Comparison of layer coefficient, back-calculate modulus and ITS.

| Section | ITS (KPa) | Layer coefficient | Back-calculated moduli (MPa) |
|---|---|---|---|
| 2 | 140 | 0.23 | 578 |
| 3 | 200 | 0.26 | 745 |
| 4 | 230 | 0.28 | 879 |
| 5 | 190 | 0.26 | 783 |
| 6 | 220 | 0.28 | 862 |
| 7 | 245 | 0.29 | 919 |

strength requirement determined in the study is slightly higher. For BSM-2 mixes, the minimum dry ITS strength requirement was 175 kPa. Figure 10 has been developed based on limited data obtained from six pavement sections

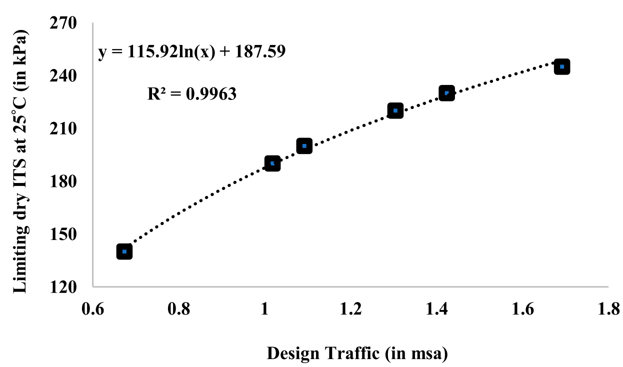


**Figure 10.** Limiting ITS strength criteria for different design traffic levels.

in LVR, and hence additional data observed from other pavement sections can strengthen the specification in the future.

## 5. Conclusion

The study presented research efforts carried out for the estimation of structural layer coefficient and back-calculated

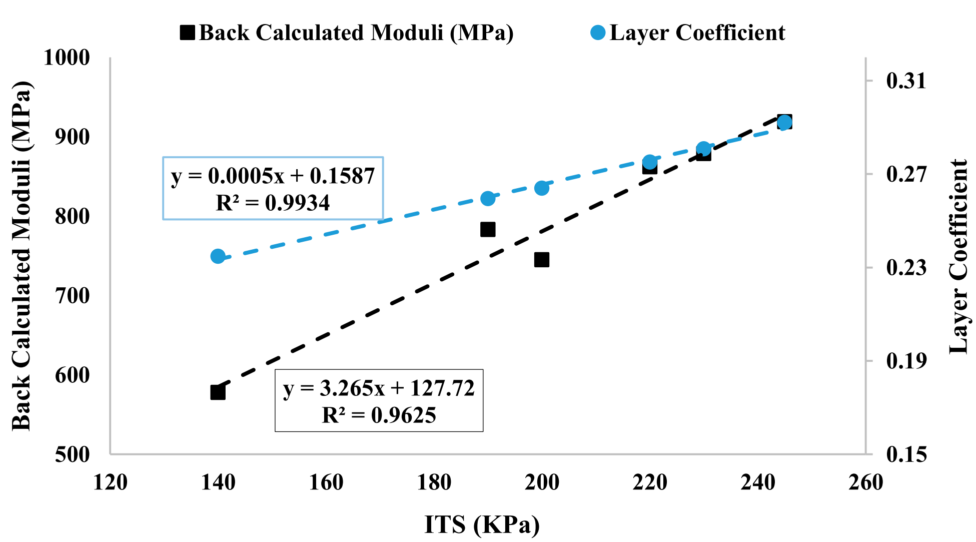


**Figure 9.** Relationship between layer coefficients, moduli and laboratory ITS of ETB.

modulus for ETB layers incorporating virgin and RAP aggregates. The material layer properties were determined from pavement deflection measurements of six test sections incorporating different emulsion dosages and aggregate types (virgin and RAP aggregates). The paper also presented the mix design specifications for ETB mixes in terms of the minimum ITS value for different design traffic for LVR applications. The specific conclusions drawn from the present study are summarised below:

- ETB mixes, irrespective of whether RAP aggregates were included or not, were found to cure 60–70% of the initial condition after seven days of construction. The mixes, after 7 days of construction, achieved 96–98% of their maximum laboratory densities, when opened to light and medium traffic after 24 h of laying.
- The stabilisation period for the test sections was found to occur 6–9 months after construction. The pavement deflection corresponding to this time is considered as the characteristic mechanistic parameter of the test section. The deflection values were found to be lower for ETB mixes incorporating higher emulsion content (OEC + 1%), indicating enhanced structural strength mobilised by these sections during this period.
- For ETB mixes having an ITS value ranging from 140 to 245 kPa, the structural layer coefficient was found to be in the range of 0.23–0.29, and the corresponding back-calculated layer moduli were found to be in the range of 578–919 MPa. Layer coefficients and the back-calculated modulus of ETB mixes incorporating RAP aggregates, at the same emulsion dosage were found to be higher than virgin aggregates. Although ETB comes under cold mix application, this increased material property can be due to the additional cohesive strength imparted by the aged binder in RAP aggregates when held together over a period of time. The layer coefficients and material moduli evaluated from the study are in comparison with the findings of other researchers who evaluated BSM mixes using field performance data.
- Relationships between laboratory-evaluated strength (in terms of dry ITS) and material layer properties (layer coefficients and back-calculated moduli) for pavement design are proposed in the study. Limiting (minimum) ITS strength criteria for ETB mixes for application in LVR are also proposed in the present study. This enables a mix designer to proportion the mix (either through modification or stabilisation), for a selected design traffic level, and recommend mixes with improved strength characteristics when compared to unbound granular layers.
- The relationships proposed in the present study were based on the data observed from six test sections constructed in identical environmental and traffic conditions. Hence, there is an empiricism associated with the proposed material layer properties and mixed design specifications. The structural number of the pavement and layer coefficients of various pavement layers can also be evaluated based on long-term field performance data. Considering the above aspects, it is recommended to estimate layer coefficients of ETB based on more field performance data collected from a wide range of environmental conditions and compare them with the values proposed in the present study.

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