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Structural Performance of Cement-treated Base Layer by Incorporating Reclaimed Asphalt Material and Plastic Waste

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ABSTRACT

The reuse of reclaimed asphalt material (RAM) and polyethylene terephthalate (PET) plastic waste is a reliable approach to limit the use of virgin aggregates for road construction and mitigate environmental challenges. This study highlights the structural performance of the cementitious base or cement-treated base (CTB) layer by incorporating reclaimed asphalt and plastic waste material. Structural compatibility of CTB layer with different proportions of RAM (20%, 45%, 70% and 95%), virgin aggregates and plastic waste (5%) is recognized by the moisture-density relationship, unconfined compressive, indirect tensile strength, flexural strength and California bearing ratio tests. In the current study, a ranking methodology is used to analyze the overall suitability of the cementitious base mix proportions using different laboratory test parameters. Furthermore, a finite element analysis using the ANSYS software is performed to investigate the effect of CTB layer on the pavement structural responses. Also, using the central public works department guidelines, a cost comparative study is provided. Experimental results showed that all the cementitious base mixes met the requirements for the unconfined compressive strength, except for the 95% and 70% RAM mixes. Therefore, 20%-45% of RAM can partially be used in the CTB layer to replace virgin aggregates partially. The finite element analysis results showed that CTB reduced fatigue strain by 57% and surface deformation by 47%. Moreover, it has been concluded that by utilizing a cementitious base with RAM, there is a 30% cost reduction.

KEYWORDS: Reclaimed asphalt material, Cement-treated base, Polyethylene terephthalate, Finite element analysis, Unconfined compressive strength.

INTRODUCTION

The construction of a cement-treated base (CTB) layer is now becoming extensively popular in India due to its improved performance. The CTB layer provides a stiffer foundation than conventional base material and minimizes the deformations induced by heavy wheel loads (Bagui, 2012). It can result in a longer pavement service life by preventing the ingress of fatigue cracking distress. A CTB layer also enhances the pavement's susceptibility to rutting and freezing-thawing cycles, providing a durable and long-lasting foundation for a flexible pavement (Halsted et al., 2006). In flexible pavement, the CTB layer is made of aggregate particles, reclaimed asphalt materials (RAMs), pulverized slag, concrete aggregates or a soil-aggregate mix and these are mostly stabilized with cement (IRC, 2018). Accordingly, due to the lack of virgin aggregates (VAs) in today's construction industry, several government organizations are increasingly emphasizing the reuse of RAMs, which is feasible because of its economic and environmental advantages (Chhabra et al., 2021).

The concept of utilizing RAMs for new pavement construction emerged around 1915 (Kasu et al., 2020). In 1935, the concept of using CTB was first employed to strengthen the foundation of a state highway in South Carolina (Arulrajah et al., 2021) and in 1950, the practical applications of inverted pavement or CTB pavement has been recognized as a cost-effective and

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durable alternative to conventional flexible pavement (Papadopoulos and Santamarina, 2009). A recent study by Chhabra et al. (2021) found that utilizing 100 percent recycled materials in CTB mixes lowers the expense of the pavement base by 50 percent compared to conventional aggregates. However, Kasu et al. (2020) observed that 30% recyclable asphalt material was effective for cement-treated recycled asphalt mixtures. The study revealed that the findings in regard to strength enhancement of base course is possible only when the virgin-aggregate content is 70% or more. Below 70%, mixing can result in lesser affinity in mixing with cement mortar. Likewise, Khay et al. (2015) mentioned that aggregates coated with asphalt form weaker transition zones than uncoated aggregates; thereby, 60% RAM mix was noted to match the compressive-strength criterion. Yuan et al. (2011) highlighted the resilience of cement-treated RAM mix depending on the recycled pavement material content and cement percentage, indicating that compressive strength is proportional to the increased cement percentage. In another research, Adresi et al. (2019) experimentally analyzed CTB mixes incorporating high proportions of RAMs concerning the structural parameters under varying conditions to identify an efficient approach for increasing recyclability. The study revealed that the CTB mixes with a high proportion of RAMs were more susceptible to 50°C test temperature than moisture levels. Taha et al. (2002) concluded that the optimum moisture content, maximum dry density and RAM performance improved with the inclusion of virgin aggregates and cement during longer curing sessions.

In recent years, apart from reuse of RAMs, plastic waste has gained popularity for conserving natural resources and addressing waste-disposal issues during the construction of pavements. Some researchers found that plastic waste, such as polyethylene terephthalate (PET) bottles (Tafheem et al., 2018; Lee at al., 2019) and high-density polyethylene (HDPE) (Naik et al., 1996) can be used as partial replacement of aggregates in the concrete. PET plastics up to 40% lead to increase the workability and achieve the recommended strength for M20 concrete, as indicated by Bamigboye et al. (2021). PET and RAM represent two categories of waste materials that are currently enduring major recycling efforts around the world. Few researchers, like Perera et al. (2019), have investigated the geo-technical parameters of loose PET mixes (3% and 5%) with recycled aggregates and cement bases, while Arulrajah et al. (2021) have highlighted the use of fly ash and slag-based geo-polymers for stabilizing 5% PET as a sustainable and durable solution for stabilizing road bases and sub-bases. Previously, Arulrajah et al. (2020) reported that stabilizing recycled 5% PET and construction and demolition with 3% cement led to achieve the unconfined compressive strength required for the granular sub-base materials used on light-traffic roads. However, in this context, using PET bottles in CTB stabilization has not yet been rigorously studied.

Overall, the literature explains the significant RAM and PET applicability as partial alternatives to aggregates in the CTB. As a contribution in that direction, this study investigates the structural compatibility of the CTB layer in flexible pavement, using experimental and numerical approaches. In this study, the proctor compaction, unconfined compressive strength, indirect tensile strength, flexural strength and California bearing ratio tests of CTB mix utilizing RAMs (20, 45, 70 and 95 %) and waste plastic have been conducted. The overall structural compatibility of all the CTB mixes was assessed using a novel ranking methodology. Furthermore, based on the recommended CTB layer parameters, a finite element analysis using ANSYS 2020R1 was carried out to determine the structural response over a conventional granular base layer, eventually justifying cost-effectiveness.

MATERIALS AND MIX DESIGN

Materials

The reclaimed asphalt material was obtained from National Highway 32 (Purulia-Chandil stretch) and the virgin aggregates were obtained from a stone quarry in Pachami, west Bengal. The mid-range aggregate gradation was adopted according to the Ministry of Transportation and Highways (MoRTH) fifth revision of Table 400.4 (MoRTH., 2013). Virgin aggregates and reclaimed asphalt materials include different aggregate sizes of 37.5mm, 19 mm, 9.5mm, 4.75mm, 0.6mm, 0.3mm and 0.75 mm with percentage passing values of 97.5, 72.5, 67.5, 62.5, 36.5, 22.5 and 5, respectively. In this study, 5% and 10% OPC 53 cement was used for stabilizing CTB mixes. The RAM, VA and cement physical properties are listed in Table 1.

The PET fibres used in this study were obtained from plastic recycling bins in the institute's canteen. For the experimental work, the plastic bottles were cleaned and dried and the plastic caps were removed before shredding. Used bottles had a maximum particle size of 10 mm with a specific gravity of 1.35 and were mixed with 5% of the total aggregate mix as mentioned in the literaturw by Perera et al. (2019) and Arulrajah et al. (2020; 2021).

Table 1. Physical properties of VA, RAM and cement

Property	**VA**	**RAM**	**MoRTH Specifications**	**Test Methods**
Aggregate impact value (%)	23	21.5	40	IS:2386 Part (IV)
Combined flakiness-elongation index (%)	27	41	35	IS:2386 Part (I)
Abrasion value (%)	25	28	30	IS:2386 Part (IV)
Water absorption (%)	1.1	.06	2	IS:2386 Part (III)
Specific gravity (coarse aggregate)	2.89	2.34	-	
Specific gravity (fine aggregate)	2.44	2.02	-	
Cement Property	**OPC-53**		**Specifications**	Ordinary Portland Cement, 53 Grade Specification: IS 12269: 2013
Normal consistency (%)	33		-	
Specific gravity	3.08		-	
Initial setting time (min)	110		Min. 30	
Final setting time (min)	240		Max.600	

Mix Design

In the current investigation, to study the RAM effect on the CTB mixes, unconfined compressive strength (UCS) samples were prepared for designing the mix. In order to achieve the desired minimum UCS value of 4.5 MPa in 7 days, 5% and 10% cements were considered. After determining the optimum moisture content (OMC) and maximum dry density (MDD), the samples were prepared at the obtained OMC to evaluate the strength characteristics of the stabilized mixes. Results of the six different laboratory test parameters for eight different CTB mixes are presented in Table 2. In Table 2, the CTB blends are designated as V75R20P5, V50R45P5, V25R70P5 and V0R95P5; the numeric values represent the percentage of material composition, while V, R and P represent VA, RAM and PET, respectively.

EXPERIMENTAL INVESTIGATION

Moisture-density relationship was determined by modified proctor compaction according to IS: 2720-Part VIII (BIS, 1983). The CTB mixes were compacted in five layers with 55 blows using a 4.9 kg rammer falling from a height of 450 mm. Unconfined compressive strength test was conducted as per IS: 516 on 150 mm cube aged for 7 days under a compression testing machine and the samples were moulded at OMC following IS: 2720 (Part 8) (BIS, 1983). Fig. 1(a) shows the experimental setup of UCS test. Indirect tensile strength (ITS) test was conducted following ASTM D6931 (ASTM, 2012) at a loading rate of 51 mm/min. The CTB mixes were compacted to the requisite MDD with internal dimensions of 101.6 mm in diameter and 63.5 mm in height, removed after 24 hours and cured for 7 days. Flexural strength (FS) test was conducted following IS 516 (BIS, 1959) on a 150 × 150 × 700 mm size beam mould subjected to third-point loading. The load was applied at a constant rate of 0.7 N/mm^2/min till the ultimate load was obtained. Fig. 1(b) shows the experimental specimen of FS test. California bearing ratio (CBR) test was conducted in accordance with IS: 2720-Part XVI (BIS, 1987) using a 150-mm-diameter and 2250-cm^3-volume compaction mould. The aggregate portion on the 19-mm IS sieve was replaced with material ranging in size from 4.75 mm to 19 mm, as was done for the compaction test.

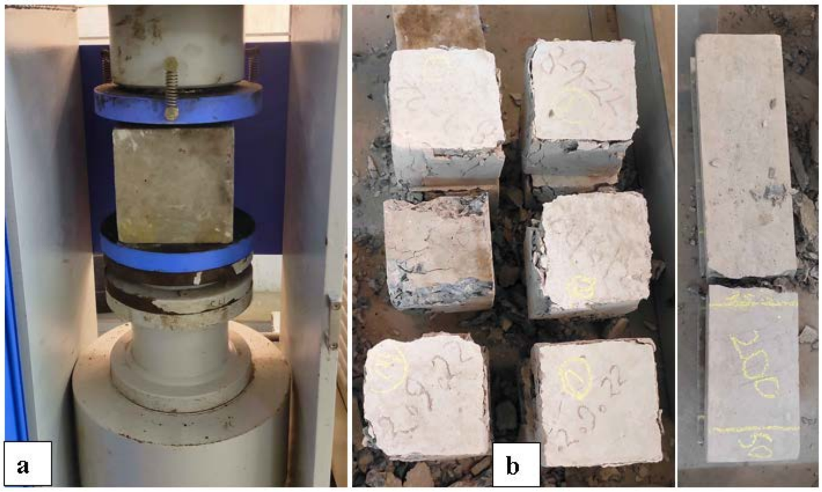


Figure (1): Experimental setup of (a) Compressive strength and (b) CTB specimens

Ranking of CTB Mixes

This study investigated six main assessment factors (MDD, OMC, UCS, ITS, FS and CBR) of eight different RAM-PET-modified CTB mixes. Test methods provide findings with variable units (e.g. %, g/cm^3 and MPa); so, equalizing the results to a standard scale is necessary. Experimental result values (Rv) were adjusted in Eq. 1, where NRV is the normalized result value; Rv is the experimentally obtained result value for a specific test; Rvmax is the maximum test value and Rvmin is the minimum test value. A ranking was considered for each experiment result using a ranking value (1 < R < 6). For best experimental results, we selected ranking with a smaller R and *vice versa* for lowest values. The total rank value (TRV) of every possible combination was determined using its given R-value (Choudhary et al., 2020).

$$\mathrm{NRV} = {(\mathrm{Rv} - \mathrm{Rvmin})}\big/{(\mathrm{Rvmax} - \mathrm{Rvmin})} \qquad (1)$$

RESULTS AND DISCUSSION

Moisture-Density Relationship

The findings for OMC and MDD are listed in Table 2, where the MDD values range from 1.91 to 2.11 g/cm^3 and the OMC remained within the 7.02 to 7.74 % range. This experiment aims to establish the correct amount of water to attain maximum density to assist in the hydration process of the cement (Ismail et al., 2014). Fig. (2) shows the modified proctor compaction curves in relation to zero air-void (ZAV) line. This figure represents that as the percentage of water content increases, the MDD increases until it influences the OMC results. Increasing the water percentage causes a decrease in dry density, because the additional water replaces the RAM mixes, causing the dry density to decrease. In this regard, ZAV line indicates the state of the CTB mix if all air was removed. This curve is calculated using effective specific gravity of the RAM, VA, PET and cement by plotting over a range of water contents. These results imply that MDD is minimal at 95% RAM and increased with aggregate percentage, because reclaimed asphalt aggregates have a low specific gravity. While using a high percentage of RAM, it was clear that less water content is required due to RAM's decreased water absorption caused by its bitumen coating. This means that bitumen prevents water from being absorbed by RAM.

Unconfined Compressive Strength (UCS)

The unconfined compressive strength of CTB mixes for 7-day curing is given in Table 2, ranging from 3.45 to 7.68 MPa. Fig. (3) shows a strength improvement with increasing VA and a reduction with increasing RAM %. This could be due to the coating of RAMs with bitumen, which makes them inappropriate for cementitious material use. According to the design specifications for a 7-day curing period, RAM blends containing 20–45% RAM (V75R20P5 and V50R45P5) have a UCS of 4.9–7.68 MPa and meet the IRC: SP:89 (IRC, 2018) specification values. However, among the CTB mixes 70-95% of RAM (V25R70P5 and

V0R95P5) did not satisfy the criteria using 5% cement content; i.e., a minimum of 4.5 MPa. The composition with 95% RAM and 5% PET at a cement content of 5% has a minimum UCS of 3.45 MPa, whereas the combination with 20% RAM (V75R20P5) and 10% cement has a maximum UCS value of 7.68 MPa. It was clear that the smooth surface of PET pieces causes inadequate inter-particle adhesion, which lowers the UCS value of the mix. Moreover, it was found that the UCS value reduced by a factor of 1.16 by increasing the RAM proportion in any composition combining 5% and 10% cement.

Table 2. Performance characterization results

Mix Type	Cement (%)	OMC (%)	MDD (g/cm^3)	Density of mix (kg/m^3)	UCS (MPa)	ITS (MPa)	FS (MPa)	CBR (%)
V75R20P5	5	7.74	2.02	2313.55	5.15	0.71	0.73	97
	10	7.65	2.12	2319.88	7.68	1.01	1.28	110
V50R45P5	5	7.57	1.99	2309.66	4.9	0.62	0.64	93
	10	7.39	2.07	2317.70	7.1	0.74	1.11	104
V25R70P5	5	7.51	1.96	2297.50	4.35	0.45	0.55	86
	10	7.32	2.03	2315.85	6.85	0.58	1.05	97
V0R95P5	5	7.24	1.91	2297.78	3.35	0.32	0.44	83
	10	7.02	1.99	2313.88	5.54	0.43	0.88	90

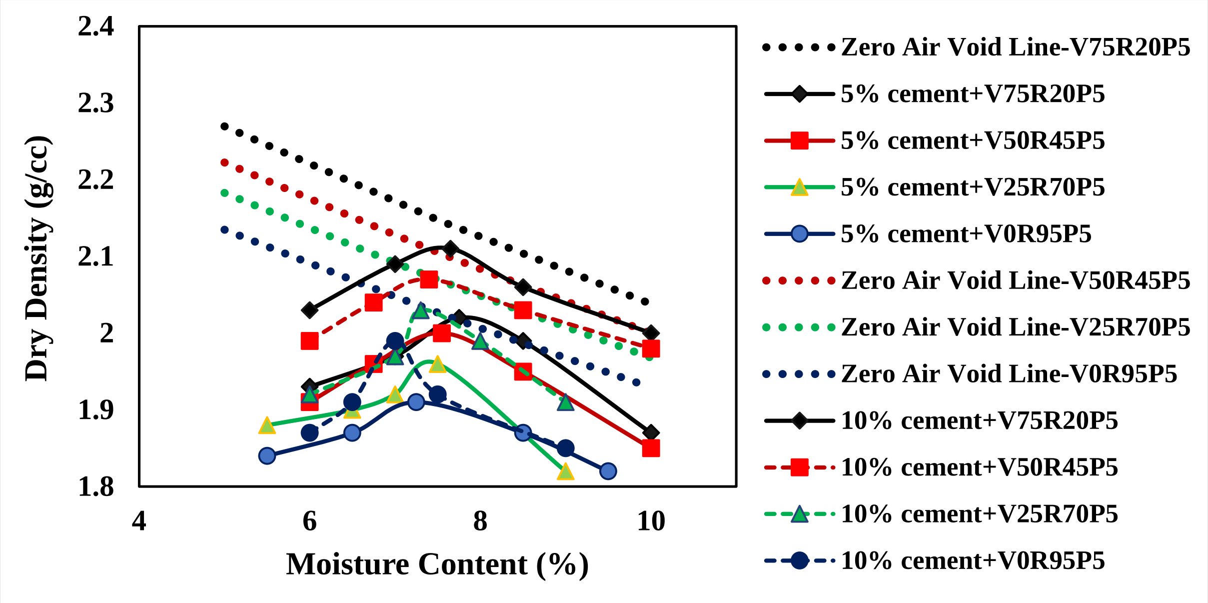


Figure (2): Modified compaction curves of CTB mixes with 5% and 10% cement

Indirect Tensile Strength (ITS)

In pavement evaluation, the higher the tensile strength, the better the base layer's resistance to tensile stresses. Therefore, it is essential to understand the cracking behavior using an indirect tensile strength test. Table 2 shows the findings of the ITS after 7 days of curing, which range between 0.32 and 1.01 MPa. As seen in Fig. (4), similar to the results of UCS, ITS results also show that strength characteristics decrease with an increase in RAM content and increase with an increase in cement content. This decrease was due to the presence of bitumen film in RAM, which is considered as a hydrophobic material and is chemically incompatible with hydrophilic cement paste, thus forming a lower strength at the interface transition zone. These results are consistent with those of prior research by Kasu et al.

(2020). Accordingly, it was concluded that the ITS value of RAM-treated bases is around 0.11 times the UCS value. The composition of V0R95P5 with a cement percentage of 5% exhibited the lowest tensile strength. It was also noticed that cement percentage significantly impacted ITS with a strength gain of 33%. Moreover, it was also observed that the ITS to UCS relationship was around 0.11 times for CTB mixes.

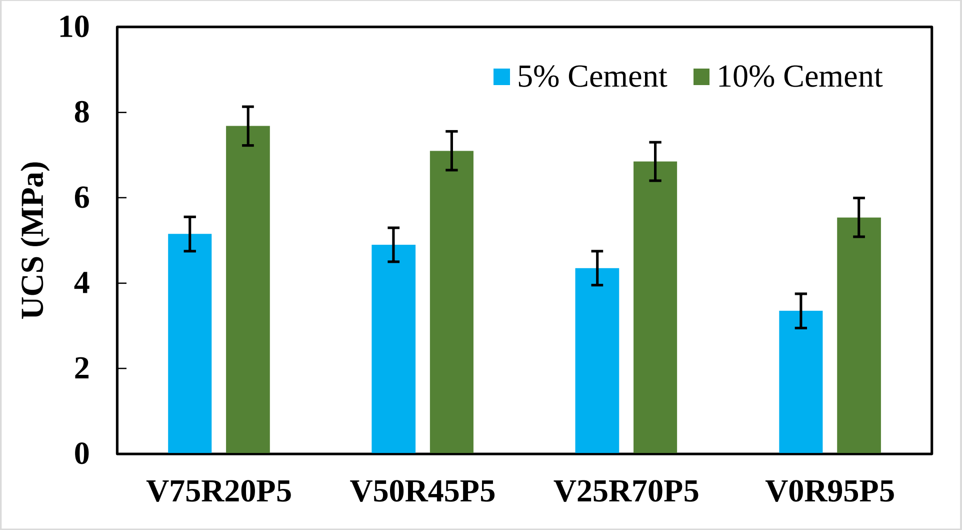


Figure (3): Results of unconfined compressive strength

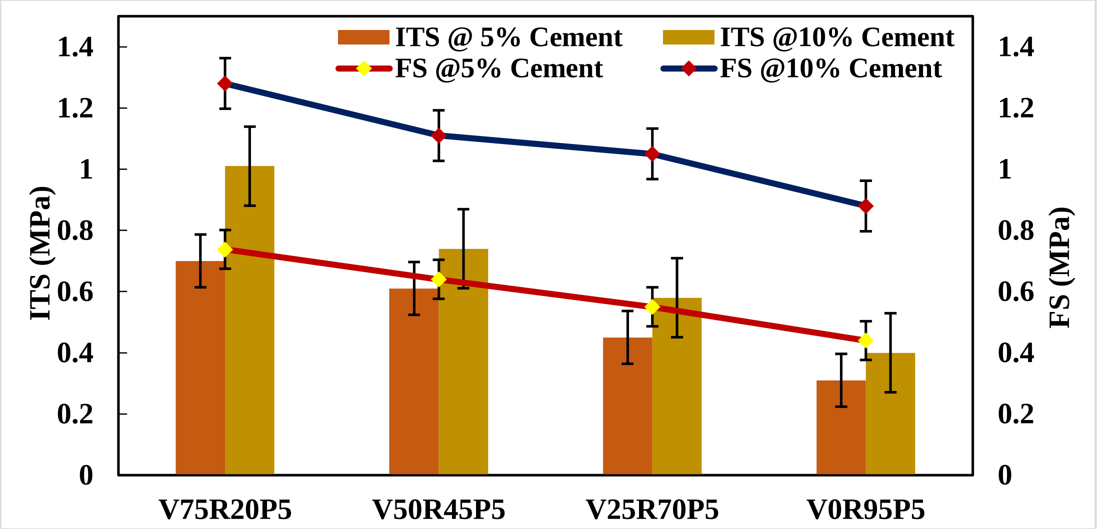


Figure (4): Results of indirect tensile and flexural strengths

Flexural Strength (FS)

The findings of the flexural-strength test at 7 days of curing are given in Table 2. The FS was noticed to be in the range of 0.44 to 1.11 MPa. From Fig. (4), it was observed that FS increased as VA increased. The composition with 95% RAM at 5% cement content has the minimum FS value, whereas the combination V75R20P5 at 10% cement has the maximum FS value. It was also observed that when cement content increases, the ratio of FS to UCS increases from 10% to 17%. This was due to the weak interface bond strength between cementitious material and RAM. Accordingly, the flexural strength decreases with increasing RAM%.

California Bearing Ratio (CBR)

The soaked CBR values of various CTB mixes are given in Table 2. The CBR increased with an increase in VA and cement content. All CTB combinations showed CBR values of 83% to 110%. The composition with 95% RAM at 5% cement content has the minimum CBR value, whereas the combination V75R20P5 at 10% cement content has the maximum CBR value. The CTB samples were inspected for expansion and no sign of expansion was observed under soaked conditions.

Ranking of CTB Mixes

The effectiveness of the CTB combinations was evaluated from various perspectives by conducting different laboratory studies as mentioned in the preceding sections. Therefore, identifying the optimum RAM-PET content was not always evident from the experimental results. A normalized result value is shown in Table 3, where each cell represents the normalized result by equalizing the respective units to a standard scale. Table 4 shows the final ranking of all mixes, where the V75R20P5 (10% cement) mix was the optimum CTB mix, followed by the V50R45P5 (10% cement) mix, the V25R70P5 (10% cement) mix, the V75R20P5 (5% cement) mix and so on. It was observed that the V75R20P5 composition displayed superior performance due to its lower RAM content; however, the V50R45P5 mix combination can be considered optimum based on higher RAM usage.

Table 3. Normalized values of various parameters

Mix Type	Cement (%)	OMC (%)	MDD (g/cm^3)	UCS (MPa)	ITS (MPa)	FS (MPa)	CBR (%)
V75R20P5	5	1.00	0.52	0.42	0.57	0.35	0.52
	10	0.88	1.00	1.00	1.00	1.00	1.00
V50R45P5	5	0.76	0.38	0.36	0.43	0.24	0.37
	10	0.51	0.76	0.87	0.61	0.80	0.78
V25R70P5	5	0.68	0.24	0.23	0.19	0.13	0.11
	10	0.42	0.57	0.81	0.38	0.73	0.48
V0R95P5	5	0.31	0.00	0.00	0.00	0.00	0.00
	10	0.00	0.38	0.51	0.16	0.52	0.26

Table 4. Total rank value and assigned priority values of various parameters

Mix Type	Cement (%)	OMC	MDD	UCS	ITS	FS	CBR	Final Ranking
V75R20P5	5	1	4	5	3	5	3	3
	10	2	1	1	1	1	1	1
V50R45P5	5	3	5	6	4	6	5	5
	10	5	2	2	2	2	2	2
V25R70P5	5	4	7	7	6	7	7	7
	10	6	3	3	5	3	4	4
V0R95P5	5	7	8	8	8	8	8	8
	10	8	6	4	7	4	6	6

Finite Element Modeling

Finite element (FE) modeling based on general-purpose FE programs has been extensively used in analyzing the structural performance of pavements under various pavement geometry and loading conditions (Hadi et al., 2003; Saad et al., 2006; Kim et al., 2009; Cortes et al., 2012). This study aims to evaluate the structural response of conventional pavement model and CTB layered or inverted pavement model using ANSYS 2020R1 software.

Model Geometry and Material Properties

The pavement under investigation consists of the layers as shown in Fig. (5) and the layer thicknesses are taken from the design catalogue given in IRC 37 corresponding to 7% CBR value and 50 msa traffic load. A quarter of the pavement block is selected for three-dimensional (3D) FE modeling having 1.30 m in length, 1.50 m in width and 3.16 m in depth. The use of a quarter symmetric block was supported by Hadi et al. (2003).

The material parameters of two different pavement structures are listed in Table 5. These material parameters are taken from the recommended modulus values of IRC 37 and published literature. The material behavior of bituminous and granular layers is assumed to be linear elastic. The properties of CTB layer is experimentally determined and adopted based on the optimized combination of RAM (45%), VA (50%) and PET (5%). The sub-grade is simulated by Mohr-Coulomb plasticity model with a cohesion of 45kPa and an angle of internal friction of 39° for a clayey sub-grade stabilized with PET (Banerji et al., 2022).

Table 5. Pavement layer material properties

Conventional Pavement					
Parameter	**BC**	**DBM**	**WMM**	**GSB**	**Subgrade**
Elastic modulus (MPa)	2000	2400	192	156	62
Poisson's ratio	0.35	0.35	0.35	0.35	0.35
Density (kg/m^3)	2400	2400	1800	1800	1900

Pavement with CTB Layer						
Parameter	**BC**	**DBM**	**SAMI**	**CTB**	**CTSB**	**Subgrade**
Elastic modulus (MPa)	2000	2400	170	4900	600	62
Poisson's ratio	0.35	0.35	0.35	0.25	0.25	0.35
Density (kg/m^3)	2400	2400	1200	2317	2242	1900

Legend: BC = Bituminous Concrete; DBM= Dense Bituminous Macadam; WMM= Wet Mix Macadam; GSB= Granular Sub-base; CTB= Cement-treated Base; CTSB= Cement-treated Sub-base.

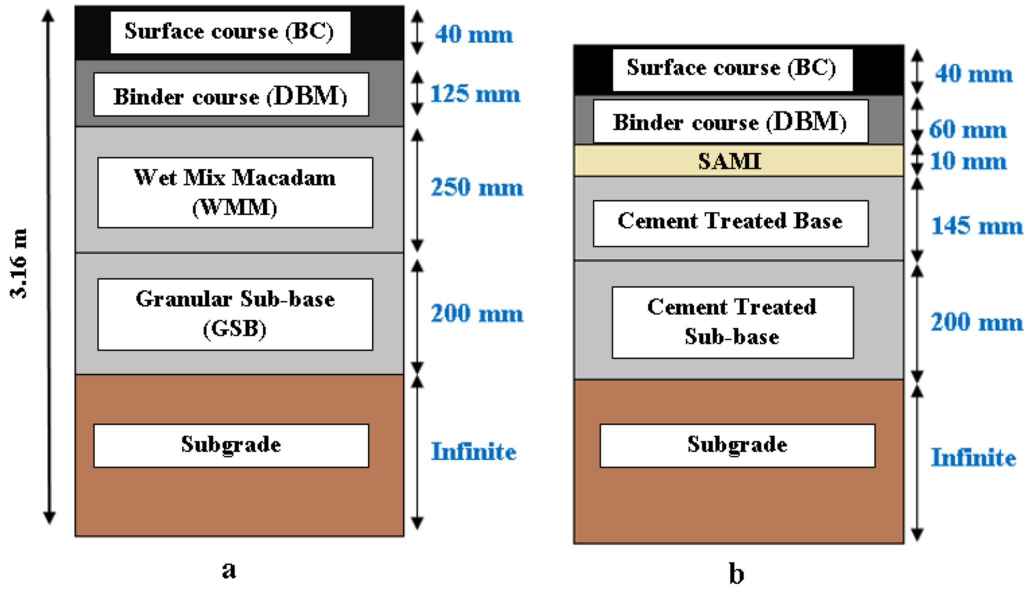


Figure (5): Cross-section of (a) Conventional pavement and (b) Pavement with CTB layer

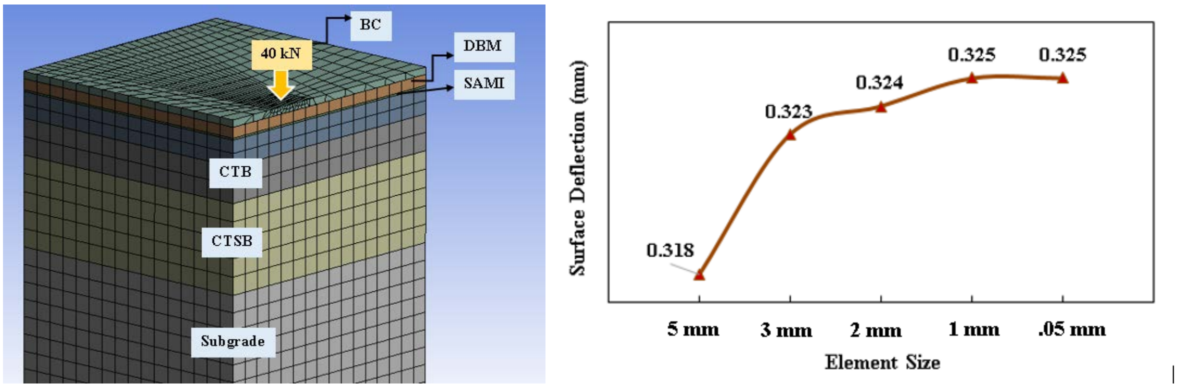
Mesh Generation

SOLID 185 element is used to model the pavement block in ANSYS having a total of 24 degrees of freedom. As the element type and mesh size influence the efficiency of modeling in FE analysis, a convergence study is fulfilled by comparing surface deflection responses obtained from varying mesh sizes. Element size of 5 mm to 0.05 mm has been adjusted under the loading area and further 1 mm mesh size is assigned. Meanwhile, a finer mesh is applied directly under the wheel load and a medium mesh is applied away from the loading area, as shown in Fig. (6).

Boundary Conditions and Loading

The boundary conditions are based on the relevant work available in literature of Hadi et al. (2003) and

Saad et al. (2006). By taking advantage of symmetry, orthogonal displacements to the plane of symmetry are restrained; i.e., on the inside vertical faces. Roller support is adopted for the outside vertical surfaces and fixed support has been considered at the bottom face of the model. Similar to the road-surface conditions, the top of the model is free of any boundary conditions. In this model, the perfect bond is considered at each interface of consecutive layers' interaction to simplify the calculation.



(a) **(b)**

Figure (6): (a) FE meshed model in ANSYS 2020R1 (b) Convergence of surface deflection for different sizes of mesh element

For evaluating the pavement responses, an effective single-wheel load of 40 kN is applied. The contact area (a) is around 71,557 mm^2 for a uniform contact pressure of 560 kPa. On converting into equivalent rectangular imprint area, the dimensions are obtained as 320 mm in length and 220 mm in width. In previous studies (Hadi et al., 2003; Saad et al., 2006), the shape of two semi-circles and a rectangle are converted into a rectangular shape, having a contact area (a) of 0.5227 L^2, a length of 0.8712L and a width of 0.6L, where L is calculated as $\sqrt{(a/0.5227)}$.

Comparative Analysis between the CTB Layered and Conventional Pavements

The conventional pavement structure was used as a reference model to examine and compare the structural compatibility of the CTB layered pavement. The surface deflection was 0.325mm, which was higher than that of the CTB layered pavement deflection of 0.172mm, as shown in Fig. (7). The CTB layered pavement provides a better deformation resistance of 47%. The maximum horizontal tensile strain at the bottom of the dense bituminous macadam (DBM) layer for conventional pavement model was 199.60 micro-strain, which was much higher than 85.30 micro-strain in the CTB layered pavement structure. The stress distribution in the CTB layered pavement model was also entirely different from that of the conventional pavement model.

In this comparative analysis, service life ratio based on fatigue strain is also investigated. Fatigue service life ratio (FLSR) is an important indicator in identifying the effectiveness of the CTB layer in pavement structure. FSLR is expressed in Eq. 2, considering the maximum horizontal tensile strain obtained at the bottom of DBM with CTB (εxx2) to the pavement model with conventional base layer (εxx1).

$$\text{FSLR}=\frac{\varepsilon xx1}{\varepsilon xx2}. \qquad (2)$$

These strains are obtained from ANSYS simulation results at critical positions. Based on the calculations from Eq. 2, CTB layered pavement provides a better fatigue resistance with an FSLR of 2.29. This was because of the lesser tensile strain value in comparison to conventional pavement by 57%, representing the significance of the CTB layer. However, in CTB pavement, the composition of thin bituminous layers is more likely to shear failure and top-down cracking (Cortes et al., 2012). Therefore, for the design of CTB layered pavement, more critical mechanical response parameters need to be studied.

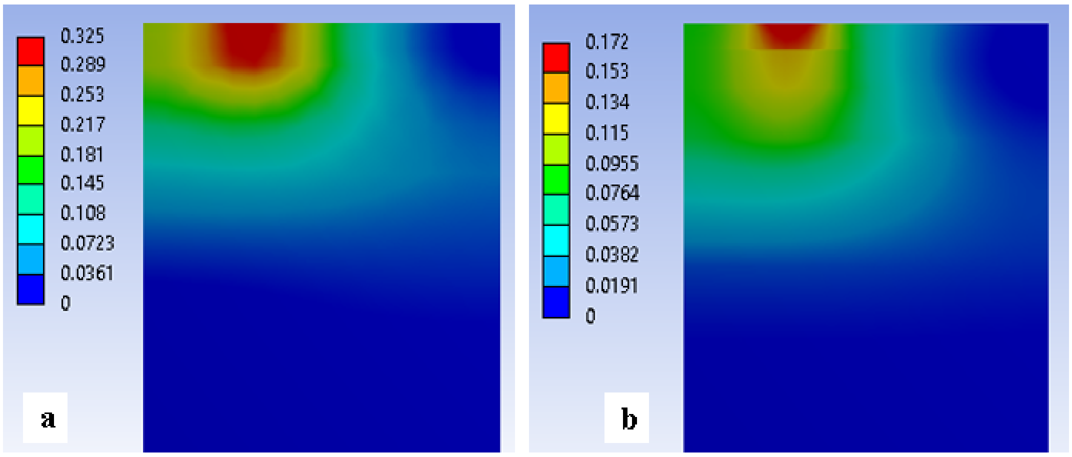


Figure (7): Pavement deformation of (a) Conventional pavement and (b) Pavement with CTB layer simulated in ANSYS

Cost Benefits

Addition of RAM to a cement-treated base layer helps minimize the required quantity of virgin aggregates and total pavement layer thickness. In addition to the environmental advantages, the CTB layer has considerably reduced the pavement thickness by 26% (from 615mm to 455mm), thus resulting in construction cost reduction. Based on the IRC-37 (IRC, 2018) recommended design thickness, the material requirements were calculated for a 1000-m long stretch and a 3.75-m wide pavement section. In general, the cost analysis is performed in meter run of road length. In India, the Central Public Works Department (CPWD, 2021) sets guidelines and supplies the procedure for unit-cost analysis. In this paper, practice procedure as per CPWD is adopted to perform cost analysis. The comparative analysis of cost of construction involves CTB and granular base layer, as shown in Table 6, suggesting that combining RAM and PET wastes with cement for constructing the base layer is economically advantageous. For CTB layer construction, the cost of OPC 53 grade cement was considered to be INR 5,000 per tonne and the aggregate price was INR 1,350 per cubic meter. In addition, the PET quantity is calculated based on 5% of the total aggregate requirement. Overall, the total cost reduction was estimated to be 33.85 lacs per kilometer stretch. Utilizing 45% RAM with 10% cement additive and 5% PET waste results in a cost saving of 30%. Therefore, it was evident that using CTB mixtures as base layers led to an overall reduction in construction cost.

Table 6 (a). Cost estimate for conventional flexible pavement

Item	Thickness (mm)	Length (m)	Width (m)	Quantity	Rate (INR)	Amount (INR)
Bituminous Concrete	40	1000	3.75	150 m^3	10870	16,30,500
Dense Bituminous Macadam	125	1000	3.75	468.7 m^3	10013	46,93,593
Wet Mix Macadam	250	1000	3.75	937.5 m^3	2803	26,27,812
Granular Sub-base	200	1000	3.75	750 m^3	2592	19,44,000
Prime Coat		1000	3.75	3750 m^2	45	1,68,750
Tack Coat-a		1000	3.75	3750 m^2	36	1,35,000
Tack Coat-b		1000	3.75	3750 m^2	11	41,250
Cost of per km section						₹ 112.40 (Lacs)

Legend: INR = Indian Rupee.

Table 6 (b). Cost estimate for flexible pavement with CTB Layer

Item	Thickness (mm)	Length (m)	Width (m)	Quantity	Rate (INR)	Amount (INR)
Bituminous Concrete	40	1000	3.75	150 m^3	10870	16,30,500
Dense Bituminous Macadam	60	1000	3.75	225 m^3	10013	22,52,925
SAMI	10	1000	3.75	37.5 m^3	100	3,750
Cement-treated Base	145	1000	3.75	543.75 m^3	2800	15,22,500
Granular Sub-base	200	1000	3.75	750 m^3	2592	19,44,000
Prime Coat		1000	3.75	3750 m^2	45	1,68,750
Tack Coat-a		1000	3.75	3750 m^2	36	1,35,000
PET shredding and processing	145	1000	3.75	56520 kg	25	1,41,300
Milling	100	1000	3.75	375 m^3	150	56,250
Cost of per km section						₹ 78.55 (Lacs)

Legend: SAMI-Stress absorbing membrane interlayer; INR = Indian Rupee.

CONCLUSIONS

In this study, the structural performance of CTB mixes with varying cement and RAM percentages was evaluated. CTB mixture specimens were prepared and their strength characteristics were examined using experimental investigations. Using the ranking methodology, experimental results were analyzed to determine the optimum proportion of RAM usage. In addition, the importance of using CTB over conventional pavement has been assessed through FE analysis and a cost comparison was made. The following are the study's conclusions.

1. All of the CTB mixes prepared by RAM incorporation showed that maximum dry density (MDD) values increase as the RAM % decreases.
2. Unconfined compressive strength (UCS) values were found to be in the range from 3.35 to 7.68 MPa. The UCS values for CTB specimens of 20% and 45% RAM surpassed the minimum UCS requirement of 4.5 MPa range at 5% cement content.
3. The indirect tensile strength (ITS) varied from 0.32 to 1.01 MPa and similar to UCS, as RAM% is reduced, ITS increases.
4. The RAM blends show an increasing trend in the flexural strength (FS) percentage with the same PET content and varying cement contents. FS values lie in the range from 0.44 to 1.11 MPa and decrease with an increase in the RAM content.
5. The optimal composition was identified by priority-based ranking and after considering six experimental results, where 20%-45% RAM usage was found to be suitable for CTB layer. Moreover, the results confirm that CTB layered pavement structures can achieve satisfactory performance even without using virgin aggregates.
6. According to FE analysis, surface-deformation resistance improves by 47% and horizontal tensile strain decreases by 57% with the implementation of CTB. Therefore, CTB layered pavement shows a superior performance in surface deflection and tensile strain at the bottom of the bituminous layer.
7. From the cost-comparison findings, it was evident that using RAM and PET materials by substituting virgin aggregates reduced the cost by 30%. The total cost reduction was estimated to be 33.85 lacs per kilometre stretch.

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