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Stabilization of cement-treated base mixes incorporating high reclaimed asphalt pavement materials using stabilizer rich in SiO_2 and Al_2O_3

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ABSTRACT

Using RAP material can be one of the promising solutions for solving the new material issues, reducing haulage distance and fuel cost to a great extent as the complete process is done at site only using the Full-depth reclamation (FDR) technique. However, the effect of the high amount of RAP material with stabilizer has not been completely understood for constructing the CTB layer. In the present study, a mixed design of the CTB layer has been formulated considering the requirements of Indian Specifications to utilize maximum RAP material in a sustainable approach. Mechanical and durability properties of CTB mix were evaluated to identify the effect of different cement, stabilizers, and RAP aggregates on the laboratory mixtures. The efficacy of stabilizer with cement was examined to judge the suitability of the same as potential pavement construction materials. The optimal mix was decided mainly based on the Unconfined Compressive Strength (UCS) value and flexural strength of aggregate specimen at 7-days of moist curing. However, for a detailed study, UCS values were checked at three days, seven days, and 28 days. Also, the durability properties of the CTB mix were analyzed by performing a durability test, sorptivity, and rapid chloride penetration test (RCPT). Present laboratory studies firmly indicated that using a stabilizer with cement using 70 % RAP leads to a strong and durable CTB mix.

1. Introduction

Cement-treated base (CTB) is a mixture of crushed stone, crushed rock, crushed gravel, reclaimed asphalt pavement (RAP) material, or a combination of soil-asphalt mixture and water with cementitious materials such as cement, lime, constructed in one layer [1–8]. However, these materials are required in large quantities and are not readily available in many regions in India due to the ban on mining, depletion of natural resources, or long hauling distances [9–12]. Reclaimed asphalt pavement (RAP) can play an essential role in addressing the scarcity of natural aggregates by reusing them at the site for CTB construction. RAP not only can reduce the problem of natural aggregates NA but also helps in reducing the overall project cost and can reap environmental benefits resulting in sustainable construction [2,9,10]. RAP can be obtained by a process known as milling, full depth reclamation, or pavement demolition [13]. Removal of an existing pavement up to the desired depth is known as milling [13]. While several studies looked at using reclaimed asphalt pavement (RAP) material in flexible and rigid pavements, few looked into the feasibility of using them in cement-treated base (CTB) mixes. Fig. 1 shows the flowchart of the procurement of RAP material by various reclamation techniques. CTB is prepared either by in-plant mixing or mechanized in-place mixing by full-depth reclamation technique [1].

Traditionally, base and sub-base layers were laid one after the other, requiring a massive amount of new aggregate requirements. However, in today's scenario, it is not helpful as it requires a huge amount of new aggregates and sand. Besides cost and material availability issues, constructing base and sub-base layers as a single layer with desired compaction requirements is of great concern for the Engineers. Due to the recent massive road construction activities, quality aggregates are depleting very fast for all roads and use of RAP material as fresh aggregates had increased in the recent past [10,11,14,15]. It, therefore,

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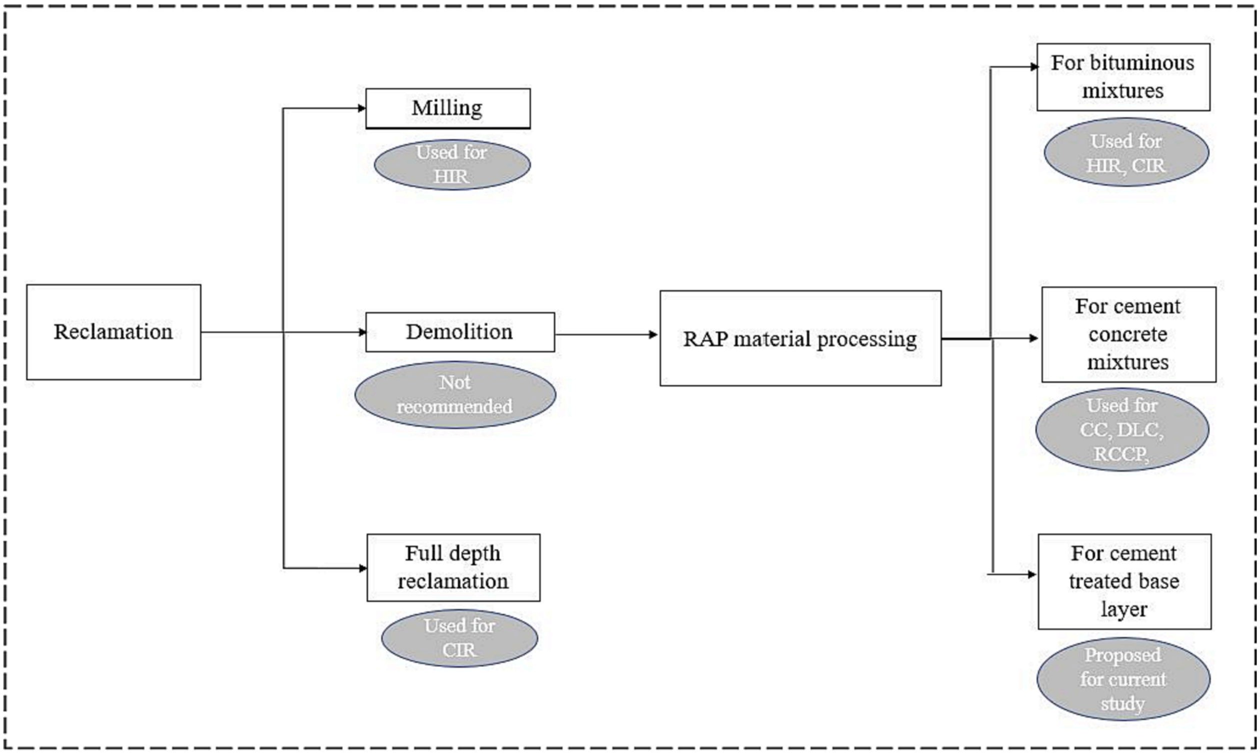


Fig. 1. RAP material procurement flowchart.

becomes necessary to perform a detailed research study to use the available pavement material in a constructive and sustainable approach. Therefore, this research explores how a solid and durable cement-treated base layer using a high RAP material is designed without compromising strength and durability. Cement has been used as a stabilizer in pavement stabilization for ages to modify the Engineering properties of pavement [7,16,17]. However, there are certain limitations while adding cement to the CTB layer due to its high rigidity properties and appearance of shrinkage cracks. The strength of the CTB layer increases due to the constant hydration of cement. Contrary, higher cement content and fluctuation in temperature could be contributing factors to reflecting cracking on the road surface [3,4,6,10,18]. Yuan et al. *(2011)* studied the effect of RAP and cement on the CTB layer by full-depth reclamation (FDR) technique and found that on increasing the cement content (2 %, 4 %, 6 %), the unconfined compressive strength (UCS) increased with a constant RAP percentage, whereas, UCS value got decreased on increasing RAP percentage (50 %, 75 %, 100 %) irrespective of the cement content. However, the effect of stabilizer with cement and the durability properties of CTB mixes in the laboratory are still unclear.

Stabilization with soil cement was first prepared in 1935 to enhance the pavement base for State Highway 41 Johnsonville, South Carolina [19]. Since then, cement has been used as a stabilizer for improving the base or sub-base for pavements. However, as discussed above, shrinkage is still a primary concern for highway construction authorities. To overcome this problem, the Government of India recommends using a commercial stabilizer, which will modify the properties by adding it with cement, and it is believed that the chances of shrinkage cracking will be reduced [20]. However, no such study is available to support this statement. Therefore, the current study addressed these problems using different RAP content and stabilizer with cement. It is theorized that incorporating a stabilizer into the cement during Stabilization modifies the microstructure, enhances its binding property with Soil, and significantly retains the flexibility, eliminating the risks of shrinkage cracks.

Previous researchers have established that aged bitumen coating around RAP aggregate makes it a different material from NA. Therefore, this changes its behavior and is the possible reason for increasing the optimum water content (OMC) requirement for the CTB layer whereas decreasing its maximum dry density (MDD) [2,10,11,21,22]. Shi et al. [23] found that the interfacial transition zone (ITZ)'s porosity and a preferential asphalt cohesion failure together had a significant impact on the reductions in strengths of PCC containing RAP (RAP-PCC). This view is supported by other researchers, who also reported that RAP material typically fails in asphalt cohesion, which means that the asphalt layer arrests cracks through the asphalt layer surrounding the RAP particles [24–26]. Based on their laboratory findings, Senff et al. [20] reported that as a nano-filler, SiO_2 nanoparticles could better understand the mechanism of nano silica and the effect of nano-silica on fresh cement paste properties and mortar covering various pores between gel of calcium silicate hydrate (C—S—H) particle.

Furthermore, the amount of C—S—H also rises due to the pozzolanic reaction with calcium hydroxide, increasing the matrix's density and enhancing the material's strength and durability. Due to its high surface energy, nano silica speeds up the hydration of cement. It also enhances the physical properties of a concrete mix by altering the packing density through particle filling [27]. Therefore, the present study also includes microstructural properties with the help of scanning electron microscopy (SEM) to understand better the mechanism through which the RAP-CTB mixture was prepared by using a silica-rich cement additive known as stabilroad stabilizer.

2. Research objective and significance

In the light of the above discussion, the advantages, disadvantages, and limitations of using RAP and silica-based stabilizers should be identified as a critical subject for further research. By doing so, sustainability will be promoted, and the proper use of RAP materials in constructing RAP-CTB will be increased soon. Previous research has not dealt with the effect of stabilizers with cement and a high amount of RAP material for constructing the RAP-CTB layer. However, few researchers have been able to draw on any systematic research into using RAP with

Table 1
Chemical composition of Cement (OPC-43) and Stabilizer.

Component	Cement* (OPC-43)	Stabilizer*
SiO_2	19.4	38.29
Al_2O_3	3.7	26.03
Fe_2O_3	3.8	0.57
MgO	2.9	2.3
CaO	66.1	15.58
Na_2O	0.22	5.23
SO_3	1.8	0.63
K_2O	0.45	6.9

Note: *Amount in %.

Table 2
NA and RAP Physical Properties.

Description	Standard Specification	Specified Limits	Test Results	
			Natural Aggregate	RAP Aggregate
Combined FI & EI	ASTM D4791	Max 35 %	12 %	7 %
Aggregate Impact Value	ASTM D5874	Max 27 %	15.82 %	21 %
Aggregate Crushing Value	ASTM D5821	Max 30 %	13 %	15.57 %
Los Angles Abrasion Value	ASTM C131	30	18 %	24.59 %
Specific gravity (coarse aggregate)	ASTM C127	–	2.619	2.559
Water absorption (coarse aggregates)	ASTM C127	–	0.629	1.54
Plasticity Index (%)	ASTM D4318	Min 6	–	Non-Plastic (N.P.)
Residual Asphalt Content (RAC) (%)	ASTM D2172	–	–	3.70 %

different cement content, but no fixed percentage of RAP material is defined by any researcher [2,3,16,28–30]. Despite the importance of RAP, there remains a paucity of evidence on the durability characteristics of CTB mix by incorporating RAP material. While some researchers have been carried out on the percentage of cement and the effect of 100 % RAP on MDD, OMC, and UCS values, there is little published data on the understanding of durability against wetting and drying. This paper highlights the importance of utilizing not only the higher RAP percentage but also importance has been given to durability characteristics of the RAP-CTB mixes. Considering pavement infrastructures are continuously in contact with alterations in groundwater table and capillary action, an investigation of the sorptivity behavior of CTB treated with and without RAP material was attempted in this study as per ASTM C 1585 [31].

Furthermore, previous studies tried to use 100 % RAP based on its mechanical properties only. Here, in this study, the percentage of RAP was decided based on the gradation of the RAP material, mechanical properties, and durability properties of the mixes. The behavior of stabilizer with cement and different RAP percentages was also studied in detail and compared with NA. As a result of the increased possibility of shrinkage cracks caused on by the increase in cement content, the addition of a stabilizer and stress-absorbing membrane interlayer (SAMI) between the CTB layer and binder or surface layer has been recommended to prevent the top of flexible pavement from experiencing further shrinkage cracking. In addition, analysis of variance (ANOVA) was carried out to understand the relationship between independent (Cement content, stabilizer content) and dependent variables (strength such as UCS, flexural). Apart from ANOVA, the main effect plot is drawn to examine the differences between the mean value of the independent variables on the dependent variable which gives a clear idea about the significance of each variable in a graphical form.

3. Experimental program

3.1. Materials

For cement-treated base mixes, materials used in this study are Natural aggregate (NA) (20 mm, 10 mm, and stone dust), RAP material, Ordinary Portland Cement (OPC – Grade 43) conforming to IS:8112 [32], silica-based stabilroad stabilizer (SR) rich in SiO_2 and Al_2O_3, and water were used. Table 1 shows the chemical compositions of the cement and silica-based SR used in the study. NA was procured from the local stone quarry. RAP material was extracted from NH-344 from the 15-year-old highway using the milling technique. During the milling process for getting RAP material, it was seen by visual observation that the material lying under the binder and surface layer was also milled. That material consists of water-bound macadam (WMM); dust was also wrapped around the aged bitumen-coated RAP material. Therefore, the RAP material was studied for the plasticity index in accordance with ASTM D4318 [33]. Before using RAP material, it was kept in the oven for 24 h at 100 °C to remove the excess moisture so that the results could be

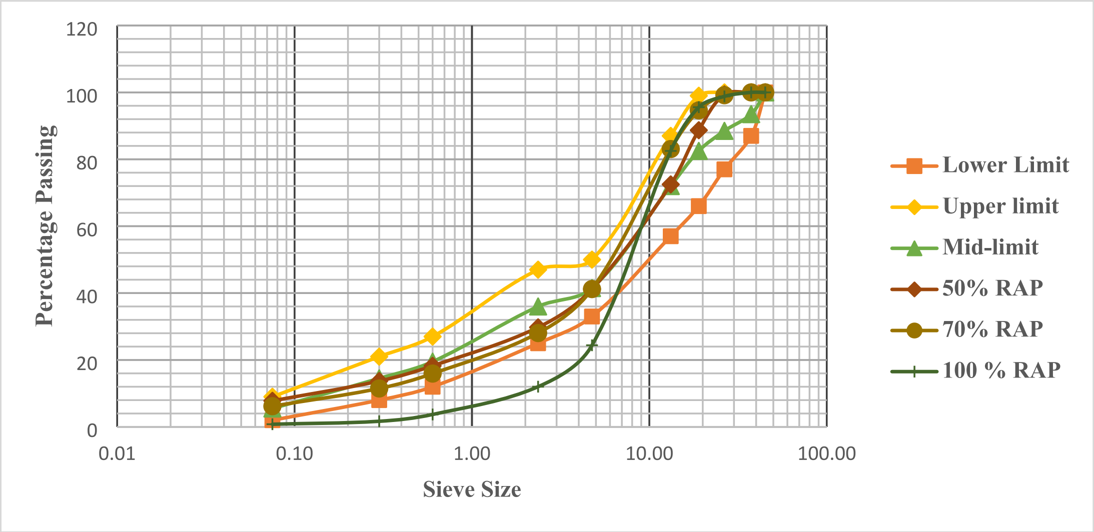


Fig. 3. Gradation of RAP material.

studied carefully. The physical properties of both NA and RAP material are shown in Table 2. The combined flakiness and elongation index of NA and RAP were determined in accordance with ASTM D4791 and found to be 12 % and 7 % respectively. The specific gravity and water absorption of CA were noted as 2.619 and 0.629 % whereas for RAP aggregates it was 2.559 and 1.54 %, respectively, when determined as per ASTM C127. Residual bitumen content was found to be 3.2 % by the total weight of the mix. Bitumen was extracted from aged RAP using centrifuge extraction with ASTM D2172 [34]. OPC grade 43 was used in accordance with IS:8112 [32]. A stabilizer was procured from the industry in Hyderabad, India. It was in powdered form and odorless. Its dosage is just 0.5 % to 5.0 % of cement as recommended by IRC:SP:89 [20]. Whereas potable water was used to prepare and cure the cement-treated base mixtures in accordance with IS:456 [35].

3.2. Gradation

For both NA and RAP material, gradation was adopted based on Indian specifications [1,36]. Gradation plays a vital role in mixture properties and can affect its performance to a more considerable extent [5,28,37]. Since the RAP material was extracted via milling technique, it is believed that the material crushed and the use of RAP percentage will depend on the gradation obtained from the RAP material. Gradation of all considered RAP material is shown in Fig. 3. It can be observed clearly from Fig. 3 that 100 % RAP cannot be used for the current study as it does not satisfy the gradation requirements as here the mid-line gradation is targeted to get the optimum percentage of RAP materials. Hence, 0 % RAP (or 100 % NA), 50 % RAP (or 50 % NA), and 70 % RAP (or 30 % NA) were studied for the CTB mixes.

3.3. Mix design

To study the feasibility of using RAP aggregates with stabilizer and cement, first MDD of the mix was calculated, and corresponding to the MDD, OMC is to be calculated on which mix has to be cast. Five cement content, 3.0 %, 3.5 %, 4.0 %, 4.5 % and 5.0 % with three RAP content, i.e., 0 % RAP, 50 % RAP, and 70 % RAP were used in this study to find out optimum percentage of cement. For each mix, nine 150 mm × 150 mm × 150 mm specimens were casted and there was total 19 mixes which were then tested for three days UCS, seven days UCS, and 28 days UCS. The samples were wrapped with wet gunny bags and placed for 3, 7, and 28 days of moist curing. After finding the optimum cement content of the mix, optimum stabilizer content needs to be found; stabilizer percentages used in the study are 3.0 %, 3.5 %, 4.0 %, and 4.5 % by weight of optimum cement content. Although the 28-day flexural strength of CTB mixes should not be greater than 1.4 MPa, or 20 % of the mix's 28-day UCS value. Therefore, in the current research study, an attempt has been made to determine the CTB mixes' actual flexural strength [1].

3.4. Determination of mechanical properties

To determine the mechanical properties, the current laboratory investigation is split into three sections; firstly, the physical properties of NA and RAP materials were checked, and the percentage of RAP used was decided based on the mid-value gradation line. Based on it, 50 RAP and 70 RAP were selected for the current study. The RAP aggregates were thoroughly studied and compared properties with NA. In the second phase, after determining the MDD-OMC relationship, the mix was formulated using NA only, i.e., 0 % RAP, and studied for its mechanical properties such as UCS value, and flexural strength. Finally, durability against wetting and drying has been studied in brief. Finally, in the third phase, NA was replaced by 50 % RAP and 70 % RAP to check the feasibility of using maximum RAP material for the current study.

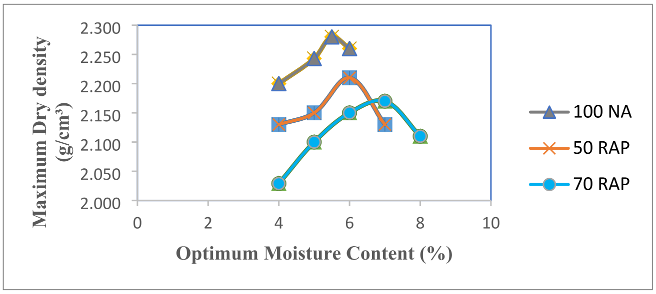


Fig. 4. Moisture density relationship.

3.5. Determination of durability properties

To ensure the results for highway construction suitability, the materials were thoroughly investigated for durability properties using RAP aggregates. After performing 12 cycles of wetting and drying test, the cylindrical samples were further evaluated for the residual strength test. For testing water sorptivity of mixes, a total of 8 test specimens (two replicates for each mix) of 100 mm diameter and height of 50 mm were cast and cured for 28 days as per ASTM C 1585 [31]. The rapid chloride ion penetration (RCPT) test was also tried in the current study to evaluate the electrical conductance of charge as per ASTM C 1202 – 19 [38], which will give the idea about the qualitative durability parameter of the stabilized mixes.

4. Results and discussion

4.1. Aggregate properties

The results obtained from the preliminary analysis of RAP material and NA reveal that RAP satisfies the fundamental physical properties of aggregate but is lower than that of NA. Impact value, a relative measure of the resistance to sudden shock or impact, was noted as 21 % for RAP aggregates, whereas 15.82 % for NA. Whereas the crushing value, which signifies a resistance to crushing under a gradually applied compression load, was 15.57 % for RAP and 13 % for NA. Los angles abrasion value was 24.59 % for RAP, while 18 % was reported against NA. Los angles abrasion value is an important parameter to judge the suitability of aggregates as it is the indication of abrasion against rubbing, as relative rubbing action between the aggregates and steel balls which were used as an abrasive charge. Moving on to the specific gravity and water absorption results, the specific gravity of NA was more than RAP. Whereas water absorption of RAP aggregates was more than those of NA, the higher water absorption content of RAP might be due to the dust particle around the RAP aggregate surface which is in confirmation with previous studies [39–41]. Interestingly, 100 % RAP does not meet the particle size distribution as per relevant ASTM standards; hence 100 % RAP was not considered for study in the present study, and only 50 % RAP and 70 % RAP have been used for CTB mixes.

4.2. Modified compaction

To compact CTB mix to its maximum density, optimum water content (OMC) is required. Here, the studied RAP material was kept in a thermostatically closed oven for 24 h at 100 °C at least 24 h before being taken to ensure no excess moisture was present in the laboratory sample as the sample was stored in an open bin. Hence, OMC must be determined in the laboratory for a proper mix design procedure of CTB mix. In the current study, the MDD and OMC for the mix were determined as per IS 2720 (Part VIII) [42]. On closely observing Fig. 4, as the percentage of RAP increases, its density decreases, whereas OMC increases. Mix prepared with 0 % RAP has MDD reported as 2.280 gm/cm^3 against the lowest OMC of 5.5 %. In contrast, 50RAP and 70RAP reported 6 % and 7

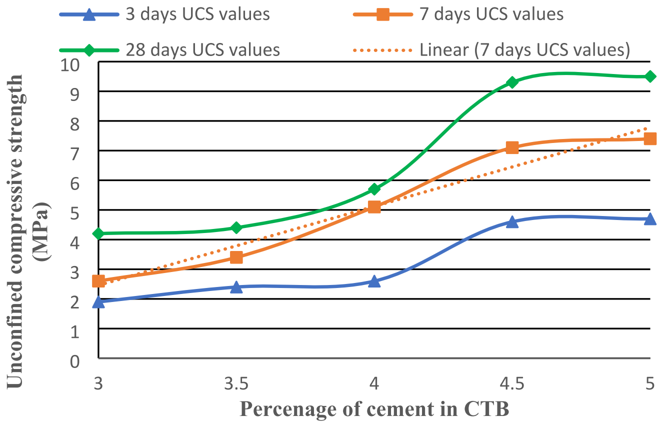


Fig. 5. Unconfined Compressive Strength (UCS) Value of NA with cement.

Table 3
Two-way ANOVA results for obtained UCS.

Source of variation	SS	DF	MS	F-Value	P-Value
Cement (%)	146.932	4	36.733	386.44	2E-25
Curing	88.0288	2	44.0144	463.04	3E-23
Interaction	11.8968	8	1.4871	15.645	9E-09
Within	2.85167	30	0.09506		
Total	249.709	44			

% OMC respectively. The increasing OMC is owing to the presence of dust particles, duration of stockpiling, and foreign matter present in the RAP mixes, which tend to absorb more water as compared to the NA [6,28,37,43,44].

4.3. *Unconfined compressive strength*

The unconfined compressive strength (UCS) values for aggregate mixtures are obtained by testing on 150 mm cube size specimens. The mixture is prepared using a vibratory table in three layers to ensure proper compaction. Before putting another layer in the mold, the material has to be scarified with the help of a spatula to make sure proper bonding between the upcoming layer above it. First, optimum cement content was decided based on three days, seven days, and twenty-eight days of moist curing by wet haisen bags. The cement percentage used in this study was 3 %, 3.5 %, 4 %, 4.5 %, and 5 %, and prepared a total of nine molds for each cement content. Out of these nine molds, three molds were tested at three days, three molds at seven days, and the rest three molds at 28 days UCS values were reported. The average of the three specimens was reported for each cement with stabilizer or RAP content. On closely observing Fig. 5, UCS results of 3 % cement content and 3.5 % cement content did not get enough strength, and 4.5 % and 5 % results are more than the required strength. So, the 4 % cement content is the optimum cement percent of CTB.

The two-way ANOVA in this study was used to find the relationship between the independent and dependent variables. This relationship can be used to assess the significance between independent variables. The main intend of the study was to find the significance level of following: (a) curing and cement on UCS and (b) curing and cement with SR on UCS. Three replicates were made and analysis for the experimental investigations. The probability value and the Fischer test value are used to assess the validity, significance, and acceptability of a mathematical model established using the regression technique (known as p-value and F-value, respectively). The p-value can be used to determine the effect of multiple sources of variations. For any attribute to significantly affect the responses, the p-value should be less than 0.05 at a confidence level of 95 %. Table 3 summarises the results of the two-way ANOVA analysis of the experimental data for the UCS results with variable cement content and curing days. As can be seen in Table 3, both the curing and cement content significantly affect the UCS values (p less than 0.05). However, cement content has more dominant effect in comparison to curing. To further understand the effects of these mix components, main effect plots for variable cement content, and curing days were plotted. Fig. 6 depicts the variation of these parameters with the change in mix attributes. As can be seen increase in curing days and cement content considerably increases the UCS values of the mix [2,6,7].

Other CTB molds were cast using an SR stabilizer with this optimum cement content of 4 %. The stabilizer percent used in this study was 3 %,

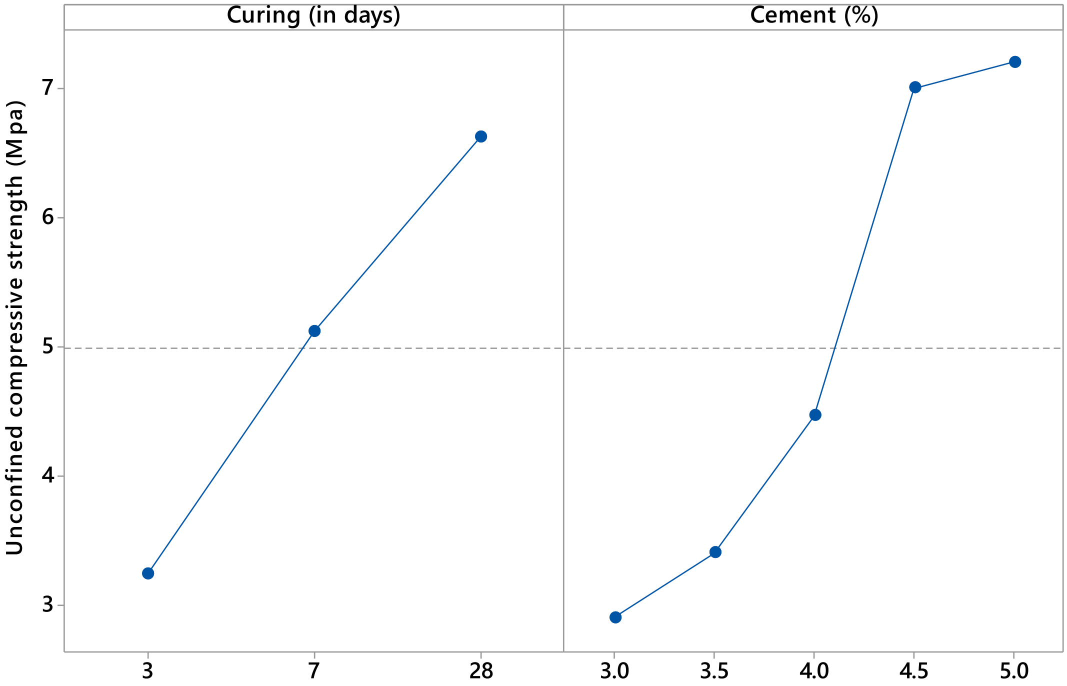


Fig. 6. Main effect plots for curing and cement.

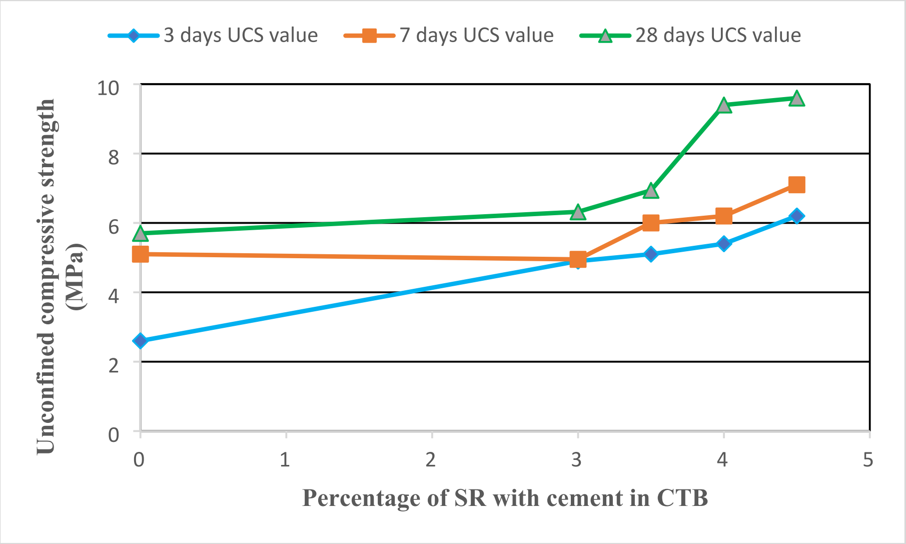


Fig. 7. UCS value of NA with cement and stabilizer.

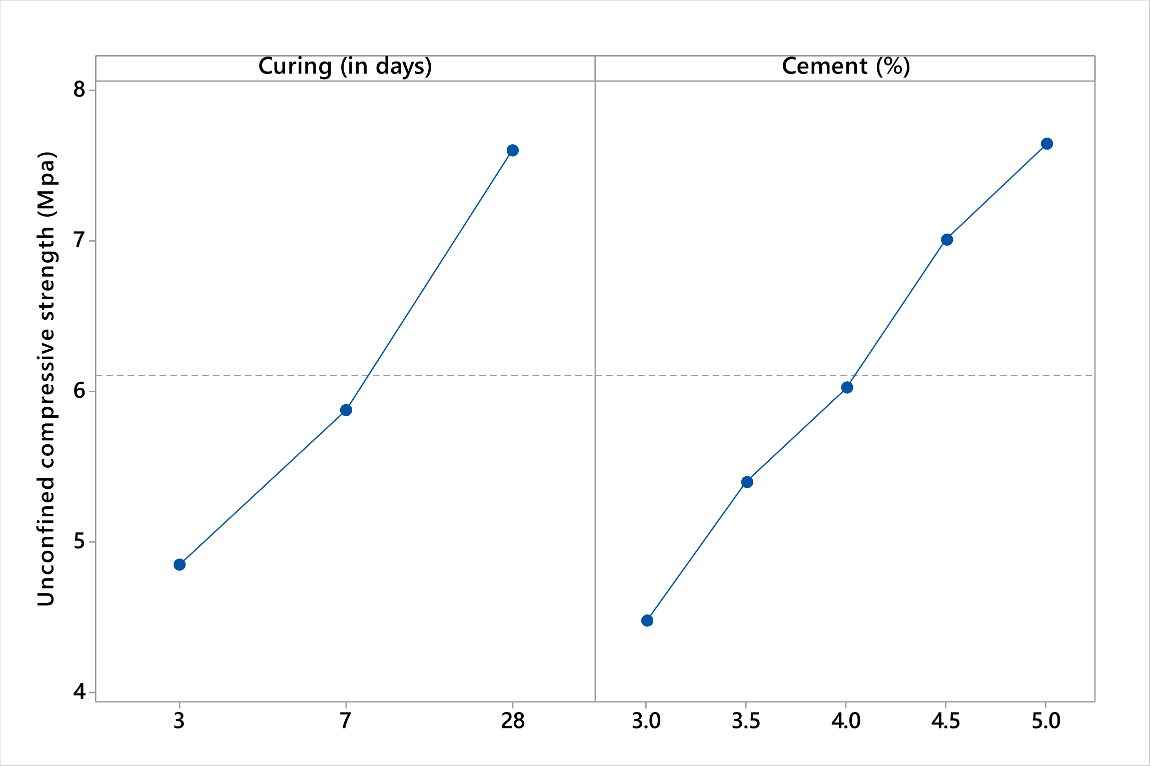


Fig. 8. Main effect plots for curing and cement (effect of cement with SR).

Table 4
Two-way ANOVA results for obtained UCS (cement with SR).

Source of variation	SS	DF	MS	F-Value	P-Value	F crit
Cement (%)	49.2026	4	12.301	320.89	3.8E-24	2.68963
Curing	118.47	2	59.235	1545.3	5.5E-31	3.31583
Interaction	13.7391	8	1.7174	44.801	1.4E-14	2.26616
Within	1.15	30	0.0383			
Total	182.561	44				

3.5 %, 4 %, and 4.5 % by weight of cement content and prepared nine molds for each SR percent and were tested similarly. The results of the average of three molds and UCS values are shown in Fig. 7. From Fig. 7, CTB with SR 3.5 % is the highest value within the range of 4.5 to 7 MPa. So, 3.5 % SR content by weight of cement content is the optimum SR content. Further, for 50RAP and 70RAP, using optimum cement content of 4.0 % and optimum stabilizer content of 3.5 % SR content by weight of cement content, CTB molds were cast and tested instead of natural aggregate.Fig. 8..

Table 4 summarizes the results of the two-way ANOVA for obtained UCS (cement with SR). It can be seen that addition of stabilizer with cement also affects the UCS values. Unlike the results shown in Table 3,

Table 5
Average UCS results of CTB mixes with RAP.

Percentage Rap		UCS value (MPa)		
		3 Days	7 Days	28 Days
70 % RAP	**Mean**	4.073	4.887	4.957
	Standard deviation	0.121	0.174	0.173
50 % RAP	**Mean**	4.533	5.01	5.56
	Standard deviation	0.178	0.123	0.144

the significance was found to be prominent for curing days as compared to cement with stabilizer. Similar trends (as shown in Fig. 6) was obtained, indicating higher the curing and stabilizer content, higher will be the UCS value.

Table 5 provides the experimental data on RAP with stabilizer and cement. It is concluded from UCS results that CTB mixes strength kept increasing with time. This is due to the continuous hydration of cement, stabilizer, and water. However, comparing the above results of 50RAP and 70RAP with that of 100NA, these UCS values were very less because these are RAP aggregates but are well within the specified limits [1].

4.4. Flexural strength

For carrying out fatigue damage analysis, flexural strength (or modulus of rupture M_{rup}) of the CTB mix is of prime consideration. Flexural strength is calculated as 20 % of the 28-day UCS value of the CTB specimen, which is limited to a maximum of 1.4 MPa [1]. However, in the current study, efforts were made to calculate the flexural strength of the casted beam to cross-check the values specified in the specifications. Fig. 9 displays the flexural strength of the CTB mixes using 100 % NA. Based on the twenty-eight days of moist curing of the beam, flexural strength value was reported, and 4 % cement was decided as the optimum cement content, limited to a maximum of 1.4 MPa. Here, for natural aggregate mix (0 % RAP), the flexural strength tends to increase

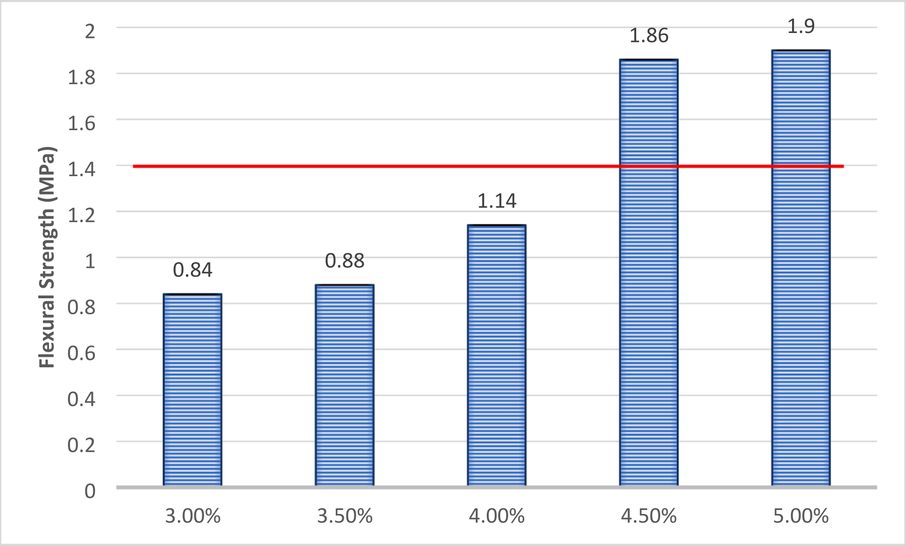


Fig. 9. Flexural strength value (MPa) using cement and 100NA.

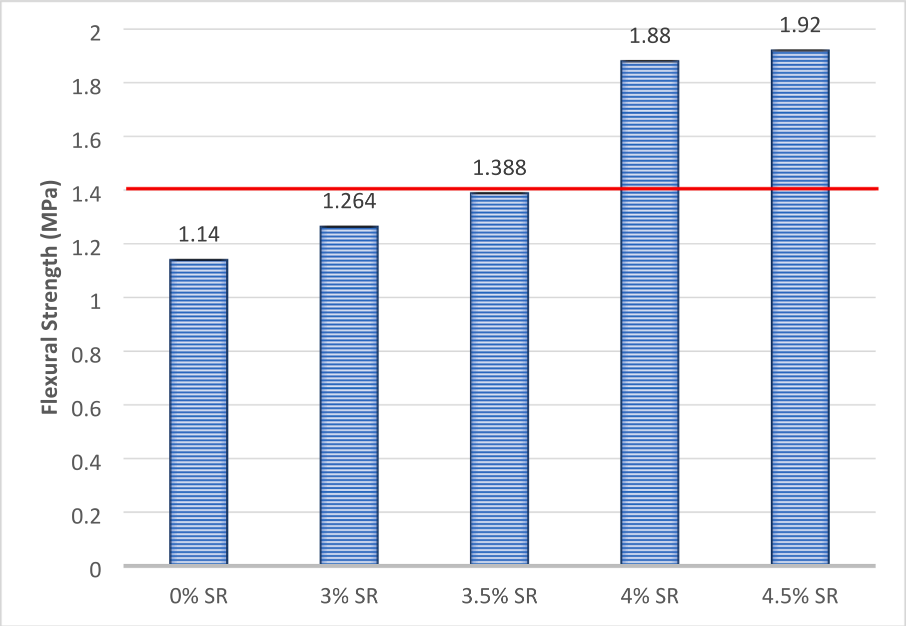


Fig. 10. Flexural strength (MPa) using stabilizer with cement for 100NA.

Table 6
Durability against wetting and drying.

DESCRIPTION	NA		50RAP	70RAP
	Loss %	Loss %	Loss %	Loss %
	(4 % Cement)	(4 % Cement + 3.5 % Stabilizer)	(4 % Cement + 3.5 % Stabilizer)	(4 % Cement + 3.5 % Stabilizer)
Durability Test ASTM D559	12 Cycles of 48 h each			
Weight Loss after Durability test (14 % Permissible	2.31	1.97	1.79	1.69
Residual UCS after Durability Test	5.5 MPa	5.8 MPa	5.4 MPa	4.9 MPa

on increasing the cement content. Similar patterns were seen in the literature on the stiffness and strength of CTB mixes [3,25,30,45]. However, flexural strength for the CTB mixes can be taken up to 20 % percent of the 28-days UCS value (MPa) as per the Indian specifications [46].

As shown in Fig. 10 above, a 3.5 % stabilizer with an optimum cement content of 4 % gave the maximum flexural strength per the specification [3,30]. However, for 50RAP and 70RAP, the values of M_{rup} were calculated and reported as 1.15 MPa and 0.84 MPa, respectively. Hence, the value of M_{rup} keeps decreasing while increasing the RAP percentage. This could possibly be explained by the bitumen coating around the RAP particles, which decreased the friction between the aggregates and could affect the interfacial transition zone (zone between the aggregate particle and cement paste) [6,30,45,47].

4.5. *Durability characteristics*

4.5.1. *Durability test*

The durability test is commonly known as durability under wetting and drying. It is considered one of the best test methods, as it shows the resistance of the cylindrical specimen against wetting drying. A durability test is recommended as it simulates the wetting-drying condition, which simulates the field condition [19,48,49]. Durability against wetting and drying tests was determined per ASTM D559 [50]. Samples were cast on optimum cement content only and were tested for 12 cycles. Each cycle is 48 h, out of which the samples were immersed underwater for 42 h and then taken out, weight was noted each time, and vertical strokes with the help of a wired brush were given to each sample. After this, the samples were kept in a controlled oven at a temperature of 40 °C for the next five hours. This constitutes one complete cycle. The weight loss after 12 such cycles is reported below in Table 6.

The above Table gives insight into the durability test results; weight loss in NA is more compared to the RAP aggregates. However, the values are significantly low as the maximum permissible loss percentage is 14 % after 12 cycles [50]. Despite inferior mechanical properties of RAP inclusive mixtures, lower weight loss was observed. The more weight loss in NA compared to those of RAP specimens might be due to the addition of silica base stabilizer which holds the particle firmly [6,25,47]. After durability cycles, samples were tested for residual UCS values to ensure the performance of the samples even after twelve durability test cycles. As expected, the residual UCS of NA was higher than that of the RAP samples.

4.5.2. *Sorptivity*

The capacity of water or other liquids to permeate the microstructure of concrete under various environmental conditions throughout its service life is a crucial factor in the long-term durability of concrete [51,52]. The term “sorptivity” describes a porous material’s capacity to absorb and carry water by capillary action [31]. Therefore, the idea of measuring durability through sorptivity is attempted in the present study, and results are presented for different RAP contents. After 56 days of moist curing, the sorptivity (i.e., rate of water absorption) of a 100 mm diameter disc with a 50 mm height and epoxy paint on the periphery but not the upper and lower borders was examined in accordance with ASTM C1585 [31]. The stabilised specimens were put in a pan with tiny rubber circular ring supports at the bottom. The water level was maintained 1 to 3 mm above the top of the support device. Tables 5 and 6 display the regression equations (Eqs. 1–8) and associated correlation coefficients (R) for the examined stabilised pavement mixtures with various RAP levels at the primary and secondary stages of water absorption. According to the slope values of the best-fit linear regression equations (Tables 7 and 8), the control mixture absorbed water at the fastest rate.

Table 7
Regression equations for determining absorption (I) as a function of time at the initial stage ($\text{sec}^{0.5}$).

Mix identity	Equation	Correlation coefficient (R)	Slope (S)
C4NA	$I = 0.0206(\text{sec}^{0.5}) + 0.1769$ (3)	0.8771	0.0206
C4NASR	$I = 0.0287(\text{sec}^{0.5}) + 0.0941$ (2)	0.9821	0.0287
50RAP	$I = 0.0264(\text{sec}^{0.5}) + 0.1776$ (1)	0.9779	0.0264
70RAP	$I = 0.0192(\text{sec}^{0.5}) + 0.0863$ (4)	0.9071	0.0192

Table 8
Regression equations for determining absorption (I) as a function of time at the secondary stage ($\text{sec}^{0.5}$).

Mix identity	Equation	Correlation coefficient (R)	Slope (S)
C4NA	$I = 0.0007(\text{sec}^{0.5}) + 4.075$ (7)	0.9318	0.0007
C4NASR	$I = 0.0003(\text{sec}^{0.5}) + 3.9793$ (6)	0.9317	0.0003
50RAP	$I = 0.0037(\text{sec}^{0.5}) + 29.91$ (5)	0.9714	0.0037
70RAP	$I = 0.0006(\text{sec}^{0.5}) + 3.6547$ (8)	0.9604	0.0006

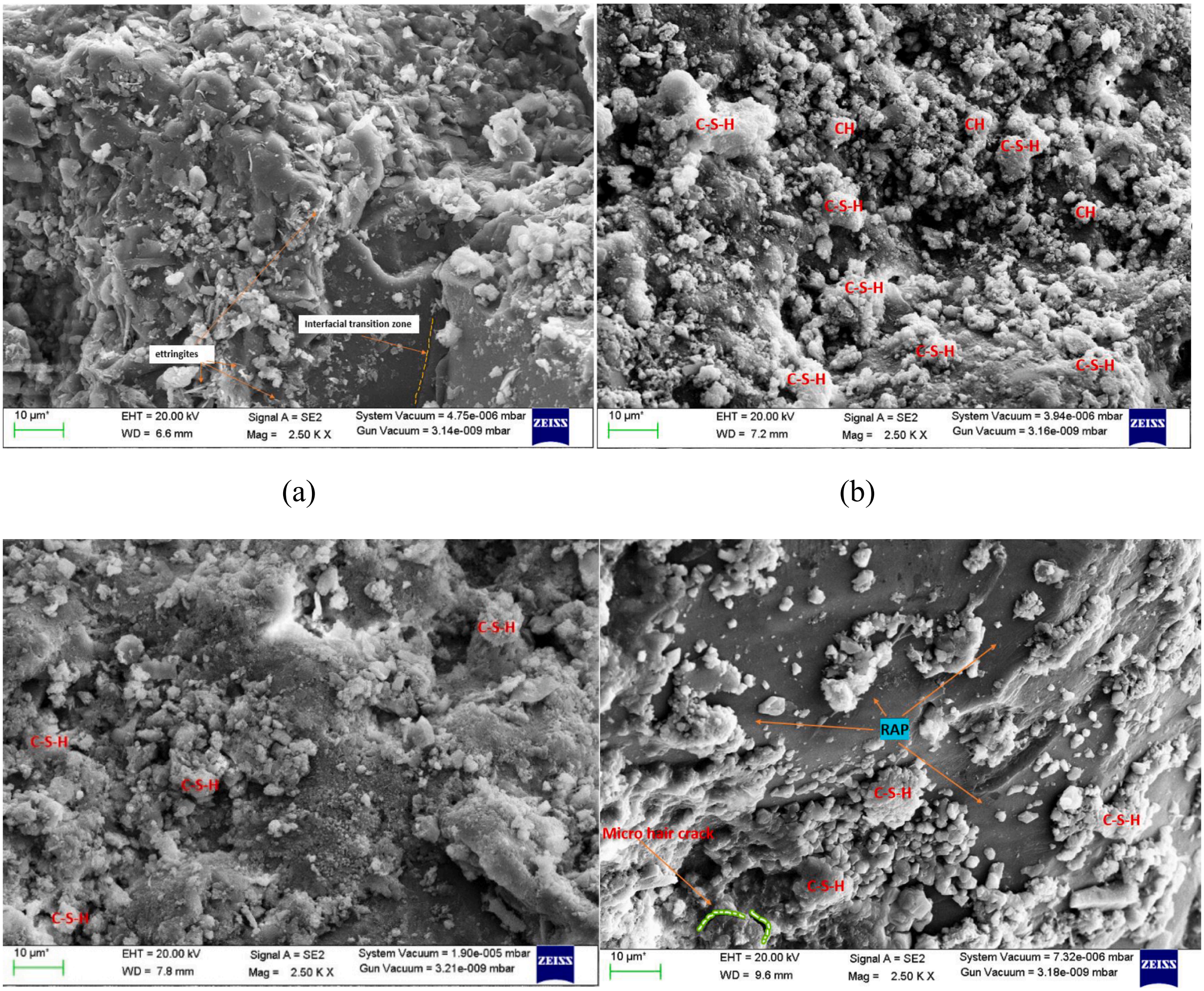
The reduction was incremental with increasing stabilizer and RAP - content in the mixture. This reduction could be attributed to the filler effect of fine silica-based stabiliser particles filling the micro- and macro-pores seen in bulk cement mortar paste and at the interfaces between aggregate and cement paste (ITZ). Abraham and Ransinchung [53] observed similar results for concrete regarding the influence of RAP on the sorptivity, findings of which showed that due to the presence of substructures exposed to moisture, sorptivity becomes a more accurate attribute to explain the endurance of compacted materials.

4.5.3. *Rapid chloride penetration test (RCPT)*

This test used the Prooveit software together with an RCPT device. The specimens were exposed to an electric current for six hours in this test. The specimen’s ends were separated by a potential difference of 60 V direct current (DC), with one end submerged in a solution of sodium

Table 9
RCPT results for different stabilized mixes.

Mix identity	Voltage used	Testing time (hour)	Charge passed (Coulombs)	Chloride ion permeability class
NA	60	6	5154	High
NA + SR	60	6	4953	High
50RAP	60	6	4831	High
70RAP	60	6	3056	Moderate



(a) (b)

(c) (d)

Fig. 11. Sem images of stabilized mixes at 28 days (*C—S—H* calcium silicate hydrate, *ITZ* interfacial transition zone, *RAP* reclaimed asphalt pavement): (a) 100NA mix, (b) 100NA + cement additive mix, (c) 50 RAP mix, (d) 70 RAP mix.

chloride that was 3.0 percent (by mass) and the other in a solution of sodium hydroxide that was 0.3 N. The RCPT results of the CTB mix containing different replacement levels of RAP and stabilizer at the age of 90 days and are shown in Table 9. The test findings reveal that the mix with 70 RAP had the lowest value of charge that passed. The 70RAP and stabilizer-based CTB mixes showed much higher penetration resistance and a more significant decrease in the amount of charge passed relative to the control 100NA CTB mix. The higher the quantities of the RAP and silica-based stabilizer, the more substantial the decrease in the amount of charge discharged for zero, 50, and 70 % replacement of RAP levels, respectively. The charge passed at 90 days of the mix with stabilizer and RAP for 100NA, 50 and 70 % were 4953, 4831 & 3056 respectively. The depletion of calcium ions in the gel pore fluids, the resulting drop in pH, and the development of constricted discontinuous and tortuous pore structure could all be contributing factors to the reduction in the amount of charge transmitted. Because of the pozzolanic reactions and micro filling effects of the silica-based stabiliser, the pore structure became substantially more refined, which reduced the chance that the ions would travel along the least-resistive path. Similar observations were found from the SEM image: due to the addition of a stabilizer, additional C—S—H gel formed, and pore structure was refined. However, RAP has variable pore solution properties, and stabilizer-based CTB mixtures are distinct from conventional CTB mixes. Since the only mechanism by which ions diffuse through the control mix is electrolytic conduction, the amount of current flowing under the influence of voltage directly affects the properties of the pore solution [27].

The conductivity or flow of ions in the 70 RAP mixtures is decreased by the addition of RAP and stabiliser. In general, the 70 RAP and stabilizer based 100NA CTB mixes showed lower chloride ion penetrability than the control 100NA CTB mixes without a stabilizer. It may be because the ability of constituent materials to bind to chloride ions determines how deeply they can penetrate [54–56]. Additionally, as seen in Table 9, an increase in compressive strength results in a reduction in the overall charge. At higher strengths, the RAP and stabilizer-based CTB mixes showed lower diffusivity values compared to lower strength CTB mixes as stabilizer acted as a filler and also densified ITZ by making more C—S—H gel. As a result, the RCPT results have shown how the RAP and stabilizer-based CTB mixes have higher durability characteristics. Table 9 details the impact of RAP and stabiliser on the chloride penetrability of CTB mixes as well as the variation in chloride penetrability with respect to the various RAP and stabiliser percentages.

4.6. SEM investigation

In order to assess pores and hydration products, SEM pictures were taken. Fig. 15 depicts scanning electron microscope (SEM) pictures of CTB mixes with various amounts of RAP (0 %, 50 %, and 70 %) and with and without stabilizer (4 %), as confirmed by SEM pictures. Fig. 11(a) shows that no additional C—S—H gel was formed in the 100NA mix, whereas in the mix of 100NA with cement stabilizer (Fig. 11b), additional C—S—H gel was formed progressively densified the mix. Whereas, Fig. 11(d) clearly shows how asphalt coating prevents the development of a bond between the aggregate surface and the cementitious matrix. Therefore, we can conclude, in comparison to 0 % stabilizer CTB mixes, adding stabilizer to CTB mixes increases compressive strength and densifies the microstructure, lowering cement requirement and improving strength characteristics. Additionally, in Fig. 11(a), the cement-treated stabilized mix (100NA) shows a large number of voids and needle-shaped structures (Ettringites), which are believed to lower the strength of the mix [25,52]. Further, the pozzolanic compounds developed by the mixture of cement and stabilizer were validated by SEM.

5. Conclusion

In the present study, higher percentage (0 %/50 %/70 %) of RAP material by using stabilizer with cement for the construction of CTB mix is assessed. The suitability of RAP material in place of natural aggregates was explored in terms of strength, performance, and durability characteristics. The following conclusions can be drawn from the present study:

- The inclusion of RAP aggregates for CTB results in increased OMC, which might be due to dust particles, pores in RAP material, and the angular surface of RAP. In contrast, including RAP results in decreased MDD value due to the RAP material present.
- Initially, mixes prepared with 3.0 % and 3.5 % cement could not produce the desired minimum UCS value of 4.5 MPa. However, adding a stabilizer improved the strength characteristics significantly, and the minimum said UCS value was achieved starting from 3.5 % cement content at three days of moist curing only.
- 7-day UCS tends to increase in almost all cases; however, the optimum percentage has to be selected based on the mix's combined UCS and flexural strength. Therefore, based on UCS and M_{rup}, 4 % cement with 3.5 % stabilizer was the optimum content for all the mixes.
- Durability against wetting and drying is considered the most critical parameter as it simulates the field condition. The mixture performed well against the durability test and even withstood 12 cycles of wetting and drying and gave acceptable results in terms of residual UCS strength. No shrinkage cracking was observed after twelve cycles of durability test.
- From SEM analysis, it is clear that additional C—S—H gel formation is in a continuous phase in 70RAP, so ITZ is densified, further increasing the hardened strength of concrete and improved durability.

Overall, stabilizing the aggregate using cementitious materials for replacing the base layer could be an eco-friendly practice in most countries to save natural resources. Also, it can be an excellent alternative material for marginal material and the best-suited method. CTB mixes containing high RAP can be an economical solution using stabilizer with cement and save large requirement of N.A.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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