Evaluating the Mechanical Performance of Cold Mix Reclaimed Asphalt Pavement Incorporating Crumb Rubber

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ABSTRACT: Cold mix asphalt (CMA), produced at ambient temperature, is less energy-intensive, cleaner and safer than hot mix asphalt, making it well-suited to rural low-volume roads. Durability is nevertheless limited by incomplete binder coating, high air voids and residual moisture, which promote moisture damage and rutting, while surface-treated crumb rubber has yet to be combined with cold-mix reclaimed asphalt pavement (RAP). This study therefore evaluated cold mix RAP incorporating NaOH-treated crumb rubber. Materials were characterised by physical, XRF, XRD and binder-recovery tests, and crumb rubber (2.00-0.075 mm) was NaOH-treated at 70 °C for 2 h, then oven-dried at 60 °C for 24 h. Three dense-graded mixes within the TRRL envelope were designed: virgin aggregate, 50:50 RAP, and RAP with rubber replacing the 0/6 mm fines at 0.5-3.0%. Initial emulsion and premix water contents followed the MS-14 formula and coating tests, while optimum contents came from second-order polynomial regression of dry density, indirect tensile strength (ITS) and air voids. Marshall specimens (50 blows, cured at 40 ± 1 °C for 72 h) were tested for dry and soaked ITS to determine the tensile strength ratio (TSR) and for rutting using the Hamburg wheel tracking test (50 °C, 705 N, 10,000 passes), and the results were compared using a t-test (? = 0.05). The RAP mix required 8.2% fluid and 6.2% emulsion, compared with 11.0% and 8.9% for the virgin mix, a 30% saving, with air voids of 9.6% versus 11.5% and TSR of 0.83 versus 0.86. At the optimum 1.8% rubber, air voids fell to 8.0%, TSR rose to 1.15 and mean rut depth fell from 2.74 ± 0.43 to 2.12 ± 0.22 mm, a significant 22.63% improvement (p = 0.043). Treated crumb rubber therefore mitigates both moisture damage and rutting, and 1.8% is recommended for cold mix RAP surfacing of low-volume rural roads carrying up to one million equivalent standard axles.

KEYWORDS: Crumb rubber, Reclaimed asphalt pavement, Rutting, Moisture susceptibility, Indirect tensile strength, Cold mix asphalt.

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I. INTRODUCTION

Cold mix asphalt (CMA) is a bituminous mix design that entails blending of unheated aggregate with bitumen emulsion at ambient temperature (Jain and Singh, 2021). CMA is widely used for light to medium traffic loads due to its ability to gain full structural strength post-compaction (Addae et al., 2023; Jain & Singh, 2021). Strength is achieved during curing of the mix when water in the bitumen emulsion evaporates, allowing the binder to break and form a strong bond between aggregate particles (Ling, Hanz and Bahia, 2016). The cold mix design method eliminates the heating of aggregate and binder to 150-180°C required for hot mix asphalt (Vaitkus *et al.*, 2016), thereby reducing carbon emissions (Dash, Chandrappa and Sahoo, 2022). For cost effectiveness, reclaimed asphalt pavement (RAP) is incorporated into CMA to produce cold-mix RAP (MS-2, 2014). The use of cold-mix RAP reduces the consumption of virgin aggregates thereby promoting de-carbonization and at the same time reducing the depletion of natural resources (Zaumanis, Mallick and Frank, 2014; Antunes, Freire and Neves, 2019). According to Mallick et al. (2008), when 20-50% of RAP is used in pavement construction, an estimated saving cost of 13-34% is achieved.
While various countries have established their own national standards for cold mix, a universal design procedure, comparable to those for hot mix asphalt, has yet to be developed (Mathaniya, 2006). The Asphalt institute, Chevron Inc., and others have developed notable design procedures with standards for field application (Tia and Wood, 1983). In this study, Asphalt Institute and the Transport and Road Research Laboratory (TRRL) have developed design procedures for cold mix, which are utilised to determine appropriate aggregate

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gradation, pre-mix water content, and optimum emulsion content (MS-14, 1989; Poranic, 2009).

Due to the significant environmental pollution and landfilling caused by crumb rubber waste, there is a critical need to repurpose this material for construction applications (Tushar *et al.*, 2022). While several studies have examined moisture susceptibility and rutting resistance of hot mix RAP – crumb rubber blends, Shams *et al.*, (2025); Xu *et al.*, (2025) and Wulandari *et al.*, (2019) investigated crumb rubber as fine aggregate replacement in cold mix without RAP and cold mix RAP has been studied independently (Poranic, 2009; Chelelgo, Gariy and Shitote, 2018). The combined use of cold mix RAP, incorporating surface-treated crumb rubber has not been reported. CMA exhibits greater susceptibility to moisture damage and rutting compared to hot mix asphalt (Rezaei *et al.*, 2017; Asiya *et al.*, 2024). This relative weakness arises from incomplete binder coating of aggregates at ambient mixing temperatures, higher residual air void content, and retained moisture from the emulsion water phase that can persist within the mix during early curing stages. Modified asphalt mixtures incorporating crumb rubber demonstrate improved fatigue life, elasticity and resistance to permanent deformation (Yu *et al.*, 2020; Wang *et al.*, 2022).

Despite this progress, no study has combined NaOH-treated crumb rubber with cold mix RAP. This gap matters because findings from hot mix crumb rubber–RAP studies (Shams *et al.*, 2025; Xu *et al.*, 2025) cannot be transferred to cold mix systems, where binder coating is incomplete, air voids are higher (8–15% vs. 3–8% for hot mix asphalt (HMA), and residual emulsion moisture persists during curing. This study addresses this gap through four contributions: (i) the first investigation of NaOH-treated crumb rubber as fine aggregate replacement in cold mix asphalt containing 50% RAP; (ii) XRD characterisation linking NaOH-induced mineralogical changes, partial desulphurisation and emergence of polar phases (Albite, Dashkovaite) to improved emulsion compatibility; (iii) identification of the mechanisms producing TSR values exceeding unity in the modified mix; and (iv) first-time characterisation of Kenyan-sourced RAP and crumb rubber, providing baseline data for tropical low-volume road design. The study evaluates the mechanical performance of cold mix reclaimed asphalt pavement incorporating crumb rubber to determine the optimum emulsion and total fluid contents for virgin and RAP cold mixes, effect of crumb rubber on moisture susceptibility, and rutting resistance using the Hamburg wheel tracking test

II. THEORETICAL BACKGROUND

A. Cold Mix Emulsion Mechanics

In cold mix asphalt, a cationic bitumen emulsion is mixed with unheated aggregate at ambient temperature. The emulsion consists of bitumen droplets (typically 1-10 μm diameter) dispersed in water and stabilised by a cationic surfactant (Salomon., 2006; Al-Mohammedawi and Mollenhauer, 2022). When the emulsion contacts the aggregate surface, the positively charged bitumen droplets are electrostatically attracted to the negatively charged siliceous aggregate surfaces (Pstrowska *et al.*, 2022; Langevin, 2009). This charge-mediated deposition initiates emulsion breaking, during which water migrates to the surface and evaporates, allowing the bitumen droplets to coalesce and form a continuous binder film coating the aggregate particles (Read and Whiteoak, 2003; Al-Mohammedawi and Mollenhauer, 2022). The rate of emulsion breaking is governed by the aggregate surface charge density, emulsion pH, ambient temperature, and the specific surface area of the aggregate gradation (Rodríguez-Valverde *et al.*, 2003). In slow-setting emulsions (CSS type), as used in this study, the breaking process occurs over hours to days, permitting adequate mixing and compaction time at ambient temperature.

B. Experimental Methodology

An experimental laboratory approach was adopted. Virgin aggregate, RAP, crumb rubber, cationic slow-setting bitumen emulsion, and hydrated lime were first characterised through standard physical, chemical (XRF/XRD), and binder recovery tests. Three dense-graded cold mixes were then designed: a virgin aggregate mix, a 50:50 RAP mix, and a crumb rubber-modified RAP (CR-RAP) mix incorporating NaOH-treated rubber as a partial replacement of the 0/6 mm fine fraction at 0.5–3.0% by mass. Aggregate gradation was proportioned to the TRRL envelope, and optimum total fluid and bitumen emulsion contents were established from dry density, indirect tensile strength (ITS), and air void data. Marshall specimens compacted at 50 blows per face and cured at 40 ± 1°C for 72 hours were tested for dry and soaked ITS (EN 12697-23) to obtain the tensile strength ratio, while rutting resistance was assessed using the Hamburg wheel tracking test (EN 12697-22). The overall research methodology is presented in Figure 1.

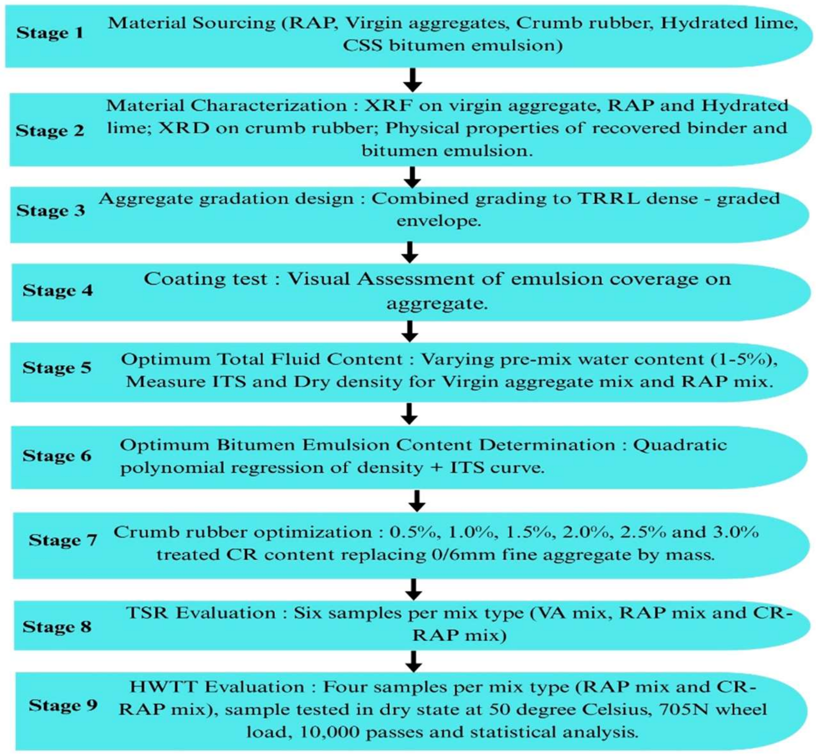

Figure 1 Overall Research Methodology

C. Data Analysis

The experimental data were analysed using Microsoft Excel. Optimum contents for total fluid, bitumen emulsion, and crumb rubber were determined by fitting second-order polynomial regression curves to the measured dry density, ITS, and air void data. The regression model takes the general form:

$$y = ax^2 + bx + c \quad (1)$$

Where y is the response variable, x is the independent variable (fluid content, emulsion content, or crumb rubber content), and a, b, and c are regression coefficients. For concave downward curves ($a < 0$), the optimum x corresponding to the peak response is obtained by setting the first derivative to zero:

$$X(opt) = -\frac{b}{2a} \quad (2)$$

The coefficient of determination (R^2) is reported for each curve. Statistical comparison between mix types was performed using the independent samples t-test:

$$t = \frac{\bar{x}_1 + \bar{x}_2}{\sqrt{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}} \quad (3)$$

Where, $\bar{x}_1$ and $\bar{x}_2$ are the sample means, s_1^2 and s_2^2 are the sample variances, and n_1 and n_2 are the sample sizes. The degrees of freedom were computed as $df = n_1 + n_2 - 2$. A significance level of $\alpha = 0.05$ was adopted; the null hypothesis of equal means was rejected when $p < 0.05$. All results are reported as mean ± standard deviation from triplicate specimens for ITS and quadruplicate specimens for HWTT.

III. MATERIALS AND EQUIPMENT

A. Materials

The study utilises crumb rubber obtained from Kirinyaga County, which was further processed in the laboratory to yield size of 0/2 mm. Reclaimed asphalt used in the study was sourced from the James Gichuru Junction–Rironi Highway (A8) rehabilitation. It was then processed to a size of 0/20 mm. To ensure aggregate compatibility, high stability, and slow breaking, a cationic slow-setting bitumen emulsion, sourced from BPL Quality Bitumen Ltd, was utilized as the binder. Virgin single-size aggregates (0/6 mm, 6/10 mm, 10/14 mm, and 14/20 mm) were sourced from H-Young Quarries Ltd. in Machakos County, Kenya. Previous research indicates that cold mix typically suffers from prolonged curing times and low early strength (Chu *et al.*, 2025). To address these limitations, hydrated lime [$Ca(OH)_2$] was used as an additive to accelerate strength development and resistance of the mix to stripping. This study utilises these materials to develop a cold mix design incorporating reclaimed asphalt pavement (RAP) and crumb rubber.

B. Material Characterisation

1. Aggregates

Virgin aggregate and reclaimed asphalt pavement aggregate were subjected to pre-qualification tests to assess their viability for use. Bulk density, Los Angeles abrasion value, aggregate impact value and water absorption properties of these materials were determined in accordance with AASHTO T85, ASTM C535, BS 812-112, and ASTM C127, respectively. The aggregate impact value and Los Angeles abrasion value for the virgin aggregate were 14.53% and 17.68%, respectively; the physical properties are presented in Table 1. To determine the mineralogy of the virgin aggregate and RAP, samples were pulverised into a fine powder using a HERZOG mill. The resulting powder was analysed using a Bruker S1 TITAN X-ray fluorescence (XRF) analyser, which revealed SiO_2 contents of 67.08% for the virgin aggregate and 50.04% for the RAP. These findings confirmed that the parent rock for the virgin aggregate is felsic (likely granite), while the intermediate composition of the RAP aggregate, with its net negative surface charge, ensures compatibility with the cationic bitumen emulsion intended for the mix. The X-ray fluorescence (XRF) results for both virgin aggregates and RAP aggregate types are presented in Table *2*.

Table 1 Physical Properties of Virgin Aggregates

Size	**14/20mm**	**10/14mm**	**6/10mm**	**0/6mm**
Bulk specific gravity (kg/m^3)	2524	2520	2477	2420
Water absorption (%)	2.22	2.49	2.90	3.00

Table 2 Chemical Composition of Virgin and Reclaimed Asphalt Aggregates

Chemical composition	**Percent in virgin aggregates (%)**	**Percent in reclaimed asphalt pavement aggregates (%)**
SiO_2	67.079	50.040
Al_2O_3	17.305	16.657
K_2O	7.181	3.070
Fe	5.000	10.887
CaO	1.695	15.220
Ti	0.764	2.332
P_2O_5	0.089	0.663
Mn	0.379	0.212
Cl	0.306	0.351
Other Elements	0.192	0.315

2. Preparation of the crumb rubber

Crumb rubber was prepared in the laboratory by sieving the material through a 2.0 mm sieve and retaining particles on the 0.075 mm sieve. The crumb rubber was divided into two categories: treated and untreated crumb rubber. The treated crumb rubber was produced by immersing crumb rubber in a sodium hydroxide (NaOH) solution, then heating and stirring the mixture for two hours at 70°C. Afterward, the sample was washed through a 0.075 mm sieve and oven-dried at 60°C for 24 hours (Ramarad *et al.*, 2015: Nuzaimah *et al.*, 2020). The alkaline treatment promotes surface oxidation and partial desulphurisation of the rubber surface, removing the non-polar outer layer and generating polar functional groups (hydroxyl, carboxyl) onto the rubber surface, enabling hydrogen bonding and dipole interactions with the bitumen binder and improving chemical adhesion at the rubber–binder interface. The treatment also increases surface roughness, enhancing mechanical interlocking with aggregate. The untreated crumb rubber did not undergo the specific treatment procedure, both treated and untreated samples were analysed via XRD to determine their mineralogical properties.

3. Lime

Hydrated lime was sourced from Legacy Lab Africa Limited in Nairobi, Kenya. A 100 g sample was analysed using a Bruker S1 TITAN XRF analyser at the Ministry of Mining in Nairobi to determine its chemical composition.

4. Residual Bitumen Binder

The residual bitumen binder from the reclaimed asphalt pavement was recovered following the BS EN 12697-3, (2021) standard method. The reclaimed asphalt pavement (RAP) was dissolved in trichloroethylene (manufactured by China Chemical Company), and the binder was extracted using the rotary evaporator method. To ensure the removal of any residual trichloroethylene, the extract underwent fractional distillation to recover the pure binder. The recovered bitumen softening point (ring and ball) and needle penetration were determined following ASTM D36, (2020) and ASTM D5, (2020), respectively. Table 3 shows the properties of the recovered bitumen.

Table 3 Properties of Recovered Bitumen

Property	**Standards**	**Value**
Penetration (d, mm)	ASTM D5	18
Softening point (°C)	ASTM D36	67
Percentage in total mix (%)	BS EN 12697-1	3.6

The recovered RAP binder exhibited a penetration of 18 dmm and softening point of 67°C (Table 3), classifying it as a heavily aged, stiff binder. The fresh emulsion residue showed a penetration of 67 dmm and softening point of 53°C (Table 4). In cold mix applications, full blending between aged and fresh binders does not occur at ambient temperature; instead, the fresh emulsion coats the aggregate surfaces while the aged binder remains largely encapsulated within the RAP particles. Therefore, the stiffness differential contributes positively to the mix by providing a stiffer aggregate matrix (from RAP) while the fresh binder provides flexibility and adhesion at contact points.

5. Bitumen Emulsion

Bitumen emulsion was evaporated in an oven to determine the percentage of bitumen content in the emulsion as per the procedure outlined in ASTM D6934-22 (2022). Thereafter, ASTM D36 (2020) and ASTM D5 (2020) were utilised to determine the softening point and penetration of the residue binder, respectively.

Table summarises the properties of the residue binder obtained.

Table 4 Properties of Bitumen Emulsion

Property	**ASTM designation**	**Value**
Penetration (d, mm)	ASTM D5	67
Softening point (°C)	ASTM D36	53
Percentage Residue	ASTM D6997	67
Particle charge test		+ve

C. Mix Design

In this study, dense graded cold asphalt was prepared purposely for surfacing of lightweight traffic roads or rural roads. Three cold mix types were developed: the virgin mix (virgin aggregate only), the RAP mix (50% virgin aggregate + 50% RAP) and crumb rubber-modified RAP mix (CR-RAP mix), comprising the RAP mix blend with treated crumb rubber partially replacing the fine aggregate (0/6 mm) fraction by mass within the virgin aggregate component. According to the Asphalt Institute Manual (MS-14), the step-by-step procedure for cold mix design involves material quality checks (aggregate, bitumen, crumb rubber, and additives), determining combined aggregate gradation, and establishing optimum levels for pre-mix water, bitumen emulsion, and crumb rubber content.

1. Combined Aggregate Gradation

In developing cold mix emulsion asphalt, virgin aggregate of single size 14/20 mm, 10/14 mm, 6/10 mm and 0/6 mm were used. According to Thanaya, (2007), aggregate size between 0/20 mm is recommended for cold mix surfacing for lightweight roads. The mathematical expression in Equation (4) was used to blend constituent materials to form a mix.

$$P = aA + bB + cC \quad (4)$$

where P is the percentage of combined aggregate passing a particular sieve size, a, b and c are the percentage of individual proportion used for the mix, and A, B and C are the percentage of individual aggregate passing a particular sieve size. The 50% RAP content was selected based on Mallick, Kandhal and Bradbury, (2008) report that 20-50% RAP yields cost savings of 13-34% without compromising mix performance, and preliminary gradation trials confirmed that a 50% blend of RAP (0/20 mm) and 50% virgin aggregate (0/20 mm) conformed to the TRRL dense-graded gradation envelope for cold mix surfacing. Higher RAP contents (≥ 60%) produced gradations with excessive fines that fell outside the TRRL envelope. The plot for actual blend for the virgin aggregate mix and reclaimed asphalt pavement aggregate mix is presented in Figure 2 and falls within the recommended gradation envelop of Transportation and Road Research Laboratories (TRRL).

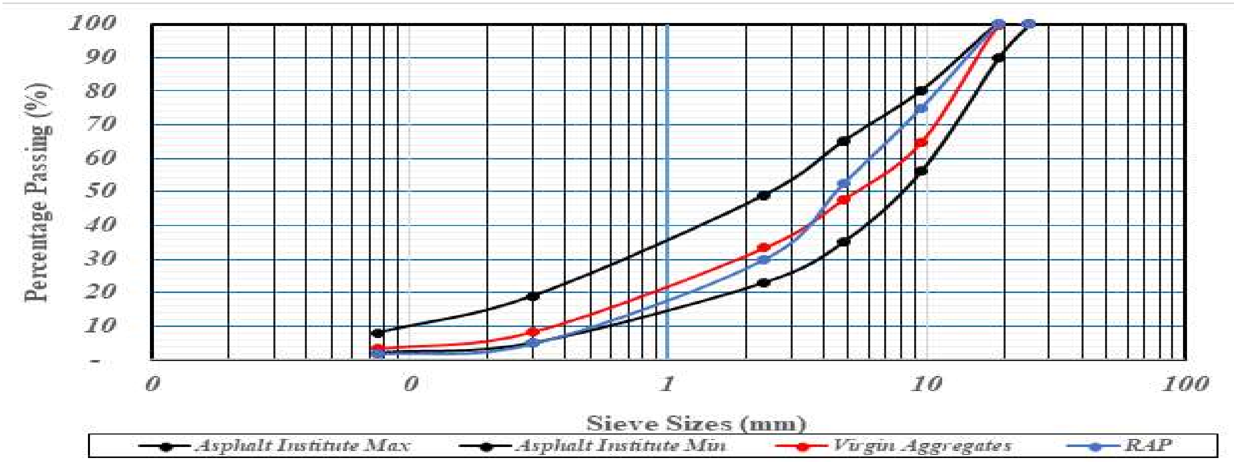

Figure 2 Gradation of Blended Virgin and Reclaimed Asphalt Pavement Aggregates

2. Initial Emulsion Content (IEC)

The amount of emulsion needed for the trial mixes for dense graded asphalt is determined using centrifuge kerosene equivalent test (C.K.E) but because of the absence of the laboratory equipment an approximate empirical formula was used as recommended by Asphalt Institute Manual (MS-14), as presented in Equation (5).

$$P = (0.05A + 0.1B + 0.5C) \times (0.7) \quad (5)$$

Where P_{ea} is the percent by weight of emulsified asphalt, based on weight of dry aggregate, A is the percent of aggregate retained on sieve 2.36 mm, B is the percent of aggregate passing sieve 2.36 mm and retained on sieve 0.075 mm, and C is the percent of aggregate passing sieve 0.075 mm. This study used emulsified asphalt binder, which led to using Equation (6) to determine the initial emulsion content.

$$\text{IEC} = (\frac{P}{X}) \times 100 \quad (6)$$

Where IEC is the initial emulsion content by mass of total mixture, and X is the percentage of bitumen in emulsion. The bitumen emulsion used in this study was cationic slow setting emulsion and contained 67% bitumen and 33% water content. The residual binder content for virgin aggregate and reclaimed asphalt pavement aggregate was determined using Equation (5) which yielded 5.49% and 5.11% binder contents, respectively. The initial emulsion content for virgin aggregate mix was 8% using Equation (6) and 5% for reclaimed asphalt pavement mix when Equations (7) and (6) are used.

$$P_{nb} = P - \frac{(100-r)\, P_{sb}}{100} \quad (7)$$

Where P_{nb} is the amount of additional new binder, P_{sb} is the bitumen content of the reclaimed asphalt, and r is the percentage of virgin aggregate in the mix.

3. Coating Test

The coating test was performed on 10 samples with varying aggregate water content. Two groups, virgin aggregate and RAP, consisted of five samples each. These tests were prepared at a constant IEC, with the premix water content increased in 1% increments for each mix. The test identifies the premix water content needed for effective asphalt coating, as inadequate levels cause the fines to ball together (Darter *et al.*, 1979). In this study, physical observation of the mix showing 90% coating for both the virgin aggregate mix and RAP mix was achieved at 4% premix water content.

4. Optimum Total Fluid Content

The total fluid content (TFC) of a cold asphalt mix is the summation of its emulsion content, premix water content and the moisture content of the aggregate; however, according to recent research, moisture content has no significance effect on determining the total fluid content (Chelelgo, Gariy and Shitote, 2018). The IEC remained constant while varying the pre-wetting water content (PWC) from 1-5% for the virgin aggregate mix and RAP mix making TFC range from 9-13% and 6-10%, respectively. To determine the optimum fluid content, five triplicate samples were prepared for both the virgin aggregate and RAP mixes. The specimens remained in their molds inverted 24 hours before extrusion. After extrusion, the samples were divided into dry and soaked samples. The dry samples were placed in a ventilated oven at 40 ± 1°C for 72 hours to simulate field curing and evaporate residual emulsion water. Soaked samples have identical curing regime to that of dry samples (Oven dry at 40 ± 1°C for 72 hours). After cooling to 25°C, samples were immersed in a water bath at 20 ± 1°C for 24 hours without vacuum saturation. The omission of vacuum saturation follows EN 12697-12 Annex A, which specifies direct water immersion for cold-processed mixtures. Vacuum conditioning can cause premature disintegration of specimens that have not yet achieved full binder coalescence.

Emulsion breaking and curing completeness was verified by monitoring specimen mass loss during the 72-hour oven-drying period. Specimens were weighed at 24-hour intervals. Mass stabilisation was achieved for all specimens by 48 hours, with the final 24 hours showing negligible mass change (mean: 0.03% ± 0.02%). This confirms that residual emulsion water had fully evaporated and binder coalescence was substantially complete prior to testing.

After curing and conditioning, samples were tested for indirect tensile strength using a UNIFRAME50 (Automatic universal 50 kN load frame) following (BS EN 12697-23). Additionally, dry density and air void content were determined, the optimum values from each test were then determined and averaged.

5. Optimum Bitumen Emulsion Content

To optimise the emulsion content, the Optimum Total Liquid Content (OTLC) remained constant while the bitumen emulsion content varied for the virgin aggregate mix and for the RAP mix, both in increments. Six triplicate specimens were prepared for each mix type, demoulded after 24 hours. The curing regime is the same with the previously stated curing regime. Testing for indirect tensile strength (ITS), dry density, water absorption, and air voids was performed on both dry and soaked samples to determine the optimum emulsion content (OEC).

6. Method and Level of Compaction

In this study, 50 blows to each face of the sample were applied on both virgin aggregate mix and RAP mix using marshal compaction machine as recommended by Indian Roads Congress, (2014) for medium compaction level. However, for high-level compaction effort, 75 blows would be required on each face of the sample.

7. Moisture Susceptibility

The moisture susceptibility of an asphalt mix usually occurs when water is present at the aggregate-binder interface, weakening the strength and durability of the bituminous mix. The moisture sensitivity of the bituminous mix was obtained through the TSR test in accordance with EN 12697-23, (2017). Six cylindrical samples and three each were prepared for dry and soaked ITS. Equation 8 was used to determine the tensile strength ratio; the closer the value of soaked ITS in comparison to dry ITS, the better the TSR produce that translate to greater resistance of the asphalt mix to moisture.

$$TSR = \frac{ITS_{Soaked}}{ITS_{Dry}} \quad (8)$$

8. Rutting Resistance

Rutting resistance was evaluated using the Hamburg wheel tracking test (HWTT). The test was conducted to evaluate the resistance of cold mix asphalt (CMA) to deformation under traffic loading. The test was carried out following the general principles stated in EN 12697-22, (2020) as a guide. A Superpave gyratory compactor (SGC) was used to prepare a cylindrical specimen of 150 mm diameter and 60 mm thickness. The test was conducted under dry conditions at 50 ± 1°C using a steel wheel at 705 ± 4.5 N and 52 ± 2 passes/minute for 10,000 passes, which is suitable for evaluating crack propagation and rutting performance of asphalt mix. Dry testing was selected because cold mix specimens at early curing stages are vulnerable to disintegration under combined water immersion and repeated loading, the dry protocol isolates rutting resistance from moisture-induced damage.

IV. RESULTS AND DISCUSSION

A. Crumb rubber

Comparison of Table 5 and Table 6 revealed that NaOH treatment produced measurable mineralogical changes consistent with its intended surface modification effect: elemental sulphur content decreased from 42.1% (monoclinic) to 21.3% (orthorhombic), confirming partial desulphurisation and reduced surface hydrophobicity. The emergence of Albite (17.6%), a sodium-bearing feldspar with a net negative surface charge directly improves electrochemical compatibility between the treated rubber surface and the cationic bitumen emulsion. The appearance of Dashkovaite (23.0%) confirms conversion of surface organic components to more polar, oxidised species, consistent with the introduction of hydroxyl and carboxyl functional groups by alkaline hydrolysis. Collectively, these mineralogical changes provide XRD-level evidence for the surface chemistry improvements that underpin the superior mechanical performance of the treated crumb rubber mix relative to what would be expected from untreated rubber in a cold mix emulsion system. The comprehensive physical properties and chemical properties for both samples derived from the XRD analyzer are summarised in Table 5.

Table 5 Physical and Chemical Properties of Untreated Crumb rubber

Parameter	Formula	Lattice	Percentage composition (%)
Materials type	Shredded waste	-	-
Size (mm)	2.00 - 0.075	-	-
Colour	Black	-	-
Specific gravity	1.06	-	-
Sulphur	S_8	Monoclinic	42.1
Tridymite	SiO_2	Monoclinic	21.6
Ravatite	$C_{14}H_{10}$	Monoclinic	20.0
Spinel	Al, Cr, Mg, Zn	Cubic	12.9
Zincite	ZnO	Hexagonal	3.40

Table 6 Physical and Chemical Properties of Treated Crumb rubber

Parameter	Details	Lattice	Percentage composition (%)
Materials type	Shredded waste		
Size (mm)	2.00 - 0.075		
Colour	Black		
Specific gravity	1.11		
Dashkovaite	$C_2H_4MgO_6$	Monoclinic	23.0
Iseite	$Fe_{0.193}Mn_{1.787}Mo_{3.01}O_8$	Hexagonal	21.6
Sulfur	S_20	Orthorhombic	21.3
Albite	$AlCa_{0.01}K0.01Na_{1.01}O_8Si_{2.98}$	Triclinic	17.6
Carbon	C	Hexagonal	7.5
Babefphite	$BaBeFO_4P$	Triclinic	5.2
Cristobalite	SiO_2	Tetragonal	3.1
Zirconium	Zr	Hexagonal	0.4

B. Hydrated Lime

The XRF results in Table 7 show that the hydrated lime is predominantly calcium-based, with CaO accounting for 97.765% of the composition. Minor constituents comprised Al_2O_3 (1.062%), P_2O_5 (0.976%), Fe (0.097%) and other trace elements (0.100%), giving a total impurity content below 2.3%. This confirms a high-purity lime suitable for use as a mix additive, since XRF reports calcium in oxide form, the CaO value reflects the $Ca(OH)_2$ content of the sample.

Table 7 Chemical Composition of Hydrated Lime

Chemical composition	Percentage concentration (%)
CaO	97.765
Al_2O_3	1.062
Fe	0.097
P_2O_5	0.976
Others	0.100

C. Optimum Total Fluid content

The optimum total fluid content was determined by jointly considering the dry density and indirect tensile strength of both the virgin aggregate mix and RAP mix as shown in Figure *3* and Figure 4, respectively. Upon increasing the total fluid content (TFC), the curves for dry density and indirect tensile strength increased until reaching a peak and then declined. Peak values were determined by fitting second-order polynomial (quadratic) regression curves to the experimental data.

The peak values for the virgin aggregate mix as depicted in Figure 3 and Figure 4 were estimated at 11.3% total fluid content for dry density of 2054 ± 14 kg/m^3, 11% total fluid content for dry ITS (235 ± 18 kPa), and 10.6% total fluid content for soaked ITS (170 ± 23 kPa). Similarly, for the reclaimed asphalt pavement mix, the peak values were recorded at 7.9% total fluid content for dry density (2050 ± 18 kg/m^3), 8.4% total fluid content for dry ITS (245 ± 27 kPa), and 8.2% total fluid content for soaked ITS (200 ± 28 kPa). To account for all conditions, the total fluid content was averaged to obtain the optimum total fluid content of 11.0% by mass of dry aggregate for the virgin aggregate mix and 8.2% by mass of dry aggregate for the RAP mix. To validate this observation, standard deviation and coefficient of variability is conducted. ITS was recorded to be higher in the RAP mix compared to the virgin aggregate mix. The aged binder coated on RAP particles (penetration 18 dmm, softening point 67°C) provides a stiff mastic layer that does not fully re-mobilise at ambient mixing temperatures, creating composite particles with inherently higher stiffness than uncoated virgin aggregates. The RAP gradation contains a higher proportion of fines (material passing 0.075 mm) generated during milling, which fills inter-particle voids and produces a denser packing arrangement (9.6% vs. 11.6% air voids). Lastly, the residual binder in RAP (3.6% by mass) effectively pre-coats the aggregate surfaces, reducing the fresh emulsion demand and allowing a greater proportion of the applied emulsion to function as bonding binder rather than being absorbed into uncoated aggregate pores.

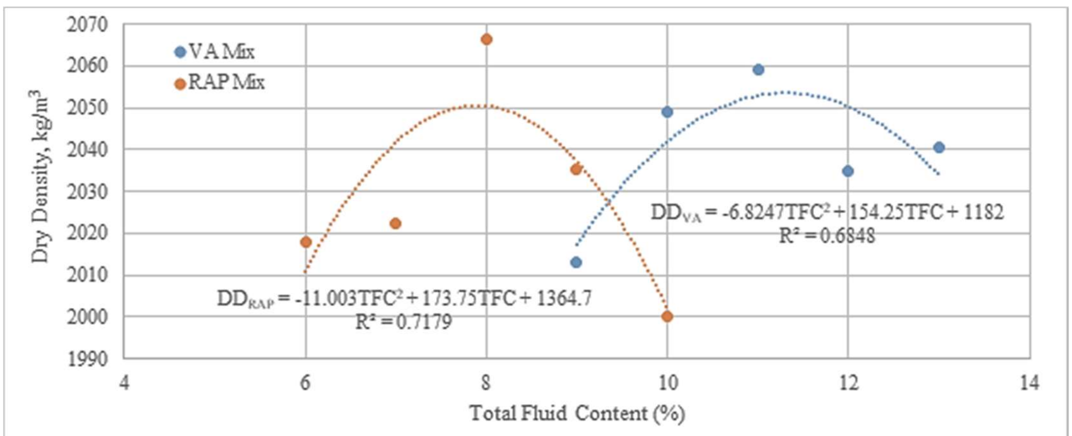

Figure 3 Dry Density for Virgin Aggregates (VA) and RAP Aggregates Mix at Total Fluid Content

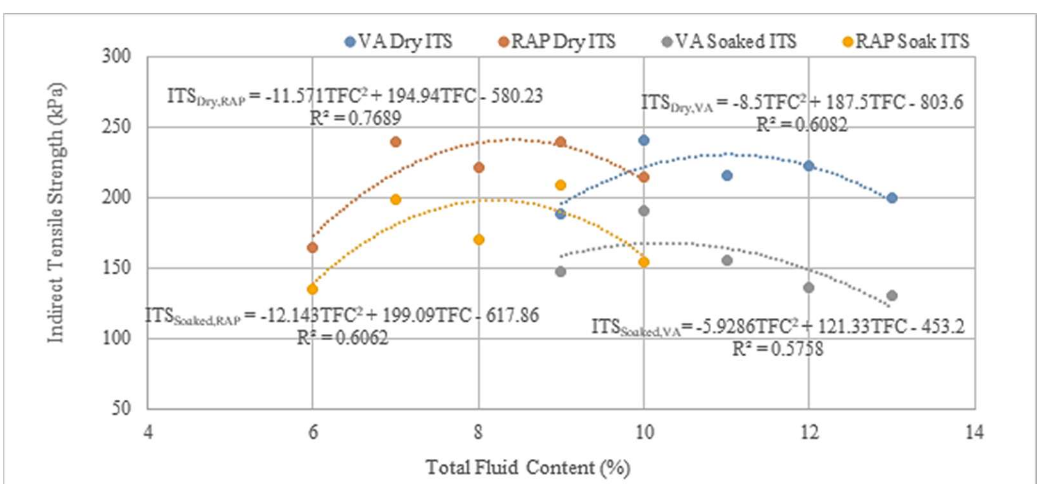

Figure 4 Indirect Tensile Strength for Virgin Aggregate Mix and RAP Mix at Total Fluid Content

D. Optimum Bitumen Emulsion Content

Figure 5 and Figure 6 illustrate the peak values for the virgin aggregate mix. The maximum values were recorded at 9% bitumen emulsion for dry density (2015 ± 5 kg/m³), 9.2% for dry ITS (310 ± 21 kPa), and 8.4% for soaked ITS (260 ± 11 kPa), resulting in an average Optimum Bitumen Emulsion Content (OBEC) of 8.9% by dry mass of aggregates. Similarly, for the RAP mix, peak values were observed at 5.9% for dry density (2045 ± 8 kg/m³), 6.5% for dry ITS (315 ± 14 kPa), and 6.1% for soaked ITS (260 ± 21 kPa), yielding an average OBEC of 6.2% by dry mass of aggregates. The results show 30% less use of emulsion in the reclaimed asphalt pavement mix compared to the virgin aggregate mix, which translates to saving in cost and reduced petroleum consumption per tonnes of mix. The lower emulsion demand of the RAP mix is consistent with findings by Chelelgo, Gariy and Shitote, (2018), who reported 25-35% emulsion savings when incorporating 40-60% RAP in cold mix designs. The higher density and strength in the RAP mix suggest superior performance attributable to the combined effects of residual binder stiffness and improved aggregate packing, as discussed in Section IV.A.

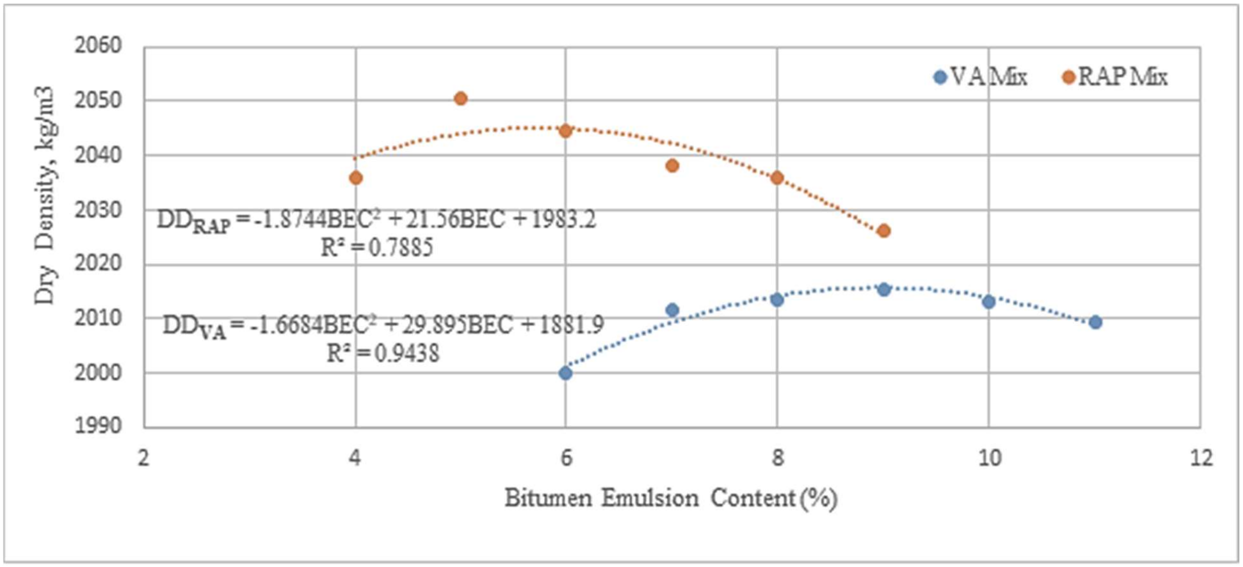

Figure 5 Dry Density for Virgin Aggregates and RAP Aggregates Mixes at Bitumen Emulsion Content

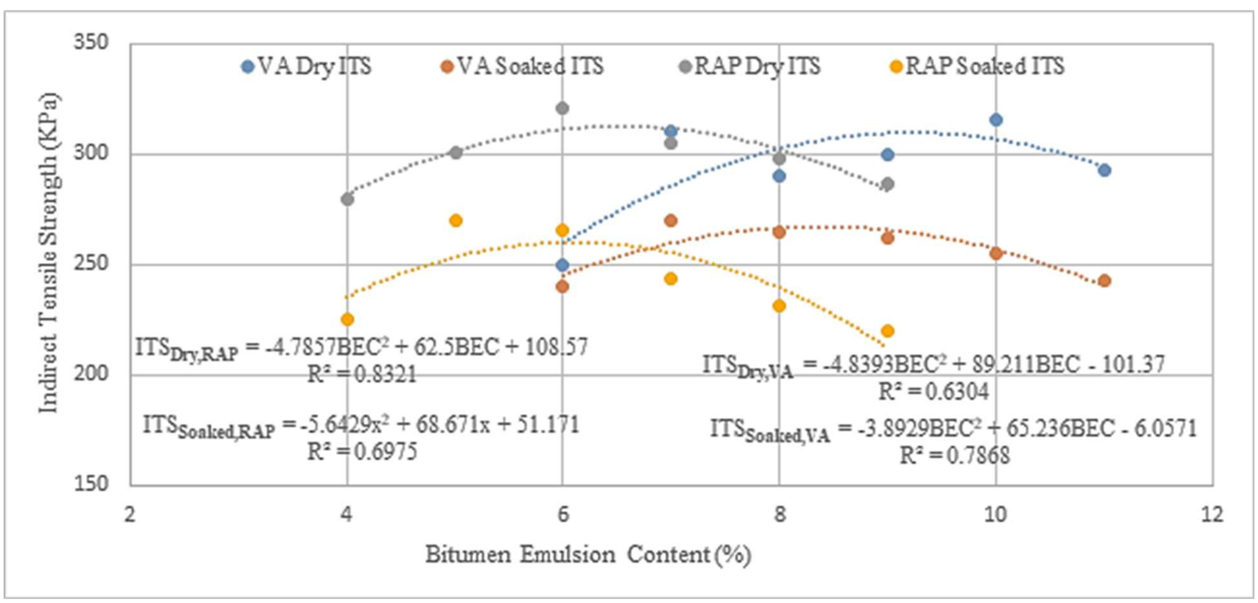

Figure 6 Indirect Tensile Strength for Virgin Aggregates and RAP Aggregates Mixes at Bitumen Emulsion Content.

E. Compaction Characteristics

Figure 7 and Figure 8 illustrate that the virgin aggregate mix reached 11.5% air voids and 1.7% moisture absorption at the optimum emulsion content. In contrast, the reclaimed asphalt pavement (RAP) mix achieved lower values of 9.6% air voids and 1.6% moisture absorption. This reduction in voids and absorption in the RAP mix is likely attributable to its higher fines content, which creates a denser matrix compared to the virgin mix. The air void values for both mixes fall within the typical range for cold mix asphalt (8-15%), as reported by Addae, Rahman and Abed, (2023). The lower air voids in the RAP mix are consistent with the higher bulk density observed at optimum emulsion content, confirming that the finer gradation of processed RAP contributes to improved packing efficiency. The further reduction to 8.0% air voids in the CR-RAP mix at 1.8% crumb rubber content indicates the elastic deformation of rubber particles under compaction fills inter-particle voids without sealing the mix excessively. The moisture absorption values of 1.6-1.7% for all mixes are below threshold typically associated with stripping risk in cold mix applications (Jain and Singh, 2021).

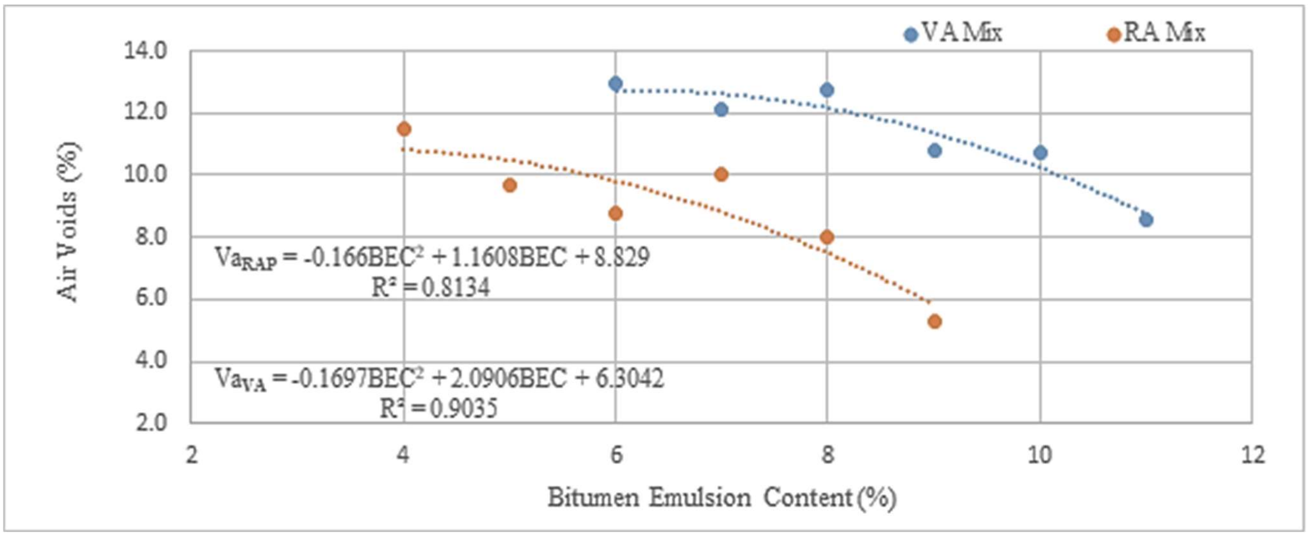

Figure 7 Air void for Virgin Aggregate and RAP Aggregates Mixes at Bitumen Emulsion Content

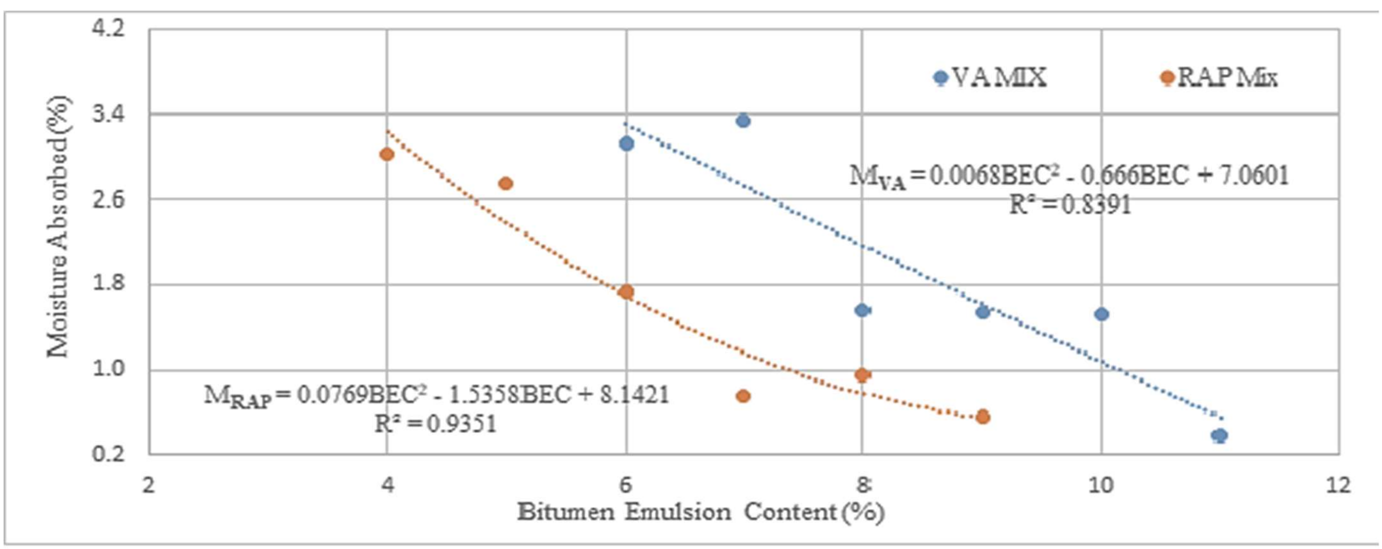

Figure 8 Moisture absorbed for Virgin Aggregates and RAP Aggregate mixes at Bitumen Emulsion Content

F. Moisture Susceptibility

As shown in Figure 9, the Tensile Strength Ratio (TSR) was 0.86 ± 0.06 at 8.9% optimum emulsion content for the virgin aggregates mix, and 0.83 ± 0.05 at 6.2% optimum emulsion content for the reclaimed asphalt pavement (RAP) mixes. In contrast, Figure 10 illustrates that incorporating treated crumb rubber as a by-mass replacement for 0/6 mm fine aggregate at six dosage levels: 0.5%, 1.0%, 1.5%, 2.0, 2.5%, and 3.0% by mass of total aggregate as a partial fine aggregate replacement that yielded a TSR of 1.15 ± 0.14 at an optimum content of 1.8% and an air void content of 8.0%. The range of crumb content was selected based on the expected optimum for cold mix application (Wulandari *et al.*, 2019). All results exceed the minimum AASHTO T-283, (2021) recommendation of 0.70, ensuring sufficient moisture resistance (Wirtgen GmbH, 2012; Buczyński and Iwański, 2017). Research on the performance of dense graded cold mix by Arshad *et al.* (2018) showed a TSR of 0.89 which is lower than the TSR of 1.15 achieved when treated crumb rubber was incorporated into cold mix asphalt in this study.

The TSR of 1.15 for the CR-RAP mix indicates that the soaked ITS (mean: 250 ± 15 kPa) exceeded the dry ITS (mean: 210 ± 12 kPa). While unusual for hot mix asphalt, TSR values exceeding 1.0 have been reported in cold mix and stabilised base materials (Thanaya, I Nyoman Arya, 2007; Buczyński and Iwański, 2017; Chelelgo, Gariy and Shitote, 2018). Three mechanisms are attributed for achieving a TSR of 1.15 for CR-RAP Cold mix. First, immersing soaked samples in water for 24-hour at 20°C extends the total conditioning period beyond that of dry specimens. In cold mix systems where emulsion breaking is moisture-dependent (cationic emulsion interacting with negatively charged aggregate surfaces), the presence of water facilitates charge neutralisation and binder coalescence at the aggregate–mastic interface, advancing the curing state of soaked specimens. Second, the 1.5% hydrated lime additive (97.8% CaO, from Table) reacts with dissolved silica from the aggregate and crumb rubber (cristobalite, SiO_2) in the presence of water to form calcium silicate hydrate (C-S-H) gel, a cementitious phase that stiffens the mastic. This reaction is activated specifically by water exposure and does not occur the same in oven-dried specimens. Third, it is hypothesised that treated crumb rubber particles may absorb water during soaking, causing slight swelling that fills micro-voids and increases contact pressure between particles, enhancing mechanical interlocking within the mix matrix. However, this mechanism was not directly verified in the present study, and rubber particle swelling measurements are recommended for future investigation to confirm this contribution.

It is acknowledged that the temperature differential between dry conditioning (cooled to 25°C) and wet conditioning (20°C water bath) could marginally increase binder stiffness in soaked specimens. However, this 5°C difference alone is unlikely to account for the full 15% increase in ITS. Both specimen groups received identical 72-hour oven curing at 40°C before divergence. A recommended verification test for conditioning-soaked specimens at 25°C rather than 20°C is identified as future work to isolate the temperature effect.

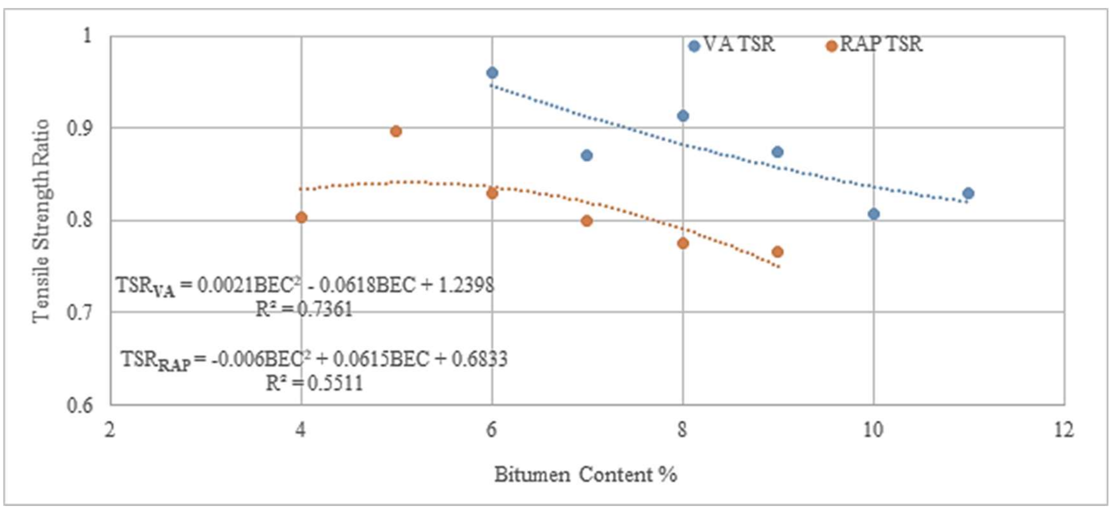

Figure 9 Tensile Strength Ratio for Virgin Aggregates and RAP Aggregate Mix at Bitumen Emulsion Contents

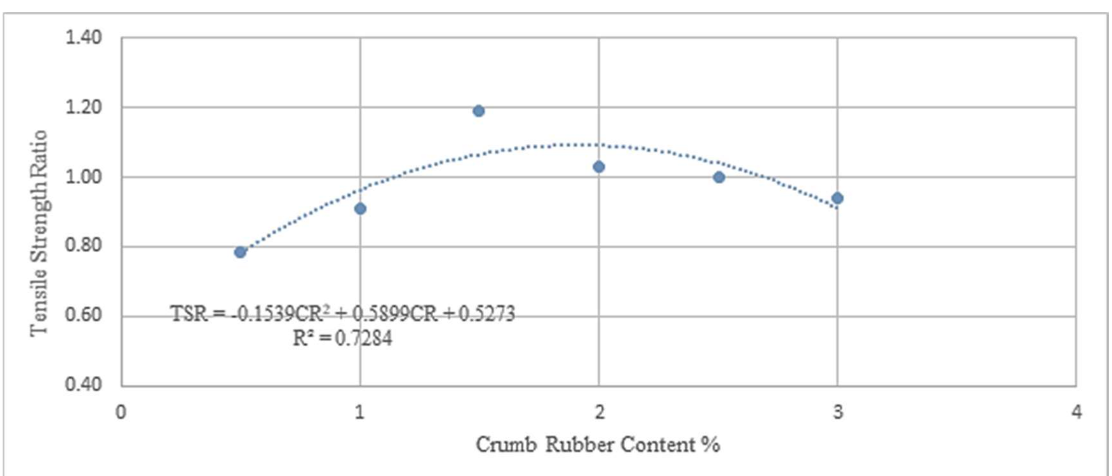

Figure 10 Tensile Strength Ratio of RAP Aggregate Mix at Crumb rubber Contents

G. Rutting Resistance

Rutting resistance was determined using the Hamburg wheel tracking test (HWTT). The quadruplicate samples were tested for each mix type for 10,000-wheel passes. At an optimum crumb rubber content of 1.8%, the mean rut depth was 2.12 mm, standard deviation of 0.22 mm, and a Coefficient of variation (CoV) of 10.38% were obtained. The CR-RAP mix performed better than the standard RAP aggregate mix, which recorded a mean rut depth of 2.74 mm, and standard deviation of 0.43, and a CoV of 15.69%. An independent samples t-test confirmed that the 22.63% reduction in rut depth is statistically significant $t(6) = -2.561$, $p = 0.043$, and 95% CI (-1.21, -0.03), confirming that the incorporation of NaOH-treated crumb rubber significantly improves rutting resistance. These results comply with the Massachusetts Department of Transportation (MassDOT) standard, which establishes a maximum allowable rut depth of 4.00 mm at 10,000 passes (West *et al.*, 2018).

The improved rutting resistance of the CR-RAP mix is attributed to the elastic recovery behaviour of crumb rubber particles. Under repeated wheel loading, the rubber particles deform elastically and recover partially upon load removal, reducing the net permanent strain per loading cycle. This mechanism is consistent with findings by Yu *et al.* (2020) and Wang *et al.* (2022), who reported that crumb rubber-modified asphalt exhibits lower accumulated permanent deformation due to the viscoelastic energy absorption capacity of the rubber phase. Additionally, the reduction in air voids from 9.6% to 8.0% in the CR-RAP mix provides a denser aggregate skeleton that better resists shear-induced lateral movement under the wheel track. It is noted that the dry test protocol does not capture moisture-coupled rutting susceptibility. In field conditions, combined moisture and traffic loading may produce higher rut depths. Submerged HWTT testing is recommended for future investigation to provide a more conservative assessment of rutting performance.

V. CONCLUSIONS

Cold mix asphalt incorporating 50% RAP aggregate performed satisfactorily relative to the virgin aggregate mix, achieving higher dry (245 ± 27 kPa) and soaked (200 ± 28 kPa) ITS than the virgin mix (235 ± 18 kPa and 170 ± 23 kPa), at a 25.5% lower optimum total fluid content (8.2% versus 11.0%). This is attributed to the stiffening effect of the aged binder on RAP particles and improved aggregate packing. Optimising bitumen emulsion and pre-mix water reduced air voids (9.6% versus 11.5%) and moisture absorption (1.6% versus 1.7%), while requiring 30% less emulsion (OBEC of 6.2% versus 8.9%). Adding 1.8% treated crumb rubber improved moisture resistance (TSR of 1.15 versus 0.83) and rutting resistance, reducing rut depth from 2.74 mm to 2.12 mm (22.63%) after 10,000 wheel passes. A treated crumb rubber content of 1.8% by mass of the 0/6 mm fine aggregate fraction is therefore recommended for cold mix RAP applications on rural and low-volume roads carrying up to 1 million ESAs.

AUTHOR CONTRIBUTIONS

K.G Yusuf: Conceptualisation, Methodology, Writing – original draft, Result analysis and Reporting.; C. Kanali: Conceptualization, Problem formulation, Methodology, Literature review and supervision.; E.B Ogunbode: Result analysis, supervision, Literature Review.

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REFERENCES

AASHTO T-283 (2021) 'Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage standard by American Association of State Highway and Transportation Officials'. USA, p. 10.

Addae, D.T., Rahman, M. and Abed, A. (2023) 'State of art literature review on the mechanical, functional and long-term performance of cold mix asphalt mixtures', Construction and Building Materials, 400, p. 132759. Available at: https://doi.org/10.1016/j.conbuildmat.2023.132759.

Al-Mohammedawi, A. and Mollenhauer, K. (2022) 'Current Research and Challenges in Bitumen Emulsion Manufacturing and Its Properties', Materials, 15(6), p. 2026. Available at: https://doi.org/10.3390/ma15062026.

Antunes, V., Freire, A.C. and Neves, J. (2019) 'A review on the effect of RAP recycling on bituminous mixtures properties and the viability of multi-recycling', Construction and Building Materials, 211, pp. 453–469. Available at: https://doi.org/10.1016/j.conbuildmat.2019.03.258.

Arshad, A.K. et al. (2018) 'Performance evaluation of dense graded cold mix asphalt', International Journal of Civil Engineering and Technology, 9(10), pp. 549–557.

Asiya, A. et al. (2024) 'Modification of Cold Mix', International Journal of engineering Research & Technology, 13(4), p. 4.

Asphalt Institute (1989) Asphalt Cold-Mix Manual. Manual Series No. 14 (MS-14). 3rd editio. Lexington, KY: Asphalt Institute.

ASTM D36 (2020) 'Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)', Standard [Preprint]. West Conshohocken, PA: ASTM International. Available at: https://doi.org/10.1520/D0036_D0036M-14R20.

ASTM D5 (2020) 'Test Method for Penetration of Bituminous Materials'. West Conshohocken, PA: ASTM International, p. 3. Available at: https://doi.org/10.1520/D0005_D0005M-20.

ASTM D6934-22 (2022) 'Test Method for Residue by Evaporation of Emulsified Asphalt'. West Conshohocken, PA: ASTM International, p. 3. Available at: https://doi.org/10.1520/D6934-22.

BS EN 12697-23 (2017), "Bituminous mixtures. Test methods Part 23: Determination of the indirect tensile strength of bituminous specimens., Standard. London.

BS EN 12697-3:2013+A1:2018 (2021) 'Bituminous mixtures. Test methods Bitumen recovery. Rotary evaporator', in Standard, p. 18.

Buczyński, P. and Iwański, M. (2017) 'Fatigue Life Comparison of Recycled Cold Mixes with Foamed Bitumen and with Bitumen Emulsion', Procedia Engineering, 172, pp. 135–142. Available at: https://doi.org/10.1016/j.proeng.2017.02.035.

Chelelgo, K., Gariy, Z.C.A. and Shitote, S.M. (2018) 'Laboratory mix design of cold bitumen emulsion mixtures incorporating reclaimed asphalt and virgin aggregates', Buildings, 8(12). Available at: https://doi.org/10.3390/buildings8120177.

Chu, F. et al. (2025) 'Investigation on the pavement performance and application of cold mix emulsified asphalt mixture in the surface layer', Journal of Cleaner Production, 507, p. 145542. Available at: https://doi.org/10.1016/j.jclepro.2025.145542.

Darter, M.I. et al. (1979) 'Design of Emulsified Asphalt-Aggregate Bases for Low Volume Roads', Transportation Research Record, 702(18), pp. 164–172.

Dash, S.S., Chandrappa, A.K. and Sahoo, U.C. (2022) 'Design and performance of cold mix asphalt – A review', Construction and Building Materials, 315, p. 125687. Available at: https://doi.org/10.1016/j.conbuildmat.2021.125687.

EN 12697-22 (2020) 'Bituminous mixtures - Test methods - Part 22: Wheel Tracking', iTeh STANDARD PREVIEW. Slovenia: iTeh Stanard Preview, p. 12. Available at: https://standards.iteh.ai/catalog/standards/sist/aa69265c-73f1-4cc8-a4c8-a4a61d321c21/sist-en-12697-22-2020.

Indian Raods Congress (2014) IRC:SP:100-2014:Use of cold mix technology in construction and maintenance of roads using bitumen emulsion. New Delhi: Indian Roads Congress. Available at: https://law.resource.org/pub/in/bis/irc/irc.gov.in.sp.100.2014.pdf.

Jain, S. and Singh, B. (2021) 'Cold mix asphalt: An overview', Journal of Cleaner Production, 280, p. 124378. Available at: https://doi.org/10.1016/j.jclepro.2020.124378.

Langevin, D. (2009) 'Complexation of oppositely charged polyelectrolytes and surfactants in aqueous solutions. A review', Advances in Colloid and Interface Science, 147–148, pp. 170–177. Available at: https://doi.org/10.1016/j.cis.2008.08.013.

Ling, C., Hanz, A. and Bahia, H. (2016) 'Measuring moisture susceptibility of Cold Mix Asphalt with a modified boiling test based on digital imaging', Construction and Building Materials, 105, pp. 391–399. Available at: https://doi.org/10.1016/j.conbuildmat.2015.12.093.

Mallick, R.B., Kandhal, P.S. and Bradbury, R.L. (2008) 'Using Warm-Mix Asphalt Technology to Incorporate High Percentage of Reclaimed Asphalt Pavement Material in Asphalt Mixtures', Transportation Research Record: Journal of the Transportation Research Board, 2051(1), pp. 71–79. Available at: https://doi.org/10.3141/2051-09.

Mathaniya, T.E. (2006) 'Characterisation of fatique performance of selected cold bituminous mixes'. Stellenbosh, p. 256.

MS-2 (2014) Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types. Manual Series No. 2 (MS-2). 7th Edicti, Asphalt Institute. 7th Edicti. Lexington, KY: Asphalt Institute.

Nuzaimah, M. et al. (2020) 'Sodium hydroxide treatment ofwaste rubber crumb and its effects on properties of unsaturated polyester composites', Applied Sciences (Switzerland), 10(11). Available at: https://doi.org/10.3390/app10113913.

Poranic, J. (2009) 'An Investigation into Cold In-place Recycling of Asphalt Pavement', The University of Nottingham. Nottingham, p. 211.

Pstrowska, K. et al. (2022) 'Adhesion in Bitumen/Aggregate System: Adhesion Mechanism and Test Methods', Coatings, 12(12), p. 1934. Available at: https://doi.org/10.3390/coatings12121934.

Ramarad, S. et al. (2015) 'Waste tire rubber in polymer blends: A review on the evolution, properties and future', Progress in Materials Science, 72, pp. 100–140. Available at: https://doi.org/10.1016/j.pmatsci.2015.02.004.

Read and Whiteoak (2003) The Shell Bitumen Handbook. 5th editio. London: Thomas Telford. Available at: https://books.google.com/books/about/The_Shell_Bitumen_Handbook.html?id=6mA-Hh0IQgEC.

Rezaei, M. et al. (2017) 'Investigation of Rutting Resistance and Moisture Damage of Cold Asphalt Mixes', Journal of Materials in Civil Engineering, 29(10). Available at: https://doi.org/10.1061/(ASCE)MT.1943-5533.0002042.

Rodríguez-Valverde, M.A. et al. (2003) 'Stability of highly charged particles: bitumen-in-water dispersions', Colloids and Surfaces A: Physicochemical and Engineering Aspects, 222(1–3), pp. 233–251. Available at: https://doi.org/10.1016/S0927-7757(03)00228-0.

Salomon., D.R. (2006) Asphalt Emulsion Technology., Transportation research circular. Washington DC: Transportation Research Board. Available at: https://onlinepubs.trb.org/onlinepubs/circulars/ec102.pdf.

Shams, H. et al. (2025) 'Investigating the performance of asphalt pavements modified with reclaimed asphalt and crumb rubber', Scientific Reports, 15(1), pp. 1–12. Available at: https://doi.org/10.1038/s41598-025-17909-y.

Thanaya, I Nyoman Arya (2007) 'Evaluating and Improving the Performance of Cold Asphalt Emulsion Mixes', Civil Engineering Dimension, 9(2), pp. 64–69. Available at: http://puslit2.petra.ac.id/ejournal/index.php/civ/article/view/16651.

Tia, M. and Wood, L.E. (1983) 'Use of Asphalt Emulsion and Foamed Asphalt in Cold-Recycled Asphalt Paving Mixtures.', Transportation Research Record, pp. 315–322.

Tushar, Q. et al. (2022) 'Recycling waste vehicle tyres into crumb rubber and the transition to renewable energy sources: A comprehensive life cycle assessment', Journal of Environmental Management, 323, p. 116289. Available at: https://doi.org/10.1016/j.jenvman.2022.116289.

Vaitkus, A. et al. (2016) 'Influence of warm mix asphalt technology on asphalt physical and mechanical properties', Construction and Building Materials, 112, pp. 800–806. Available at: https://doi.org/10.1016/j.conbuildmat.2016.02.212.

Wang, X. et al. (2022) 'Investigations on Adhesion Characteristics between High-Content Rubberized Asphalt and Aggregates', Polymers, 14(24), p. 5474. Available at: https://doi.org/10.3390/polym14245474.

West, R. et al. (2018) 'Development of a framework for balanced mix design', Project NCHRP 20-07/Task 406, pp. 7–20.

Wirtgen GmbH (2012) Wirtgen Cold Recycling Technology. 1st editio. Windhagen, Germany: Wirtgen GmbH. Available at: https://www.wirtgen-group.com/en-us/parts-and-service/training/hands-on-manuals/cold-recycling.

Wulandari, P.S. et al. (2019) 'Effect of Crumb Rubber as Fine Aggregate Replacement in Cold Mixture Asphalt', Civil Engineering Dimension, 21(2), pp. 107–112. Available at: https://doi.org/10.9744/ced.21.2.107-112.

Xu, L. et al. (2025) 'Effect of Bonding Characteristics on Rutting Resistance and Moisture Susceptibility of Rubberized Reclaimed Asphalt Pavement', Infrastructures, 10(12), pp. 1–18. Available at: https://doi.org/10.3390/infrastructures10120336.

Yu, H. et al. (2020) 'Effect of mixing sequence on asphalt mixtures containing waste tire rubber and warm mix surfactants', Journal of Cleaner Production, 246, p. 119008. Available at: https://doi.org/10.1016/j.jclepro.2019.119008.

Zaumanis, M., Mallick, R.B. and Frank, R. (2014) '100% recycled hot mix asphalt: A review and analysis', Resources, Conservation and Recycling, 92, pp. 230–245. Available at: https://doi.org/10.1016/j.resconrec.2014.07.007.