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Laboratory Mix Design of Cold Bitumen Emulsion Mixtures Incorporating Reclaimed Asphalt and Virgin Aggregates

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Abstract: Bitumen emulsion asphalts, especially those incorporating marginal and secondary aggregates, are energy efficient, environment friendly, and sustainable alternatives to hot-mix asphalts. This study set out to compare engineering properties of a bitumen emulsion asphalt composed entirely of virgin aggregates with another composed of 55% reclaimed asphalt and 45% virgin aggregates. The aggregates were bound with a slow setting cationic bitumen emulsion composed of 65% base bitumen and 35% water. Marshall specimens molded at varying pre-mix water and bitumen emulsion contents were cured in molds for 24 h before being de-molded and cured for a further 72 h at 40 °C. Dry densities, porosities, and indirect tensile strengths for the cured specimens were determined in dry and soaked states. Virgin aggregate mix, at an optimum binder content of 6.1%, had a tensile strength ratio of 1.3 with corresponding air voids and moisture absorption values of 10.1% and 0.92%, respectively. Similarly, reclaimed asphalt mix at an optimum binder content of 6.2% had a tensile strength ratio of 1.03, with corresponding air voids and moisture absorption values of 7.9% and 0.38%, respectively. Compared to virgin mix, reclaimed asphalt mix had lower air voids and lower moisture absorption values with the overall benefit of enhanced resistance to moisture damage.

Keywords: cold-mixes; emulsion asphalts; reclaimed asphalt; recycled materials; bitumen-emulsion; indirect tensile strength; tensile strength ratio

1. Introduction

A bituminous mixture is a three-phase composite material composed of a coarse aggregate skeleton, a viscous-elastic bituminous mortar, and air in the voids between the aggregates. The bitumen mortar is a blend of a filler (particles passing 75-micron sieve) and penetration-grade bitumen, whose viscosity has been reduced by heating, foaming, or emulsification. Emulsification of bitumen is achieved by mechanically dispersing minute globules of hot penetration-grade bitumen in water with the aid of negatively or positively charged emulsifiers. The emulsifiers impart positive (cationic), negative (anionic), or neutral (nonionic) charges on bitumen globules, which help to keep them continuously suspended in water [1]. Foamed bitumen, on the other hand, is produced by injecting super-heated steam into hot penetration-grade bitumen.

Hot-mix asphalts are produced by blending aggregates with penetration-grade bitumen at elevated temperatures, while cold-mix asphalts are produced by blending aggregates with either emulsified or foamed bitumen at ambient temperatures. Whereas hot-mix asphalts achieve their ultimate engineering properties upon completion of batching, strength gain in cold asphalts proceed at rates dependent on breaking of the emulsion and evaporation of the resultant water. They behave like improved granular materials in the early stages of their lives but eventually attain properties similar to those of hot-mix asphalts once all the moisture is lost through curing [2–4].

Compared to hot-mix asphalts, cold asphalts are energy efficient, cheaper, and environmentally friendly, but have the downsides of requiring longer curing times, having high air-void contents, and low early-life strengths [5]. Further, environmental and monetary savings accrue when marginal and secondary aggregates, like recycled asphalts, are used in cold-asphalt mixtures. In their study, Kandhal and Mallick [6] estimated cost savings of between 14% and 34% when recycled asphalt aggregates varying between 20% and 50% by mass of total mix were used in conjunction with virgin aggregates. In another study by Thanaya [7], energy savings of up to 40% were realized when bitumen emulsions were used in place of penetration grade bitumen in asphalt production. A study by Oke et al. [8] estimated savings of between 40% and 60% when cold reclaimed asphalt pavement mixtures were used in place of hot-mix asphalt.

Currently, there is no universally accepted laboratory asphalt mix design procedure for cold asphalt mixtures, rather a myriad of procedures have been developed by countries and agencies to suit their local conditions and needs [9–13]. In the United States, Asphalt Institute, Chevron Inc., U.S. Navy, and the states of Oregon, Pennsylvania, Indiana, California, Texas, and New Mexico [14] have developed design procedures that have been implemented in the field. Other countries such as the United Kingdom [15], France [16], and South Africa [17] have equally invested a lot in the development of credible cold asphalt mix design procedures. All the design procedures cited above aim at determining the most appropriate aggregate gradation, the optimum bitumen emulsion or foamed bitumen content, the pre-mix water content, and the most appropriate compaction effort for the mix [18].

Locally, COLAS East Africa Ltd. has developed a cold asphalt virgin aggregates mix of gradation 0/10 mm for use in surfacing of low volume rural roads in Kenya [19]. This research went further to design 0/20 mm graded virgin and reclaimed asphalt mixes suitable for minor patchworks and surfacing of roads in remote areas where hot-mix batch plants may not be accessible. The overall objective of the research was to evaluate the suitability of locally available reclaimed asphalt aggregates for use in bitumen emulsion asphalt. Ideally, reclaimed asphalt aggregates have a coarser gradation, which is attributed to binding of fine aggregates by bitumen. To correct this gradation, a percentage of fine virgin aggregates is incorporated into the mix to bring the final gradation to within a gradation envelope recommended for cold mixes by Transport and Roads Research Laboratory (TRRL) [17]. The Fuller Equation was used to iteratively blend the various fractions of the aggregates while targeting a blend within the envelope and with the maximum possible density. To evaluate the comparative performance of the reclaimed asphalt mix against the conventional virgin aggregates mix, Marshall specimens of the two mixtures were subjected to indirect tensile strength, moisture susceptibility, and porosity tests at varying pre-mix water and bitumen emulsion contents. Adoption of cold asphalts incorporating reclaimed asphalt aggregates will result in energy savings and saving of aggregate and bitumen sources, besides eliminating toxic emissions that are characteristic to hot-mix asphalt production.

2. Materials and Methods

2.1. Materials

This research made use of reclaimed asphalt aggregates (RA), virgin aggregates (VA), and a slow-setting cationic bitumen emulsion ($K_{3\text{-}65}$) to produce cold asphalt mixtures fit for pavement surfacing. Reclaimed asphalt was obtained from Ngong Road in Nairobi, which was then undergoing rehabilitation. The material was processed in the laboratory to yield aggregates of single-sizes 0/6 mm, 6/10 mm, 10/14 mm, and 14/20 mm. Virgin aggregates of single-sizes 0/6 mm, 6/10 mm, 10/14 mm, and 14/20 mm were obtained from Kay Quarries Ltd., located in Katani area of Machakos County of Kenya. Bitumen emulsion ($K_{3\text{-}65}$) that complied with BS EN 13808 [20] was sourced from COLAS East Africa Ltd., located in Nairobi's Industrial Area. The cationic bitumen emulsion was chosen for its high stability, low breaking speed, and ability to coat a wide range of aggregates [21,22].

2.2. Material Characterization

2.2.1. Aggregates

Reclaimed asphalt aggregates and virgin aggregates were characterized in terms of their mineralogy, bulk specific gravity, and water absorption. Small samples of oven-dried rocks were pulverized to 150 microns and placed in sample cups, then covered in a thin film of polypropylene to prevent contamination but still allow X-rays to penetrate unhindered. Elemental composition of the rocks was determined using S1 TITAN X-RF analyzer (manufactured by Bruker, Sandton, South Africa). The sample cups were placed under the analyzer and exposed to X-rays for 60 s. Results of X-ray fluorescence of the aggregates revealed a siliceous mineralogy with SiO_2 constituting 65.497% of reclaimed asphalt aggregates and 62.503% of the virgin aggregates. The mineralogy categorized the parent rocks as basaltic granite with a net negative surface charge, which would be compatible with positively charged cationic bitumen emulsions [23,24]. The specific gravities and water absorption of the aggregates were determined in accordance with the guidelines set out in ASTM C127-15 [25], and the results tabulated in Tables 1 and 2 for reclaimed asphalt and virgin aggregates, respectively. Results of X-ray fluorescence are presented in Table 3.

Table 1. Physical properties of reclaimed asphalt aggregates.

Size (mm)	**0/6**	**6/10**	**10/14**	**14/20**
Bulk Specific Gravity (kg/m^3)	2252	2339	2340	2365
Water Absorption (%)	4.4	3.2	3.0	2.2

Table 2. Physical properties of virgin aggregates.

Size (mm)	**0/6**	**6/10**	**10/14**	**14/20**
Bulk Specific Gravity (kg/m^3)	2405	2485	2487	2491
Water Absorption (%)	5.5	2.3	2.4	1.5

Table 3. Chemical composition of reclaimed asphalt aggregates and virgin aggregates.

Chemical Composition	**% in Reclaimed Asphalt Aggregates**	**% in Virgin Aggregates**
SiO_2	65.497	62.503
Al_2O_3	22.870	23.267
K_2O	4.746	4.866
F_e2O_3	3.132	3.212
MgO	1.970	3.712
CaO	0.942	1.061
Ti	0.370	0.283
Mn	0.152	0.503
Cl	0.018	0.203
Others elements	0.303	0.39

The particle size distributions of the single-sized virgin and reclaimed asphalt aggregates were determined from oven-dried samples in accordance with BS 812: Part 103 [26]. Drying was achieved by keeping samples to be graded in an oven (manufactured by Controls Group, Hertfordshire, United Kingdom) set at 105 °C for 12 h. The aggregates were taken out of the oven 3 h before gradation was done to allow for sufficient cooling.

2.2.2. Residual Bitumen in Reclaimed Asphalt

The percentage of residual bitumen content in the reclaimed asphalt was determined using the solvent extraction method in accordance with BS EN 12697-1 [27]. Bitumen in reclaimed asphalt was dissolved in methylene chloride (manufactured by Vats International, New Delhi, India) and recovered using the Rotary Evaporator Method, conducted in accordance with BS EN 12697-3 [28]. The softening point (Ring and Ball) and Needle Penetration of the recovered bitumen were determined, following procedures set out in BS 2000-49 [29] and BS EN 1427 [30], respectively. Table 4 summarizes properties of the bitumen.

Table 4. Properties of recovered bitumen.

Property	BS Designation	Test Result
Penetration (dmm)	BS 2000-49	16.3
Softening Point (°C)	BS EN 1427	63.4
Percentage in total mix (%)	BS EN 12697-1	4.1

2.2.3. Bitumen Emulsion

The quantity of bitumen in the emulsion was determined by evaporation following the procedures set out in ASTM D6934 [31]. The softening point (Ring and Ball) and Needle Penetration of the residue were determined, following procedures set out in BS 2000-49 [28], and BS EN 1427 [29], respectively. Table 5 summarizes the properties of the emulsion bitumen.

Table 5. Properties of the emulsion bitumen.

Property	ASTM/BS Designation	Test Result
Penetration (dmm)	BS 2000-49	58.25
Softening Point (°C)	BS EN 1427	54.5
Residue by distillation (%)	ASTM D6934	70.0
Particle charge (litmus paper)		+ve

2.3. Emulsion Asphalt Mix Design

This research adopted the Asphalt Institute procedure detailed in MS-14 [32], in developing cold emulsion asphalt mixes of gradation 0/20 mm, suitable for surfacing of low to medium traffic volume roads [33,34]. The major steps involved in the design process generally include aggregate quality tests, bitumen quality tests, aggregates blending, and determination of optimum amounts of bitumen and pre-mix water.

2.3.1. Combined Aggregates Gradation

Cold emulsion asphalt mixtures are quite sensitive to particle size distribution. A continuously and densely graded aggregate skeleton ensures sufficient aggregate interlock and thus serves to improve the early life strength of a cold asphalt mix. To optimize packing of constituent aggregates in an asphalt mix, the various aggregate fractions were blended using Cooper formula, Equation (1) [2,17].

$$P = \frac{(100 - F)(d^n - 0.075^n)}{D^n - 0.075^n} + F \tag{1}$$

where P is the percentage by mass of material passing a sieve of size d (%), d is the selected sieve size (mm), D is the maximum aggregate size (mm), n is an exponent that dictates the concavity of the gradation line (0.45 or 0.50, for optimal aggregate packing), and F is the percentage of filler by mass of dry aggregates. The maximum aggregate size D and the filler content F are usually predetermined in line with specifications or from experience. In this study, a maximum sieve size of 20 mm was selected. An exponent n = 0.45 is recommended for Superpave (superior performing asphalt pavements) Level 1 mix design since it provides optimal packing of the aggregates [34]. A filler content of 2% is recommended for cold emulsion asphalt mixtures since higher filler contents would trap more water and delay the curing process [17,21]. A higher percentage of filler, normally between 4% and 5%, is recommended for foamed bitumen mixes, since their strength largely depends on coating of the finer aggregates by the binder [35]. To blend the various fractions of aggregates that constituted the mix, the simple mathematical relation, Equation (2), was used.

$$P = aA + bB + cC \tag{2}$$

where P is the percentage of combined aggregates passing a particular sieve (%), A, B, and C are the percentages of material passing a particular sieve for individual aggregates (%), and a, b, and c are proportions of individual aggregates used in the combination (%). The various fractions of aggregates were mathematically blended in an excel spreadsheet with the aim of achieving a blend with gradation closest to the maximum density, "Cooper Curve". For the reclaimed asphalt aggregates mix, the blend that produced the best fit to the maximum density curve had 45% 0/6 mm virgin aggregates, 15% 0/6 mm reclaimed aggregates, 10% 6/10 mm reclaimed aggregates, 15% 10/14 mm reclaimed aggregates, and 15% 14/20 mm reclaimed aggregates as a percentage by mass of the total dry aggregates. For the cold asphalt mix incorporating 100% virgin aggregates, the optimum blend was made up of 55% 0/6 mm virgin aggregates, 20% 6/10 mm virgin aggregates, 10% 10/14 mm virgin aggregates, and 15% 14/20 mm virgin aggregates. Plots for the reclaimed asphalt and virgin aggregates blends are depicted in Figure 1 while blending of their constituent aggregates fractionsare presented in Table A1 of Appendix A, for reclaimed asphalt aggregates mix, and Table A2 of Appendix B, for the virgin aggregates mix. Transport and Road Research Laboratories (TRRL) gradation envelope, recommended by Asphalt Institute [36], was adopted.

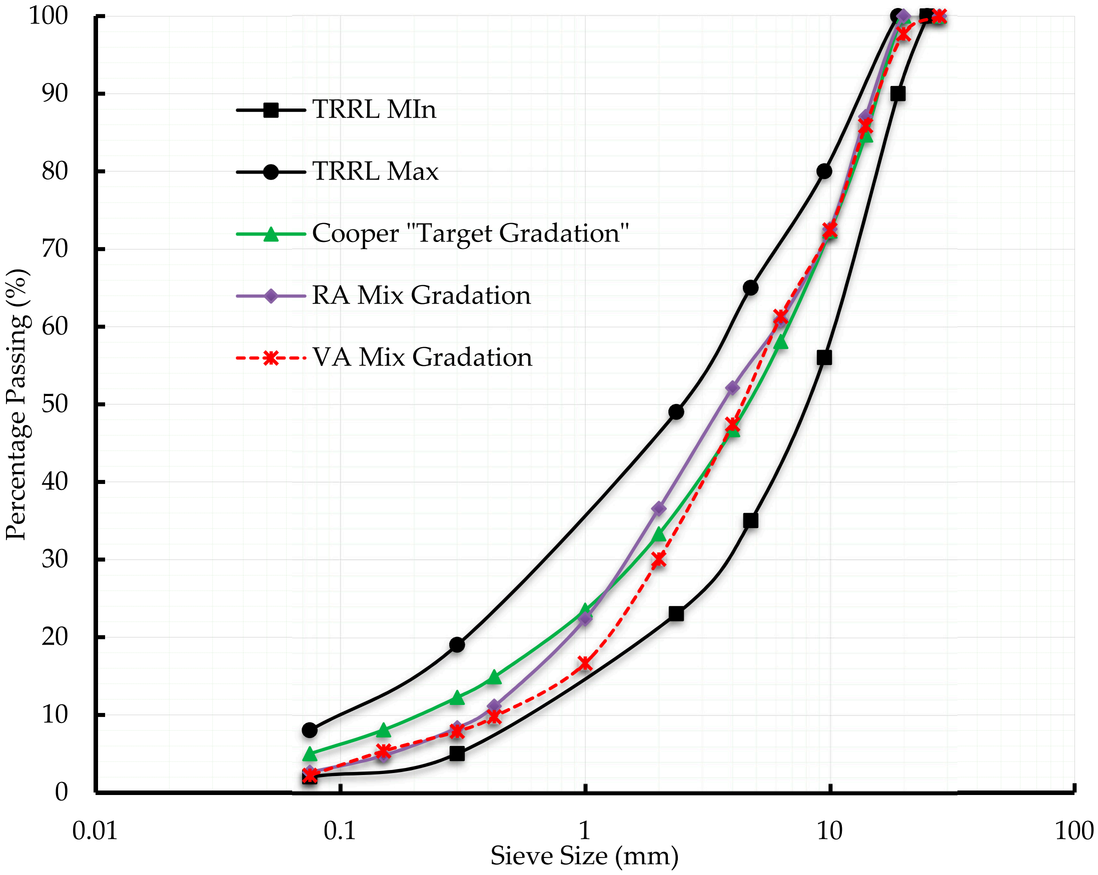

Figure 1. Design Gradations for Virgin Aggregates and Reclaimed Asphalt Aggregates Blends.

2.3.2. Initial Emulsion Content (IEC)

Once the optimum aggregate blend for a cold mix has been determined in the laboratory, the associated estimate of emulsion bitumen requirement for the trial mix is determined using the Centrifuge Kerosene Equivalent (CKE) method. In the absence of the requisite laboratory apparatus and equipment, as was the case in this study, Equation (3) empirically developed by the Asphalt Institute can be used [32].

$$P_b = (0.05A + 0.1B + 0.5C) \times 0.7 \tag{3}$$

where P_b is the total binder demand as a percentage by mass of the combined dry aggregates, A is the percentage of dry mineral aggregates greater than size 2.36 mm, B is the percentage of dry mineral aggregates passing sieve size 2.36 mm and retained on a 75-micron sieve, and C is the percentage of dry mineral filler passing a 75-micron sieve. In a situation where an emulsified binder is used, the amount of the Initial Emulsion Content (IEC) is determined using Equation (4), which considers the base bitumen content in the emulsion.

$$\mathrm{IEC} = \left(\frac{P_b}{X}\right) \times 100\% \tag{4}$$

where IEC is the Initial Emulsion Content by mass of total mixture (%) and X is the percentage of bitumen content in the emulsion (%). The total binder demand for the virgin aggregates blend was computed using Equation (3) and the design gradation presented in Figure 1. The design gradation was composed of 30% aggregates passing sieve size 2.36 mm and 2% aggregates passing 75-micron sieve. The combination of the percentages yielded an initial bitumen content of 5.1% which translates to an initial emulsion content of 7.3%, when we consider that bitumen constitutes 70% of $K_{3\text{-}65}$ emulsion used. For practical purposes, the initial emulsion content (IEC) was rounded off to 7%. For the reclaimed asphalt mix, the design gradation was composed of 37% aggregates passing sieve 2.36 mm and 3% aggregates passing the 75-micron sieve. Applying Equations (3) and (4) yielded an initial emulsion content of 5.6%. The final binder demand of the reclaimed asphalt mix was determined using Equation (5), which takes into consideration the contribution of aged binder in reclaimed aggregates to the binding action. According to Oke [37], bitumen with Needle Penetration greater than 5 dmm is considered to be active under tropical conditions. Bitumen recovered from RA in this research had an average penetration of 16.30 dmm and thus qualified for consideration as a contributing binder in the emulsion asphalt mix design.

$$P_{nb} = P_b - \frac{(100 - r)P_{sb}}{100} \tag{5}$$

where r is the percentage of the virgin aggregates in the mix, P_{sb} is the bitumen content of the reclaimed asphalt, P_{nb} is the amount of additional new binder, and P_b is the total binder demand as a percentage by mass of the combined aggregates. The design aggregates mix was composed of 45% virgin aggregates and 55% reclaimed asphalt aggregates. The residual bitumen in the reclaimed asphalt, from Table 1, was 4.1% by mass of the dry aggregates mix. Incorporating these values in Equations (4) and (5) yielded an initial emulsion content of 4.8%, which for practical purposes, was rounded off to 5%.

2.3.3. Moisture-Density Relationships

The moisture-density relations as well as the binder content have a great impact on the compaction level and stiffness of cold asphalt mixtures [38]. Besides improving mix workability, water serves to activate surface charges on the aggregates, thus enhancing emulsion "breaking" and coalescence of bitumen globules into a film. The optimum moisture content (OMC) and the associated maximum dry density (MDD) of the design aggregate blend give an indication of the ultimate density and the optimum total fluid content during compaction of the mix [22,39]. The moisture-density relations for both virgin and reclaimed asphalt mixtures were concurrently determined in the laboratory in accordance with procedures set out in BS 1377 [40]. As per BS 1377, specimens were prepared at five different moisture contents (between 3% and 8%), ensuring that two moisture contents were on either range of the estimated optimum moisture content. For each of the moisture contents, three specimens weighing approximately 5 Kg were each compacted in three layers using a vibrating hammer operating at 25 Hz. Compaction of each layer was achieved by pressing down the vibrating hammer for 60 s per layer with a downward force ranging between 300–400 N, just sufficient to prevent the hammer from bouncing up and down on the aggregates.

2.3.4. Optimum Total Fluid Content

The total fluid content of a cold asphalt mix is the summation of its bitumen emulsion content, pre-mix water content, and the moisture content of its aggregates. According to the Asphalt Institute, the combined effect of water and bitumen on binding and workability of the aggregates is established by compacting cold mixtures at varying contents of total fluids and determining the total fluid content that yields the highest density for the particular compaction effort [32]. While keeping the emulsion content constant at IEC, as determined in Section 2.3.2, emulsion asphalt mixtures were prepared with pre-mix water content increasing at 1% intervals between 1% to 5% for VA cold asphalt mix and 1% to 6% for RA cold asphalt mix. With IEC values of 7% and 5% by mass of dry aggregates, respectively, the total fluid content for VA cold asphalt mix and RA cold asphalt mix ranged from 8% to 12% and 6% to 11% by mass of dry aggregates, respectively. Marshall procedure was used to prepare 6 cylindrical asphalt specimens at each of the total fluid contents, yielding a total of 36 specimens for RA mix and 30 specimens for VA mix. Triplicate specimens from each pre-mix water content were reserved for tests in the dry state while the remainder three were reserved for moisture susceptibility tests.

The compacted specimens were labeled and left to cure in their molds at room temperature for 24 h while lying horizontally on trays with their faces free from any obstruction. After this initial phase of curing, the specimens were extruded using an extrusion jerk and transferred to a forced draft oven set at 40 °C and left to cure for a further 72 h as recommended by previous researches [41,42]. Besides determining the optimum total fluid content of the two bitumen emulsion asphalt mixtures from the maximum bulk specific gravity, this study went further to track the evolution of their soaked and dry indirect tensile strengths with varying amounts of pre-mix water content. Specimens to be tested in the soaked state were taken to a water bath set at 25 °C, where they remained fully immersed for 24 h. The specimens sat on a 20 mm coarse sand bed to allow for uninterrupted circulation of water around the bottom faces. In his research, Thanaya [34] proposed a conditioning regime that involved soaking half the heights of the specimens for 24 h, after which the specimens were inverted, and the other half also soaked for 24 h. It was noted during this research that when soaked portions of the specimens were inverted and exposed to air, water drained off and the specimen cured at the prevailing room temperature. Conditioning of specimens at 25 °C, as adopted in this study, is a common practice in cold asphalt mixture studies [37,43].

After the 24 h period, the soaked and dry specimens were taken out of the water bath and oven, respectively, and their bulk densities and porosities determined. To determine the effect of pre-mix water on strength properties of the cold asphalt mixtures, the indirect tensile strength test, conducted in accordance with ASTM D6931-12 [43], was performed on both dry and conditioned specimens. In this test, the specimens were loaded diametrically between two loading strips of the Indirect Tensile Strength equipment at a rate of 50.8 mm/min up to failure, and the ultimate load was recorded. The apparatus used in this study had a calibration ring factor of 0.0228 kN, with which all the dial readings were multiplied before computation of the tensile strengths of the specimens. The tensile strengths of the cylindrical specimens were computed based on Equation (6).

$$\mathrm{S_t} = \frac{2\ \mathrm{P_{ult}}}{\pi \times \mathrm{d} \times \mathrm{t}} \tag{6}$$

where $\mathrm{S_t}$ is the tensile strength of the specimen (kPa), $\mathrm{P_{ult}}$ is the maximum Load (N), t is the thickness of the specimen (mm), and d is the diameter of the specimen (mm).

The optimum total fluid content for the asphalt mixes was determined by plotting dry indirect tensile strengths, soaked indirect tensile strengths, and the bulk specific gravities against the total fluid content. The average of the peak values gave the optimum total fluid content and the difference of the total fluid contents and initial emulsion contents gave the optimum pre-mix water content.

2.3.5. Optimum Bitumen Emulsion Content

After the optimum pre-mix water content was determined for the two mixes, the binder content was optimized following the procedure adopted for the optimum total fluid content, but by varying the amount of the bitumen emulsion while keeping the pre-wetting water content constant [44]. The iterations employed involved varying emulsion contents at 1% intervals, starting from 4% by mass of dry aggregates and stopping at 9% by mass of dry aggregates, for both RA and VA mixtures. Six specimens were prepared at each bitumen emulsion content, yielding a total of 18 specimens for RA mix and 18 specimens for VA mix. Whereas triplicate specimens at each bitumen emulsion content were tested for dry indirect tensile strengths (ITS), percentage air voids, moisture absorption, and dry density, the remainder triplicate specimens were conditioned at 25 °C for 24 h before being tested for soaked ITS. The average values of the computed dry indirect tensile strength, soaked indirect tensile strength, moisture absorption, percentage air voids, and dry density for each set of triplicate specimens were plotted against the corresponding bitumen emulsion content

2.3.6. Compaction Characteristics

Compaction characteristics of asphalt mixtures are reflected in their air voids and moisture absorption properties. Cold emulsion asphalt mixtures incorporating virgin aggregates have been found to achieve air void levels ranging between 5% and 10% [3,8], while those incorporating reclaimed asphalt aggregates, on the other hand, have been known to achieve higher levels of air voids that range between 12% and 15% [35]. Asphalt mixtures with porosity levels higher than the recommended levels are prone to rutting, bleeding, stripping, and accelerated aging of their binders due to exposure to oxygen. Porosity (or air voids) of asphalt mixtures is determined based on their bulk densities and their maximum theoretical specific gravity. The individual bulk densities and water absorption values of the asphalt specimens were determined alongside the indirect tensile strength adopting procedures set out in AASHTO T166-16 [45].

2.3.7. Moisture Susceptibility

The moisture susceptibility test measures the ability of an asphalt mix to withstand the stripping action of water. Stripping is the process through which bitumen binder in an asphalt mix is separated from the mineral aggregate. The moisture susceptibility of asphalt is assessed in the laboratory using soaked indirect tensile tests (ITS) or freeze–thaw indirect tensile tests [24,46]. The soaked ITS test, which is the more common of the two, involves testing the dry tensile strength of one set of specimens and comparing them with soaked tensile strengths of another set of specimens from the same sample batch. The ratio of the tensile strength of the soaked specimens to the tensile strength of the dry specimens gives an indication of the moisture resistance of the asphalt mix [9,47]. In this study, moisture susceptibility was conducted alongside the optimum emulsion content determination. The tensile strength ratios (TSR) of the specimens were determined using Equation (7).

$$\mathrm{TSR} = \frac{\mathrm{ITS_{Soaked}}}{\mathrm{ITS_{Dry}}} \tag{7}$$

where TSR is the tensile strength ratio, $\mathrm{ITS_{Soaked}}$ is the tensile strength of the soaked specimen (kPa), and $\mathrm{ITS_{Dry}}$ is the tensile strength of the dry specimen (kPa).

3. Results and Discussions

3.1. Moisture-Density Relationships

Figure 2 depicts plots of dry density (DD) versus moisture content (MC). It can be observed that MDD for the virgin aggregates blend was 2052 kg/m^3 and the corresponding OMC was 6.0%. Similarly, the MDD for the blend of reclaimed asphalt and virgin aggregates was 2047 kg/m^3 with a corresponding OMC of 6.6%. The above values indicate that the virgin aggregates blend required less moisture and achieved better compaction than the blend of virgin and reclaimed asphalt aggregates. The higher optimum moisture content for the blend of virgin and reclaimed asphalt aggregates could be attributed to confinement of some moisture in between fine aggregates that are bound to the surfaces of the coarser reclaimed asphalt aggregates. The same fine aggregates bound to the surfaces of larger sized reclaimed aggregates could possibly have contributed to higher macro-texture, which as a result offered more resistance to compaction. These observations concur with the findings in Tables 1 and 2, in which reclaimed asphalt aggregates were found to be more absorptive and less dense than virgin aggregates. It can also be noted from the coefficients of determination, R^2, in Figure 2, that there's more scatter in the data of reclaimed asphalt aggregates than in virgin aggregate blends. This could possibly be due to the presence of deleterious materials incorporated during milling of the asphalt pavement.

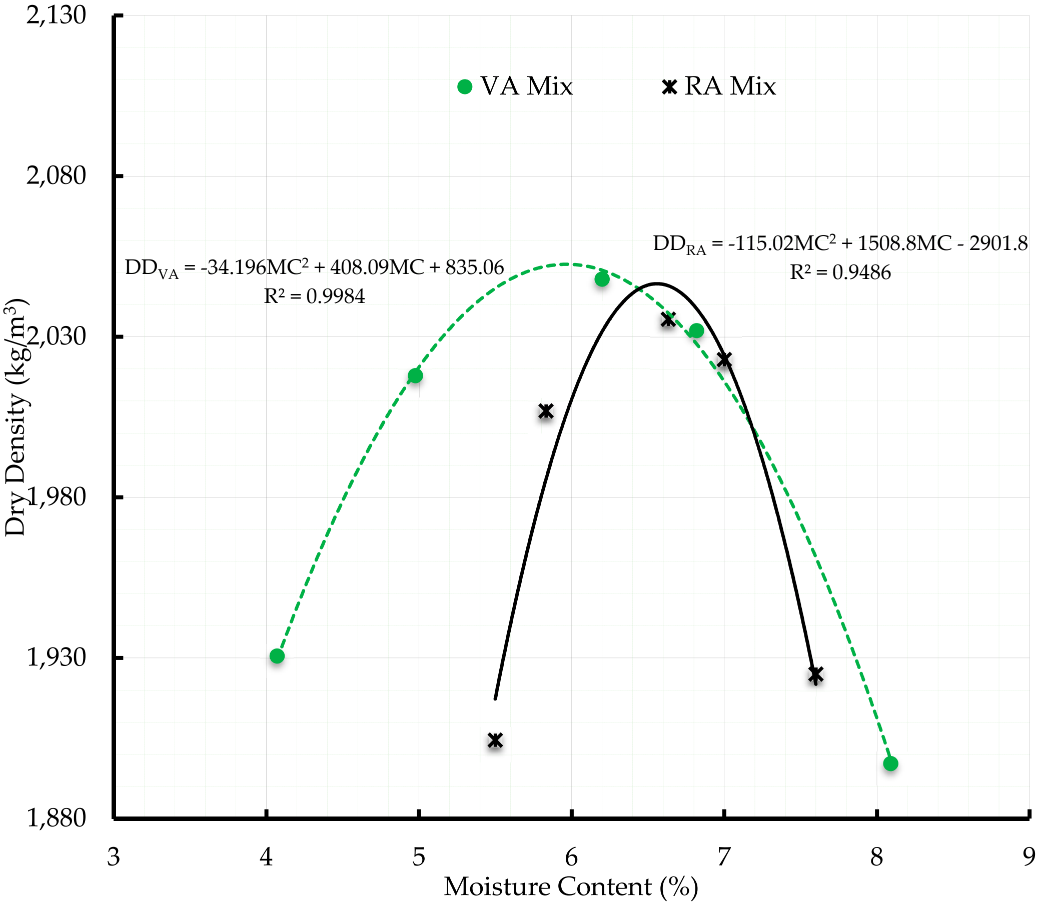

Figure 2. Maximum Dry Density and Optimum Moisture Content for Virgin Aggregates and Reclaimed Asphalt Aggregates Mixes.

3.2. Optimum Total Fluid Content

When Figures 3 and 4 are jointly considered, it can be observed that indirect tensile strengths (ITS) and bulk specific gravity (BSG) for both asphalt mixes rise with increase of the total fluid content (TFC) and decline upon attainment of a peak. Initially, the pre-mix water contributes to activation of surface charges in the aggregates leading to coalescence of bitumen globules and subsequent binding of the aggregates. As more water is added, a point is reached beyond which more water strips off the binder from the aggregates surfaces and drains it alongside fine particles. This results in an increase in air voids with subsequent reduction in both bulk specific gravity and tensile strength of the specimens.

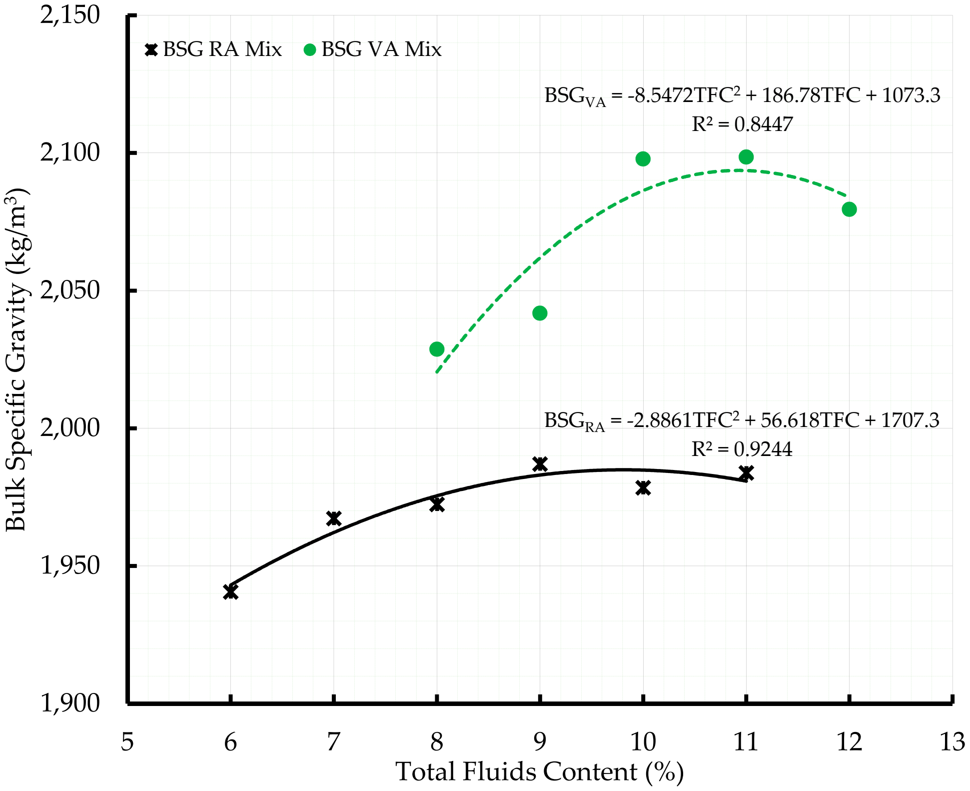

Figure 3. Bulk Specific Gravity for Virgin Aggregates and Reclaimed Asphalt Aggregates Mixes at Optimum Total Fluids Contents.

The maximum values for virgin aggregate mixtures, as estimated from Figures 3 and 4, were recorded at 11% total fluid content for bulk specific gravity (2095 kg/m^3), 10.4% total fluid content for Soaked ITS (256 kPa), and 10.7% total fluid content for Dry ITS (264 kPa). Similarly, for the reclaimed asphalt aggregate mixture, maximum values were recorded at 9.8% total fluid content for bulk specific gravity (1984 g/km^3), 8.2% total fluid content for Soaked ITS (266 kPa), and 8.4% bitumen content for Dry ITS (266 kPa). It can be observed that for both mixtures, more water was needed to achieve the maximum bulk specific gravity than that needed to achieve the maximum soaked and dry indirect tensile strengths. This observation could be due to a higher amount of moisture required for lubrication than is needed to activate surface charges in the aggregates. To cater for both conditions, the total fluid contents were averaged to obtain optimum total fluid content of 10.7% by mass of dry aggregates for VA mix and 8.8% for VA mix. The tensile strength values indicate that reclaimed asphalt aggregate mixture was marginally stronger than the virgin aggregates mixture. When optimum moisture content (OMC) and optimum total fluids content (OTFC) values of both the virgin and reclaimed asphalt mixes were considered together, the findings were contrary to the popular assumption that OMC approximates OTFC. Oke [15], while working with a reclaimed asphalt mixture, obtained an OMC value of 6.9% and a corresponding OTFC value of 8%. In a similar study by Ojum [48], an OMC value of 6.0% was obtained against an OTFC value of 8%. These results indicate that moisture–density relations can be omitted from the Asphalt Institute design process without any impact on the determination of the pre-mix water content.

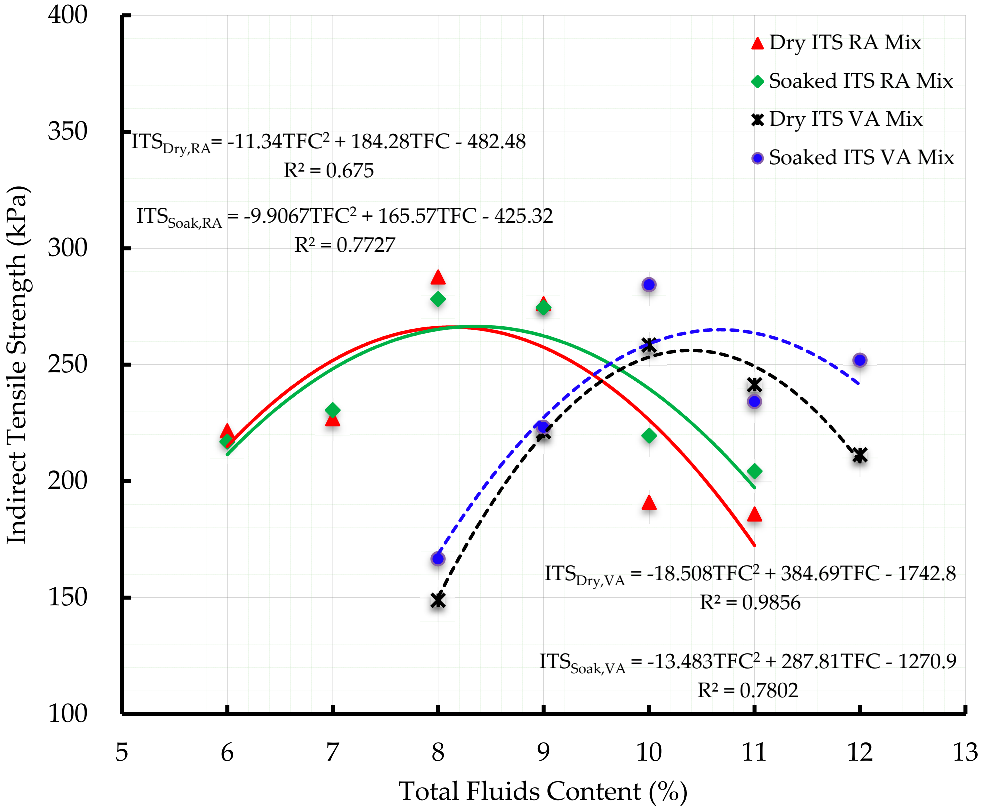

Figure 4. Indirect Tensile Strength for Virgin Aggregates and Reclaimed Asphalt Aggregates Mixes at Optimum Total Fluids Contents.

3.3. Optimum Emulsion Content

Peak values for the virgin aggregates mixture, as estimated from Figures 5 and 6, were recorded at 6.4% bitumen emulsion content for dry density (2081 kg/m^3), 5.5% bitumen content for Soaked ITS (345 kPa), and 6.5% bitumen content for Dry ITS (291 kPa). These values averaged to an optimum bitumen emulsion content (OBEC) of 6.1% by mass of dry aggregates. Similarly, for the reclaimed asphalt aggregate mixture, peak values were recorded at 6.4% bitumen content for dry density 2044 (kg/m^3), 6% bitumen content for Soaked ITS (340 kPa), and 5.5% bitumen content for Dry ITS (321 kPa). These values averaged to an optimum bitumen emulsion content of 6.2% by mass of dry aggregates.

Despite the lower density exhibited by reclaimed asphalt mixes, both reclaimed asphalt and virgin aggregate mixtures were found to have tensile strength values within the same range. This could be due to the fact that the aggregates of the two mixtures are from the same geological extract. ITS of the two asphalt mixtures exceeded the minimum recommended values of 200 kPa for dry specimens and 150 Kpa for soaked specimens [17,41,42,49]. Despite the reclaimed asphalt containing 4.1% binder, which was considered to be active, the final optimum bitumen emulsion content indicates that it contributed marginally to the binding action.

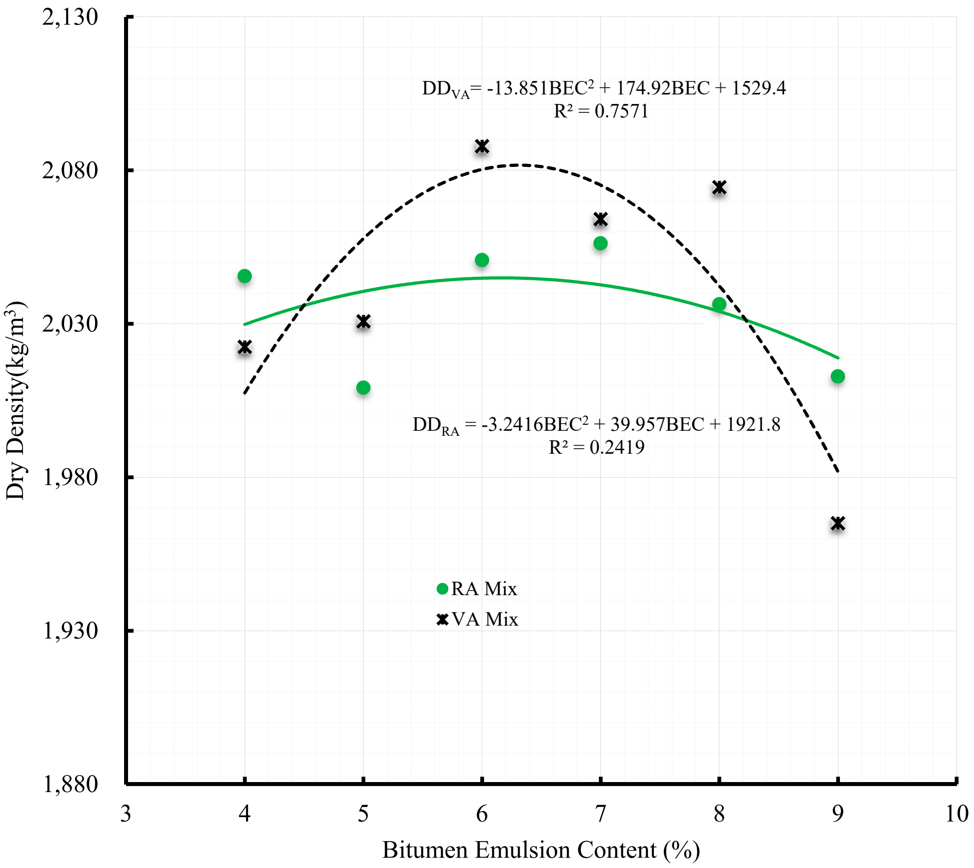

Figure 5. Dry Density for Virgin Aggregates and Reclaimed Asphalt Aggregates Mixes at Optimum Bitumen Emulsion Contents.

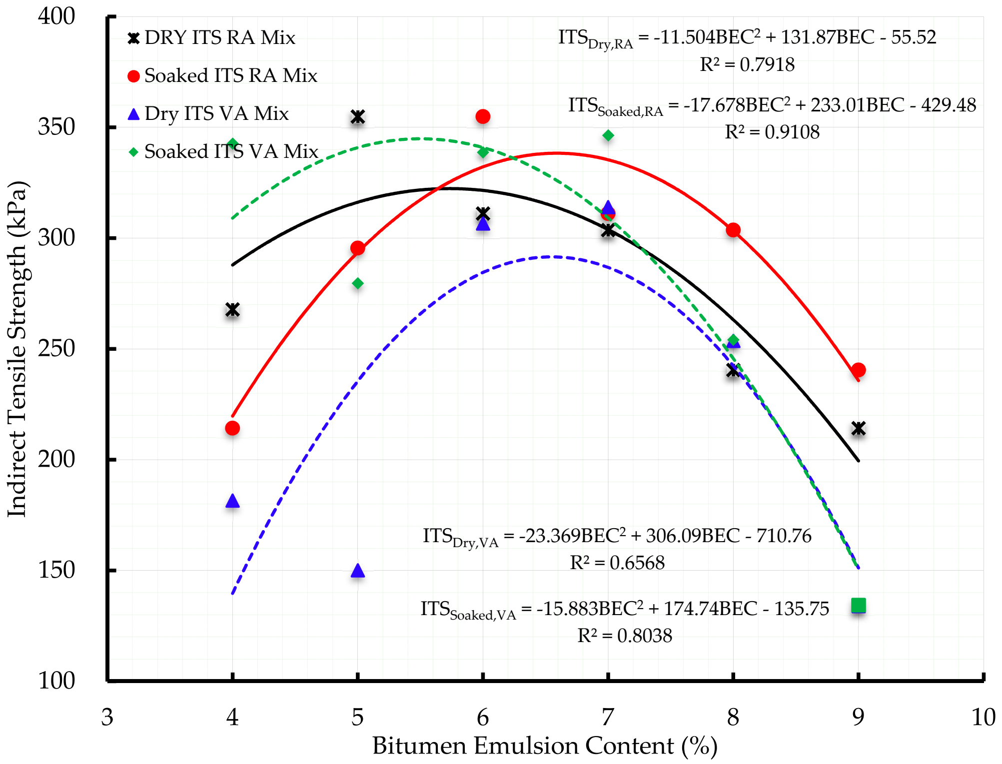

Figure 6. Indirect Tensile Strength for Virgin Aggregates and Reclaimed Asphalt Aggregates Mixes at Optimum Bitumen Emulsion Contents.

3.4. Compaction Characteristics

When the optimum bitumen emulsion content computed in Section 3.3 for both reclaimed asphalt and virgin aggregate mixtures are considered, Figures 7 and 8 indicate that the virgin aggregates achieved air voids (V_{VA}) of 10.1% at a moisture absorption level of 0.92%, while the reclaimed asphalt aggregates mixture achieved 7.9% air voids (V_{RA}) at a moisture absorption level of 0.38%. The results indicate that the reclaimed aggregates asphalt mix achieved better compaction than virgin aggregates asphalt mix, a finding that is contrary to what was observed in the determination of optimum total fluids content (OTFC). It was postulated that the higher bitumen content attained at OBEC led to dissolution of aged binder from RA leading to a general increase in the quantity of fines in the mix. The higher amount of filler in the reclaimed asphalt mix filled more voids and trapped more water in the interstices than could be evaporated under the design cure regime of 40 °C for 72 h. For both mixtures, air voids appear to increase beyond the optimum bitumen emulsion content. This phenomenon could be attributed to excess binder washing away the filler as it oozes out of the aggregate interstices. The reduction in asphalt density beyond the optimum binder content, as observed in Figure 5, could also be attributable to the same phenomenon.

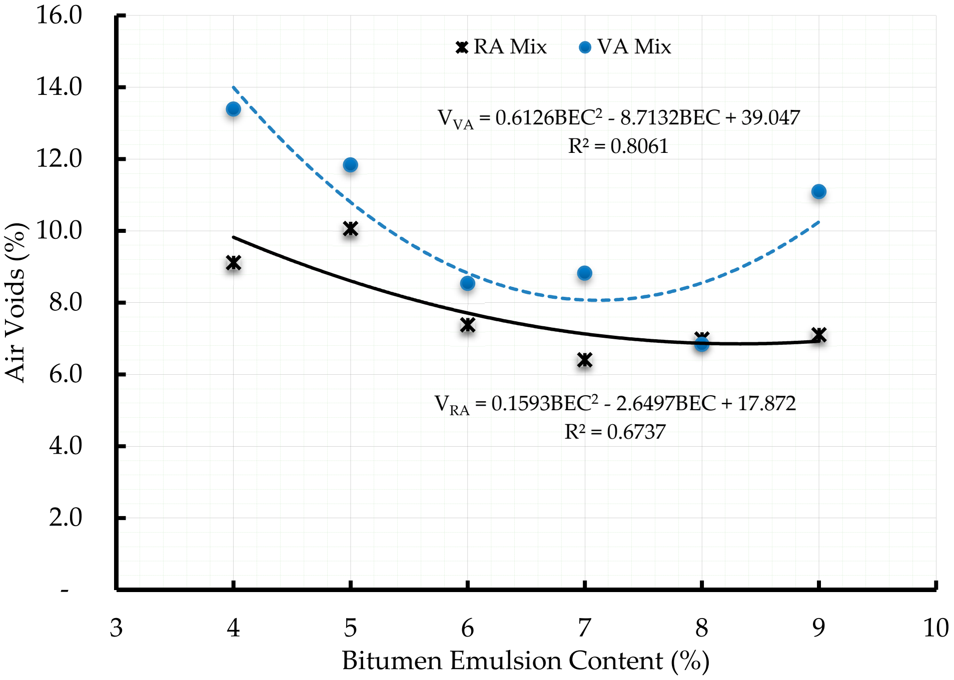

Figure 7. Air voids for Virgin Aggregates and Reclaimed Asphalt Mixes at Optimum Bitumen Emulsion Content.

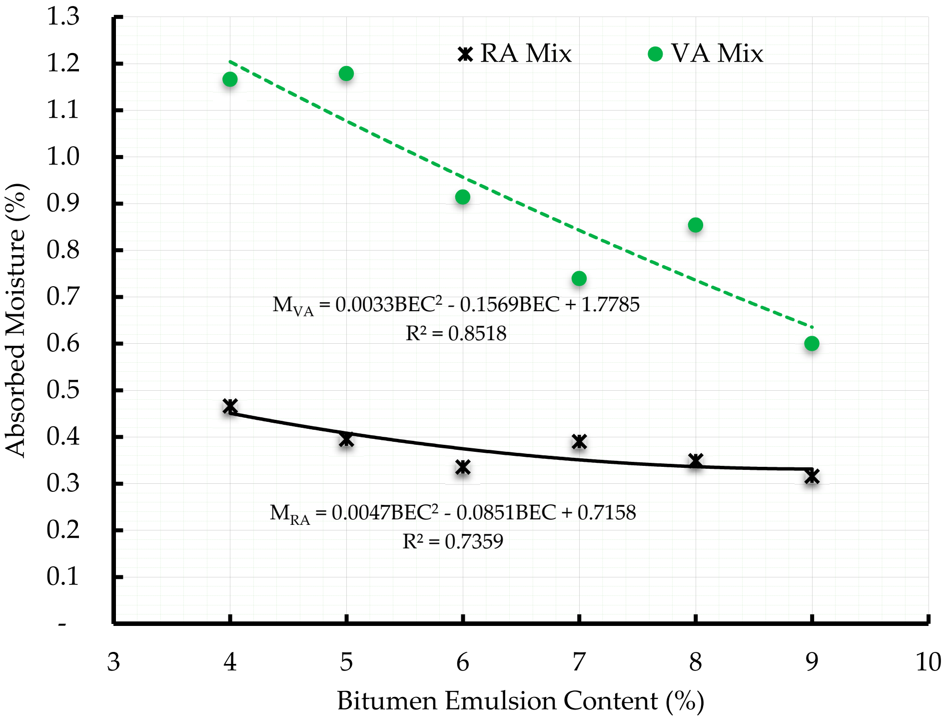

Figure 8. Moisture absorption for Virgin Aggregates and Reclaimed Asphalt Aggregates Mixes at Optimum Bitumen Emulsion Contents.

3.5. Moisture Susceptibility

At the optimum binder content of 6.1% by mass of dry aggregates for the VA mix and 6.2% for RA mix, the corresponding tensile strength ratios, from Figure 9, were 1.3 and 1.03, respectively. The minimum tensile strength ratio recommended by AASHTO T-283 to ensure sufficient moisture resistance of the mixture is 0.70 [21,23,47]. The tensile strength ratios of the two mixtures at the optimum bitumen emulsion contents were well above 1.0, meaning that the mixtures would sufficiently resist moisture damage. In a study of the effect of cement on the stripping properties of asphalt mixes employing three different aggregate sources in Texas, Kennedy and Anagnos [50] recorded TSR values ranging from 0.34 to 1.25, and they concluded that different sources of aggregates respond differently to moisture when used alongside cement in preparing asphalt mixtures. It is suspected that the emulsion bitumen used in this study, being a proprietary product, could have contained ions in the emulsifiers that reacted favorably with the pozzolanic basaltic aggregates to yield cementitious products. Alternatively, the emulsions might have contained some adhesion promoters. Active adhesion promoters are known to have surface active agents that react with silica surfaces even in the presence of water. These additives are popularly used with warm mix asphalt (WMA) to promote aggregate–bitumen adhesion in the presence of moisture [51]. As can be observed from Figure 9, while TSR values for VA mix progressively dropped, those of RA gradually rose to peak at the OBEC. This could be explained by considering that as more emulsion is added to RA, the aged binder gets dissolved and stripped from the aggregate surface, leaving room for agents in the emulsion to act on the pozzolanic basalt. The aggregates surface available on the VA, on the other hand, diminish with the increasing quantity of emulsion.

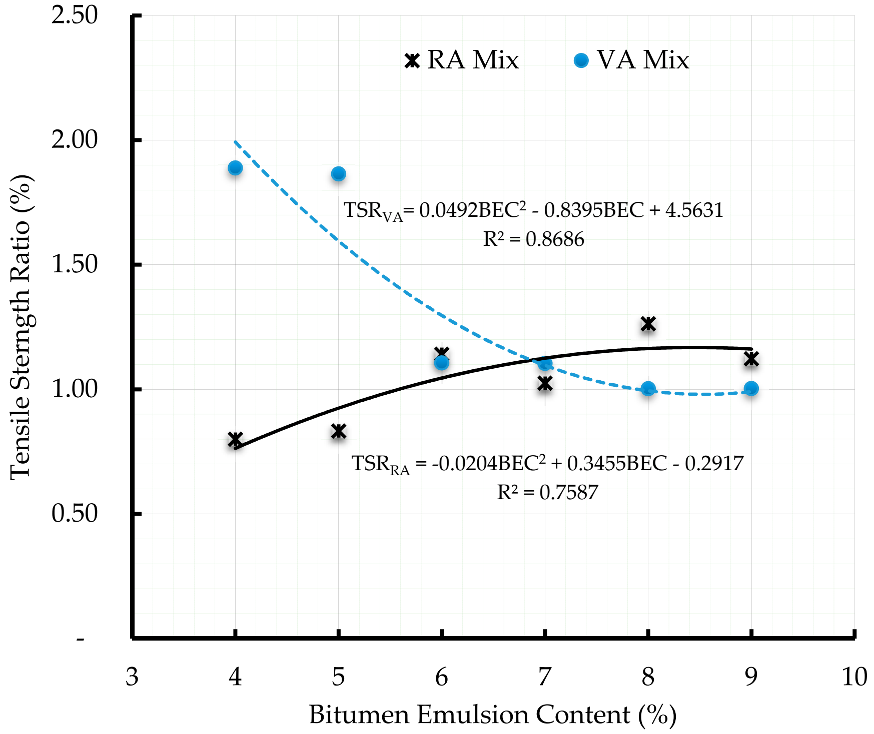

Figure 9. Tensile Strength Ratios for Virgin Aggregates and Reclaimed Asphalt Aggregates Mixes at Optimum Bitumen Emulsion Contents.

4. Conclusions

This study set out to assess the possibility of incorporating a percentage of reclaimed asphalt (RA) in conventional virgin aggregates (VA) emulsion asphalt mixtures. An emulsion asphalt mix composed entirely of VA was used as a control in the optimization. The following conclusions can be drawn from the findings of the study.

1. When properly designed, emulsion asphalt incorporating as high as 55% reclaimed asphalt aggregates can perform as satisfactorily as conventional VA emulsion asphalt mixtures.
2. Incorporation of reclaimed asphalt aggregates, with proper optimization of the binder and pre-mix water, results in reduced porosity and reduced water absorption of the mix, which leads to a reduction in moisture susceptibility of emulsion asphalt mix.
3. Emulsion asphalts incorporating reclaimed asphalt aggregates have lower densities than conventional virgin aggregates emulsion mixtures.

Author Contributions: The research was conceptualized by K.C. The methodology and experimental design were developed by Z.C.A.G. and S.M.S. Data collection and analysis was done by K.C. and checked by Z.C.A.G. and S.M.S. The article was jointly written by K.C., Z.C.A.G., and S.M.S. Additionally, Z.C.A.G. facilitated access to materials and laboratory equipment.

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Appendix A

Table A1. Aggregates Blend for Reclaimed Asphalt Emulsion Asphalt Mix

Sieve Size (mm)	0/6 mm Virgin	0/6 mm RAP	6/10 mm RAP	10/14 mm RAP	14/20mm RAP	Reclaimed Asphalt Mix Gradation	Cooper "Target Gradation"
28	100	100	100	100	100	100	100
20	100	100	100	100	100	100	100
14	100	100	100	99	19	88	85
10	100	100	100	17	1	73	72
6	99	99	13	1	-	61	58
4	92	70	1	-	-	52	47
2	67	43	-	-	-	37	33
1	42	26	-	-	-	23	23
0.425	19	14	-	-	-	11	15
0.300	14	10	-	-	-	8	12
0.150	7	6	-	-	-	4	8
0.075	4	2	-	-	-	2	5

Appendix B

Table A2. Aggregates Blend for Virgin Aggregates Emulsion Asphalt Mix

Sieve Size (mm)	0/6 mm Virgin	6/10 mm Virgin	10/14 mm Virgin	14/20mm Virgin	Virgin Aggregates Mix Gradation	Cooper "Target Gradation"
28	100	100	100	100	100	100
20	100	100	100	83	97	100
14	100	100	96	8	86	85
10	100	87	11	-	74	72
6	99	6	-	-	56	58
4	92	-	-	-	50	47
2	67	-	-	-	37	33
1	42	-	-	-	23	23
0.425	19	-	-	-	11	15
0.300	14	-	-	-	8	12
0.150	7	-	-	-	4	8
0.075	4	-	-	-	2	5

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