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Effects of asphalt content and reclaimed asphalt pavement on the performance of cold mix asphalt

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Abstract The use of Cold Mix Asphalt (CMA) for road pavement is a technique that batches, mixes, lays and compacts asphalt concrete at ambient temperatures. The application of CMA for road pavement is still limited especially in developing nations like Kenya. This is due to lack of universal standards required for the design and evaluation of cold mix asphalt. Asphalt content and type of aggregates significantly contribute to the performance of CMA. This study assessed the effects of asphalt content and recycled aggregates from Reclaimed Asphalt Pavement (RAP) on the performance of CMA. Modified Marshall Method was used to prepare two sets of specimens at varying binder content: one composed of virgin aggregates (virgin mix) and the other a mixture of virgin and RAP aggregates (RAP mix). Specimens were cured in three stages: mould curing for 24 hours at room temperature, isothermal curing in the oven at 40 ^{0}C for 72 hours and air curing at room temperature for 3 hours. The performance of CMA was analyzed in terms of stiffness, resistance to moisture damage and porosity. At varying asphalt content, the average RAP mix stiffness was approximately 26 % higher than that of the virgin mix. Moreover, the use of recycled aggregates from RAP improved the resistance of CMA to moisture damage by reducing stability loss to 28%, increasing the TSR values above 0.7 and reducing the amount of absorbed moisture to 0.06%. Recycling of RAP produced a mix with porosity higher than 10% that has negative effects on the durability of CMA pavements. In conclusion, Asphalt content beyond 3% decreases the stiffness of CMA hence it is not recommended for production of CMA pavements. Recycling of RAP aggregates is recommended as it improves the performance of CMA pavements in terms of stiffness and resistance to moisture damage.

Keywords Asphalt content, cold mix asphalt, reclaimed asphalt pavement (RAP) mix and virgin mix.

1. Introduction

The pursuit of sustainable methods of utilizing asphalt mixtures for road pavements worldwide has led to the development and use of Cold Mix Asphalt (CMA). Road pavement construction using CMA is a technique that batches, mixes, lays and compacts asphalt concrete at ambient temperatures [1]. Some of the benefits of using CMA for road pavement are: (i) Reduced energy consumption and air pollution during production [2]. (ii) Reduced depletion of natural resources and decreased need for landfills as a result of recycling of reclaimed asphalt pavements (RAP) [3]. (iii) Reduced overall production costs [4]. (iv) Use of labor based methods, which creates employment for unskilled citizens, especially those in developing nations like Kenya. Above noted benefits notwithstanding, the use of CMA for road pavement is still limited. This has been significantly contributed by lack of universal standards for the design and evaluation of CMA [5]–[8].

The pursuit to understand and use CMA on flexible pavements without universal standards has encouraged research individuals and institutions to propose design standards customized to their available resources. CMA is currently designed and assessed using Modified Marshall methods that were initially developed for hot mix asphalt [9][10]. This mainly disregards the strength gain mechanism that result from the bond between the aggregates and the binder. Kenya's "Specification for Roads and Bridge Construction" [11] only recommends the use of CMA for patch works during pavement repair and for surfacing of low volume traffic roads. The specification does not have a clear procedure for the production of CMA hence; it does not clearly elaborate the performance of CMA in relation to the binder and the aggregate type during mix design. The asphalt institute manuals [9][10] currently used in Kenya for the surfacing of low volume traffic roads have outlined a mix design procedure using the virgin aggregates. The mix design methods proposed by the manuals do not elaborate how the performance of cold mix asphalt at varying asphalt content is affected by recycled aggregates from RAP.

1.1 Strength gain of CMA

Cold asphalt emulsion mixture is produced by mixing asphalt emulsion and aggregates which are pre-wetted with water at ambient temperature [12]. The water in the mix also known as Total Fluid Content (TFC) is a combination of the water content in the emulsion and the aggregate pre-wetting water that hinders the bond between the aggregates and the bitumen binder. For CMA to gain strength as a result of bonding between the aggregates and the binder, the water must be expelled from the mix by evaporation through a process called curing [4], [13]. Expulsion of water enables the bitumen droplets to coalesce to a continuous film and coat the aggregates [14], [15]. Therefore, the binder content and the type of aggregates significantly affect the performance of CMA.

Studies on asphalt content of CMA have majorly focused on the quantity of asphalt content required for the production of an optimal cold mix asphalt during design. Some of the recommended asphalt contents include: emulsion content of 2% - 3% by mass of dry aggregate was found appropriate to produce optimal mix [16], [17]. Moghadam & Farhad [5] stated that the determination of asphalt content for CMA using the total fluids content does not give accurate results. Therefore, they concluded that the aggregate pre-mix water and emulsion content should be varied based on the type of emulsion and the aggregates used. In support of this, Nassar [18] stated that the pre-mix water and the asphalt content have different contributions to the performance of CMA and they should be considered independently. A study by Du [19] proposed the variation of pre-mix water based on the water content in the emulsified asphalt for the determination of an optimal emulsion content. The aforementioned studies on asphalt content have contributed majorly to the development of mix design of cold mix asphalt; they however do not elaborate how their recommended asphalt contents affect the performance of cold mix asphalt in terms of stiffness, resistance to moisture damage and porosity.

1.2 Reclaimed Asphalt Pavement

The use of recycled aggregates from Reclaimed Asphalt Pavement (RAP) to produce CMA has environmental and economic benefits [20], [21]. RAP is composed of aggregates coated with aged asphalt cement obtained during the rehabilitation of flexible pavements [22]. Recycling of RAP aggregates contributes positively to the environment by reducing the depletion of natural resources and limiting the amount of waste produced during pavement rehabilitation [16]. Incorporation of RAP aggregates to supplement 20% - 50% of the virgin aggregates during the rehabilitation of flexible pavements reduces the amount raw materials required hence 34 % the cost of production reduced [23].

Even with the above-mentioned sustainable attributes, the recycling of RAP aggregates is still limited in Kenya. This is because the RAP aggregates are coated with an aged binder that limits contact between the aggregates and the binder. Moreover, the bonding mechanism between the aged existing binder and the virgin bitumen emulsion is not well defined. This study determined the effect of asphalt content and RAP aggregates on the performance of cold mix asphalt in terms of stiffness, resistance to moisture damage and porosity.

2. Material and Methods

2.1 Materials

The materials required for this study were; virgin aggregates obtained from DM quarries located in Katani, Machakos County, recycled aggregates from RAP obtained from Enterprise Road Rehabilitation Project located at Industrial Area, Nairobi County and a slow-setting cationic bitumen emulsion (K3-65) obtained from

COLAS East Africa Limited located at Industrial Area, Nairobi County. The RAP material were collected in blocks, they were ground, sieved and stored in sacks as per their sizes of 0/6, 6/10, 10/14 and 14/20 mm respectively.

2.2 Material Characterization

The virgin aggregates, RAP aggregates and asphalt binder were subjected to pre-qualification tests to assess their viability for this study. The pre-qualification tests involved: Aggregate physical tests (BS 812:112) [24], aggregate mineral composition using X-Ray Fluorescence method (X-RF), and aggregates mechanical tests. The mechanical tests were: Aggregate Crushing Value (BS 812:110) [25], Flakiness Index (BS 812:105) [26] and Los Angeles Abrasion test (BS EN 1097:2) [27]. The binder in the RAP was extracted using the rotary evaporation method (BS EN 12697-3, 2013) [28]. Both the extracted binder and the K3-65 were subjected to penetration test (BS 2000-49) [29] and the softening point test (BS 2000-58) [30].

2.3 Mix design

Two cold asphalt emulsion mixtures were developed, one incorporating the virgin aggregates (virgin mix) and the other a mixture of the virgin and RAP aggregates (RAP mix) using the Modified Marshall method [9], [10]. The mix design procedure was as follows:

1. Combined aggregate grading
2. Determination of Initial Emulsion Content (IEC)
3. Emulsion Coating Test
4. Determination of Pre-mix water content.
5. Varying of the residual asphalt content.

2.3.1 Combined Aggregate Grading

A set of standard sieves were used for sieve analysis of the virgin and RAP mix (BS 812:103) [31]. Cooper's formula represented by Equation 1 was used to determine combined aggregate grading.

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

Where:
P = Material passing a sieve of size d (%)
d = Selected sieve size (mm)
D = Maximum aggregate size (mm)
n = An exponent that dictates the concavity of the gradation line (n = 0.45)
F = The filler content (%).

The objective was to obtain a dense graded mix with minimal air voids [32]. The value of n used was 0.45 for optimal parking of aggregates [33]. No fine filler (F) was used in the study. Maximum aggregates size was 20 mm. Grading results showed that combined grading of pure RAP aggregates was courser than that of the virgin aggregates. This can be explained by the presence of the aged bitumen binder coating the RAP aggregates that agglomerates the RAP fines to each other and to the coarse aggregates. The course grading of RAP mix was improved by blending it with 50 % fine virgin aggregates of size 0/6 mm using Equation 2 [9], [22].

$$P = aA + bB + cC \quad (2)$$

Where:
P = Combined aggregates sizes passing a particular sieve (%).
A, B & C = Aggregates of specific size passing a particular sieve (%).
a, b, & c = Proportions of aggregates of specific size used in combined grading (%).

Combined aggregate grading of the virgin and the RAP mix were within the acceptable limits of the grading envelope proposed by the "Technical Guide 2" [33].

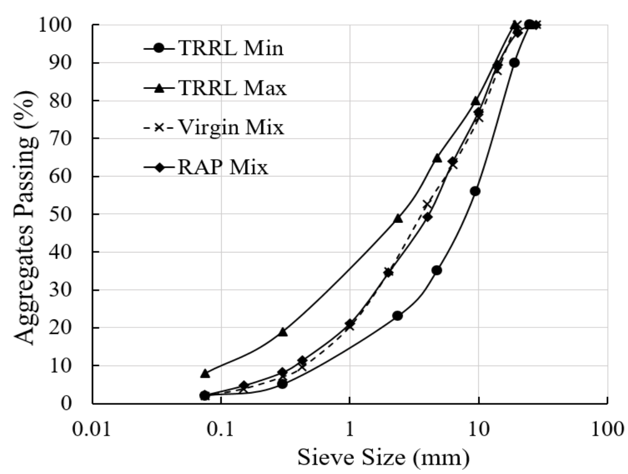


Fig 2.1. Combined Aggregate Grading (Asphalt Academy, 2009)

2.3.2 Initial Emulsion Content (IEC)

The Initial Emulsion Content (IEC) approximates the amount of binder required by the cold mix asphalt. It is obtained using the Centrifuge Kerosene Equivalent (CKE) test in the laboratory. In the absence of the CKE equipment as it was the case for this study, Equation 3 was used to estimate the binder demand [9]

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

where:

P_b = Total binder demand by mass of the combined aggregates (%).

A = Aggregates greater than sieve size 2.36 mm (%)

B = Aggregates passing sieve size 2.36 mm and retained on sieve size a 75 µm (%).

C = Mineral filler passing sieve size 75 µm (%).

The total binder content (P_b) was incorporated in Equation 4 to determine the amount of additional binder required by the RAP mix

$$P_{nb} = P_b - \frac{P_{sb}(100-r)}{100} \qquad (4)$$

where;

r = Virgin aggregates to be blended with the RAP aggregates (%)

P_{sb} = Asphalt content in RAP aggregates (%)

P_{nb} = Amount of additional binder (%)

P_b = Total binder demand (%)

The values of P_b and P_{nb} were incorporated in Equations 5 and Equation 6 to get the initial emulsion content of the virgin and the RAP mix respectively.

$$IEC = \frac{P_b}{X} \times 100 \qquad (5)$$

$$IEC = \frac{P_{nb}}{X} \times 100 \qquad (6)$$

where;

IEC = Initial emulsion content by mass of total mix (%)

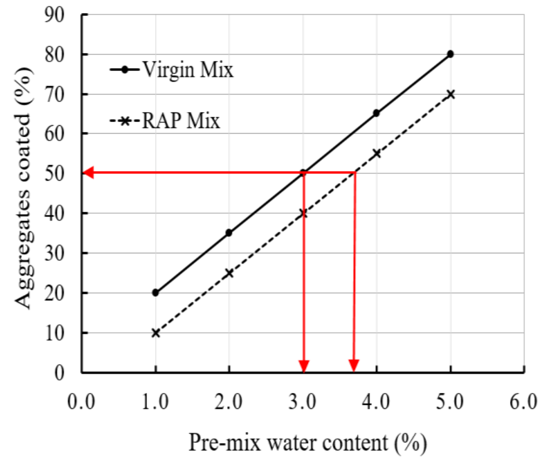
X = Asphalt content in the emulsion (%)

The asphalt emulsion (K3-65) used in this study was 65% asphalt content (X) and 35% water. Therefore, the IEC for the virgin and the RAP mix were 8% and 5% by mass of dry aggregate respectively. This is equivalent to an Initial Residual Asphalt Content (IRAC) of 5.2% and 3% by mass of dry aggregate for the virgin and the RAP respectively.

2.3.3 Emulsion Coating Test

Coating test was done to determine if the asphalt emulsion (K3-65) could effectively coat the aggregates. Five samples of blended dry aggregates each of mass 200 grams were prepared for the virgin and the RAP mix respectively. They were mixed with water for 60 seconds at varying pre-mix water content of 1% - 5%. Asphalt emulsion content equivalent to the calculated IEC for each mix was added to the pre-wetted aggregates and mixed further for 60 seconds. The samples were then placed on white filter papers and they were left to air cure for 24 hours (Fig. 2.2a). After 24 hours, the percentage of aggregates coated by the asphalt emulsion was visually estimated. Observations drawn were: (i) the percentage of RAP aggregates coated was lower than the percentage of virgin aggregates coated at equal water content. (ii) Increase in pre-mix water content increased the percentage of aggregates coated for both the virgin and the RAP mix (Fig. 2.2b). The asphalt emulsion should coat at least 50% of the aggregates for it to be suitable for the production of cold mix asphalt [9]. The asphalt emulsion (K3-65) coated 50% of the virgin and the RAP aggregates at 3% and 3.7% pre-mix water content respectively (Fig. 2.2b).

(a) Coated aggregates during curing



(b) Results of coating test

Fig. 2.2. Emulsion Coating test

2.3.4 Determination of Pre-Mix water content

Specimens composed of 1100g of blended aggregates, asphalt content equal to IEC and varying pre-mix water content were moulded and compacted using the Marshall procedure [34]. The pre-mix water was varied between 1% and 5% by mass of dry aggregates. Three samples were prepared for each pre-mix water content. Curing regimes used in this study are adopted from previous studies since there is no universal standard for curing CMA during design. Curing was done in three stages: First, the specimens were left to cure in the moulds after compaction for 24 hours at room temperature. CMA gains strength slowly, therefore mould curing enabled the CMA specimens to gain strength prior to extrusion. The specimens were then subjected to isothermal curing in the oven for 72 hours at 40 ^{0}C. Finally, they were allowed to cool at room temperature for 3 hours prior to the stability test [8], [9], [13], [35]. The stability was obtained by loading the specimen diametrically using the Indirect Tensile Strength (ITS) apparatus up to the point of failure (BS EN 12697:23) [36]. The dial reading at the point of failure was multiplied by the ring factor (0.0228 kN) to get stability. Pre-mix water has a direct correlation with stability of cold mix asphalt [19]. Therefore, pre-mix water content was plotted against stability and optimal pre-mix water content was selected at the highest stability (Fig. 2.3). Optimal pre-mix water content was 2.8% and 4.0% by mass of dry aggregates for the virgin and the RAP mix respectively.

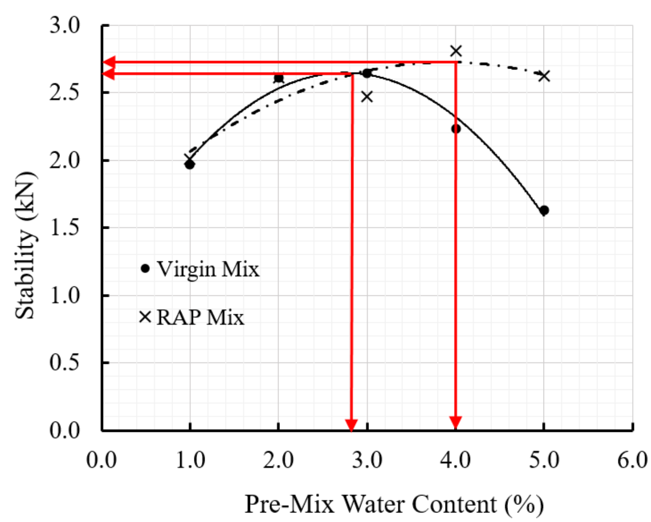


Fig. 2.3. Pre-mix water content

2.3.5 Varying of the asphalt content

The asphalt emulsion used in this study was composed of 65% asphalt and 35% water. The percentage asphalt content was varied two points above and two points below the calculated initial residual asphalt content (IRAC). The virgin mix had an IRAC of 5.2% hence the asphalt content was varied from 3.3% to 5.9% by mass of dry aggregate. The RAP mix had an IRAC of 3 % hence asphalt content was varied from 1% to 5% by mass of dry aggregate. Six specimens were prepared for each asphalt content at a constant pre-mix water. Specimen were cured in three stages as outlined in section 2.3.4. Three specimens from each batch were subjected to moisture conditioning [9] and were tested as soaked specimens. The remaining three were tested as dry specimen. The effect of asphalt content and RAP aggregate on the performance of cold mix asphalt was analyzed in terms of stiffness, resistance to moisture damage and porosity.

3. Results and Discussion

3.1 Stiffness of Cold Mix Asphalt

Indirect Tensile Strength (ITS) test is as performance-based test used to determine the stiffness of CMA [13]. Stiffness of CMA specimens during design illustrates the ability of CMA pavements to resist failure due to traffic loading. Cured specimens were loaded diametrically at a rate of 50.8 mm/min up to a point of failure (Fig. 3.1) in accordance to BS EN12697-23, 2003 [36].

Fig. 3.1. Indirect Tensile Strength (ITS) test

The load at the point of failure was recorded and multiplied by the machine calibration factor of 0.0228 kN to get the maximum load (P_{ult}). Stiffness was calculated using Equation 7

$$S_t = \frac{2000\ X\ P_{ult}}{\pi\ X\ d\ X\ t} \quad (7)$$

where;
S_t = Stiffness (kN/m^2)
P_{ult} = Maximum load (kN)
t = Thickness of the specimen (mm)
d = Diameter of the specimen (mm)

3.1.1 Effect of asphalt content on stiffness of cold mix asphalt.

Asphalt content was plotted against stiffness (Fig. 3.2). The stiffness of the virgin mix decreased gradually from 382 kN/m^2 to 324 kN/m^2 with increase in asphalt content while that of RAP mix increased to a peak of 409 kN/m^2 at 3% asphalt content then decreased with further increase in asphalt content. Gradual increase in stiffness of asphalt concrete up to a peak point followed by gradual decrease in stiffness as illustrated by the RAP mix is the most observed relationship between asphalt content and stiffness for hot mix asphalt [37] and cold mix asphalt [9], [38]. Therefore, asphalt content beyond 3% reduces the stiffness of cold mix asphalt. These observation was consistent with Valentin et al. [17] who recommended asphalt content of 2%-3%.

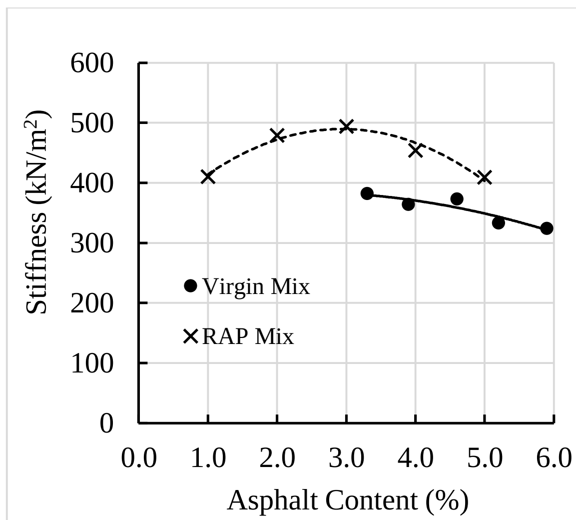


Fig. 3.2. Stiffness of cold mix asphalt

3.1.2 Effect of RAP on stiffness of CMA

The stiffness of the RAP mix was found to be higher than that of the virgin mix for all asphalt contents (Fig. 3.2). The average stiffness of the RAP mix was approximately 26 % higher than that of the virgin mix. This can be explained by the fact that the RAP material is stiff as a result of in-situ aging during service [20]. Similar studies with consistent results have recommended recycling of

RAP aggregates to reduce permanent deformation of asphalt pavement layers [20], [39].

3.2 Resistance to moisture damage of cold mix asphalt

The presence of moisture in asphalt concrete loosens the adhesive bond between the aggregates and the asphalt binder causing stripping and raveling of asphalt pavement [40]. To simulate in-situ seasonal wet weather conditions, three specimens for each asphalt content were subjected to moisture conditioning to assess their resistance to moisture damage [9]. Stability loss, tensile strength ratio (TSR) and the amount of moisture absorbed (%) were used to assess the effect of asphalt content and RAP aggregates on the resistance to moisture damage of cold mix asphalt.

3.2.1 Stability loss of CMA

The stability of dry specimens for both the virgin and the RAP mix was found to be higher than the stability of moisture conditioned (soaked) specimens (Fig. 3.3). This illustrates the deteriorating effect of moisture on asphalt concrete that reduces the stiffness and ultimately the durability of asphalt pavements [9], [40].

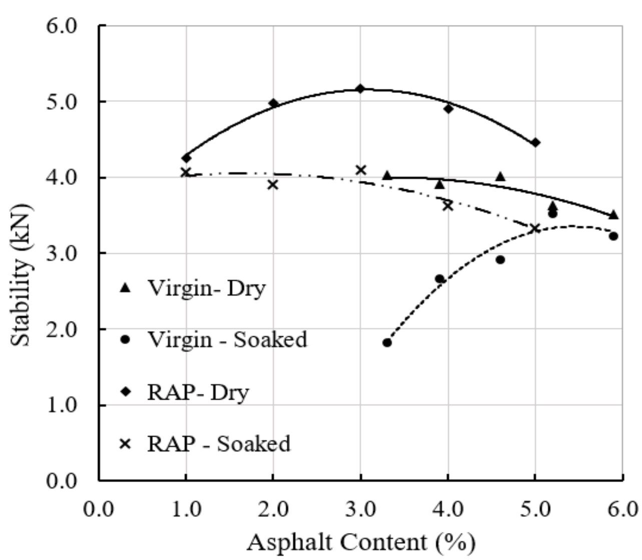


Fig. 3.3. Stability of cold mix asphalt

Stability loss is the depreciation of stability of CMA specimen due to moisture damage. It is occurs when water reduced the adhesive bonds between the aggregates and the binder. Stability loss was calculated using Equation 8 [41]

$$\Delta S = 100 \times \left[\frac{(S_1 + S_2 + S_3) - (S_4 + S_5 + S_6)}{(S_1 + S_2 + S_3)}\right] \qquad (8)$$

where:
ΔS = Stability loss (%)
S_1, S_2, S_3 = Stability of dry specimens
S_4, S_5, S_6 = Stability of soaked specimens

The virgin mix had high stability loss of 48% compared to that of the RAP mix of 26% (Fig. 3.4). The Asphalt Institute manual recommends 50% maximum stability loss of CMA subjected under moisture conditions [9]. The stability loss of virgin mix decreased linearly with increase in asphalt content while that for the RAP mix increased exponentially with increase in asphalt content (Fig. 3.4).

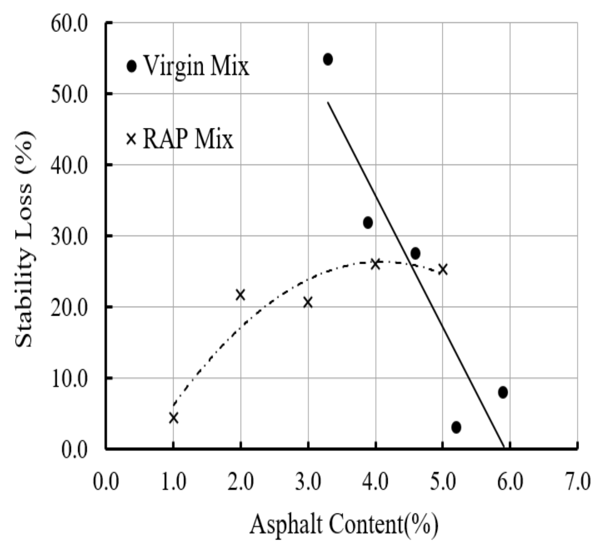


Fig. 3.4. Stability loss of cold mix asphalt

This can be explained by the fact that the virgin mix had high asphalt content demand of 5.2% illustrated by Equation 5. Therefore, at low asphalt content, the mix stability was too low to effectively resist moisture damage resulting to high stability loss. The RAP mix had a 3% asphalt demand meaning that increase in asphalt content decreased the stability of the mix causing an increase in stability loss of the soaked specimen.

3.2.2 Tensile Strength Ratio (TSR)

Tensile Strength Ratio (TSR) is the ratio of stiffness of the moisture-conditioned (soaked) specimen to that of dry specimen illustrated by Equation 9.

$$TSR = \frac{ITS_{\,Conditioned\ Specimen}}{ITS_{\,dry\ specimen}} \quad (9)$$

TSR of cold mix asphalt should be greater than 0.7 for it to be effective in resisting damage by moisture when used to surface flexible pavements [9], [42]. The virgin mix achieved TSR of 0.7 at 4.1% asphalt content. This means that below 4.1% asphalt content, the virgin mix is highly susceptible to moisture damage. For the RAP mix, TSR of 0.7 was achieved at every asphalt content (Fig. 3.5). The observed higher resistance to moisture damage in terms of TSR by the RAP mix compared to that of the virgin mix can be explained by the stiff nature of RAP aggregates as a result of in-situ aging [43].

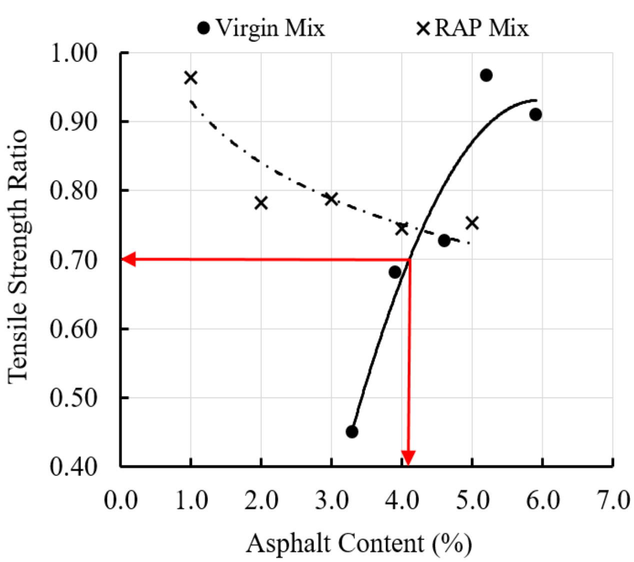


Fig. 3.5. TSR of cold mix asphalt

3.2.3 Moisture Absorbed (%)

Moisture absorbed was the amount of water absorbed by the moisture conditioned (soaked) specimens. Cold mix asphalt contains water during production. Therefore, the amount of moisture absorbed was the difference between the moisture of soaked specimens at testing and the moisture of dry specimens at testing expressed as a percentage of the mass of dry specimen illustrated by Equation 10.

$$M = \left(\frac{M_{soaked} - M_{dry}}{Mass_{\,dry\ specimen}}\right) \times 100\% \quad (10)$$

Where:

M = Moisture absorbed (%)

M_{soaked} = Moisture of soaked specimens at testing (g)

M_{dry} = Moisture of dry specimens at testing (g)

$M_{dry\ specimen}$ = Mass of dry specimen (g)

The amount of moisture absorbed by both the virgin and the RAP mix decreased with increase in asphalt content (Fig. 3.6). At low asphalt content, the virgin mix absorbed 0.13% of moisture, which was higher than 0.06% of the RAP mix. The slow rate of moisture absorption by the RAP aggregates can be explained by the fact that the aged asphalt binder coating the RAP aggregates is stiffer than the new binder added to the mix hence it limits the RAP aggregates from absorbing the water. [44].

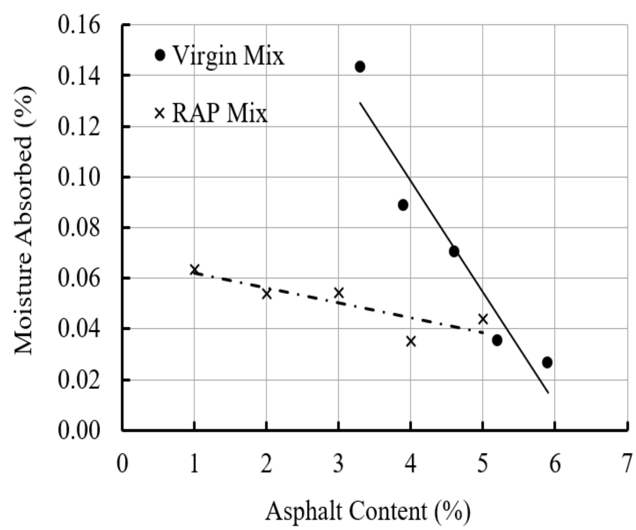


Fig. 3.6. Moisture absorption of CMA

Resistance to moisture damage of CMA was more affected by the type aggregate compared to the binder content. The use of recycled aggregates from RAP improved the resistance of CMA to moisture damage by reducing stability loss to 26%, increasing the TSR values above 0.7 and reducing the amount of absorbed moisture to 0.06%. This implies that the incorporation of recycled aggregates from RAP in the construction of CMA pavements would improve their resistance to moisture damage.

3.3 Porosity of cold mix asphalt

Air voids content expressed as a percentage was used to illustrate the porosity of the mix. Air void content ranging from 3% to 7% is recommended for asphalt concrete pavements to prevent early life permanent deformation (rutting) caused by very low air voids below 3% and moisture ingress caused by high air voids above 7% [8], [45]. For the virgin mix, increase in asphalt content increased the air voids content from 8.7% to 9.7% while the RAP mix had an inversely peaked curve where the air voids reduced with increase in asphalt content up to 3% asphalt content then started to increase (Fig. 3.7).

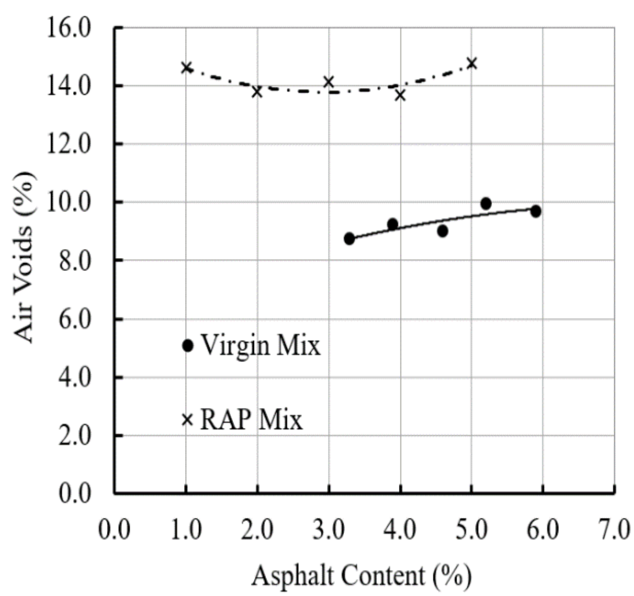


Fig. 3.7. Porosity of cold mix asphalt

The RAP mix air voids content was found to range from 13.7% to 14.8%. Observations drawn from Figure 3.7 were: high air void content of cold mix asphalt was well demonstrated with both mixtures having air void content above 7 % [1]. Secondly, the porosity of the RAP mix was higher than that of the virgin mix. This can be explained by the coarse grading of RAP aggregates caused by the agglomeration of RAP fines by the existing aged binder. Moloto [32] stated that the porosity of the RAP mix after in-situ compaction should range between 12% - 15%. Another study on cold recycled mixtures obtained air void content range of 10% - 20% [17]. The porosity of CMA was more affected by the type aggregate compared to the binder content. High air void content in asphalt concrete negatively affects the durability of flexible pavements.

4. Conclusions

The objective of this study was to determine the effect of asphalt content and RAP aggregates on the performance of cold mix asphalt in terms of stiffness, resistance to moisture damage and porosity. The study concludes as follows:

i) Increase in asphalt content beyond 3 % reduced the stiffness of the virgin mix and RAP mix. Use of recycled aggregates from RAP increased the stiffness of cold mix asphalt by an average of 26% compared to the use of virgin aggregates.

ii) The RAP mix illustrated superior performance in terms of resistance to moisture damage compared to the virgin mix. This was elaborated by TSR greater than 0.7 for all asphalt content unlike the TSR values of the virgin mix, limited moisture absorption below 0.06 % compared to 0.13% of the virgin mix and limited maximum stability loss of 28% compared to 48% of the virgin mix.

iii) The type aggregate used had superior effect on the porosity of CMA compared that of the binder content. CMA containing RAP aggregates had maximum air void content of 13.7% compared to 9.7% of the virgin mix. High porosity in asphalt concrete renders flexible pavements susceptible to water ingress. This has a negative implication on the durability of CMA asphalt pavements.

Acknowledgment

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