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Technical Note:

REVIEW AND RECOMMENDATION OF COLD ASPHALT EMULSION MIXTURES (CAEMs) DESIGN

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Note from the Editor

Cold Asphalt Emulsion Mixture (CAEM) is a mixture of aggregates and asphalt emulsion that is mixed at room temperature. It is relatively simple to produce, but the design procedure provided by the Asphalt Institute and the Ministry of Public Work of Indonesia pose some problems in its practical application. This Technical Note discusses limitations of the current design procedures and presents a simpler and more practicable design procedure

INTRODUCTION

Public transport is a vital element in mobility, since At the moment, there is no universally accepted mix design method for Cold Asphalt Emulsion Mixtures (CAEMs). In addition, correlation and assessment of test results are still vary among researchers and institutions, therefore there are lacks of uniform procedures for laboratory evaluations. In the United Kingdom (UK) attention on cold mix cold lay materials is encouraged by the issue of "Specification for Reinstatement of Openings in Highways" by the Highway Authority and Utility Committee (HAUC) in 1992 , which allows the use of Permanent Cold Lay Surfacing Materials (PCSMs) as an alternative to hot mix materials for reinstatement works in low volume roads and footpaths. The PCSMs however should perform adequately after two years of guarantee period which is becoming a major challenge [1]. Meanwhile in Indonesia, Specification on CAEMs had been available at least since 1990 provided by the Ministry of Public Works–Republic of Indonesia [2].

CAEMs have been said more suitable for low to medium traffic conditions, for works in remote areas and for small scale jobs such as reinstatement works. CAEMs are still considered inferior to hot asphalt mixture. There are three main concerns on CAEMs, namely: high porosity of the compacted mixture, weak early life strength (as it contains water) and long curing time (evaporation of water/volatile content) required to achieve maximum performance. Studies by Chevron Research Company in California, concluded that full curing of cold asphalt mixtures on site may occur between 2 - 24 months depending on weather condition [1].

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The physical targets aimed at are to produce mixtures that satisfy the following volumetric and mechanical guidelines:

- Porosity values of compacted mixtures: 5-10% [2].
- soaked stability of 3 kN [2], and/or Indirect Tensile Stiffness Modulus (ITSM) of 2000 MPa [3,4]

CAEMS DESIGN PROCEDURES REVIEWED

Before showing the limitations (problems) on the CAEMs design procedures, it is necessary to briefly give the reader a general picture about them. Three CAEMs design procedures from two institutions were reviewed by the author, namely:

- Asphalt Institutes Manual Series (MS) 14, 1989 [5]
- Asphalt Institutes Manual Series (MS) 19, 1997 [6], and
- The Ministry of Public Works Republic of Indonesia [2].

CAEMs Design Procedure of the Asphalt Institute MS 14, 1989 [5]

This design procedure basically consists of the following step:

a. Determination of Aggregates Gradation
   This can simply follow the Asphalt Institute specification which can be of dense or gap gradation.
b. Determination of Initial Residual Asphalt Content (IRAC) and the Initial Emulsion Content (IEC)
   The first step is to calculate the Initial Residual Asphalt Content (IRAC), designated as P, utilizing an empirical formula as shown below:
   $$P = (0.05\,A + 0.1\,B + 0.5\,C) \times (0.7) \quad (1)$$

where P is the percentage of Initial Residual Asphalt Content by mass of total mixture, A the percentage of aggregate retained on sieve 2.36 mm, B the percentage of aggregate passing sieve 2.36 mm and retained on 0.075 mm, and C the percentage of aggregate passing 0.075 mm.

$$IEC = (P / X)[\%]. \quad (2)$$

where IEC is the Initial Emulsion Content by mass of total mixture and X the asphalt content of the emulsion.

c. Coating Test
Using the IEC value Coating Test shall be carried out by mixing all of the batches dry aggregates and filler, and pre-wetted with varied amount of water. The asphalt emulsion is added afterwards and then mixed for about 2-3 minutes until even coating obtained. The optimum pre-wetting water content (OPWwc) that gave the best asphalt coating on the mineral aggregates (in which the mixture is not too sloppy or too stiff) then can be determined. The degree of coating should not be less than 50 % by visual observation.

d. Determination of Optimum Total Liquid Content at Compaction (OTLC)
Utilizing the IEC, the mix is compacted at a pre-determined medium compaction level (50 Marshall blows on each side of the sample). The loose mixtures were compacted at OPWwc and at varying water content at compaction with 1 % steps by air drying. This stage will give the OTLC at which the dry density of the sample is a maximum.

e. Variation of Residual Asphalt Content (RAC)
Whilst maintaining a constant OTLC value, the RAC was varied at two points above and two points below the RAC in steps of 0.50 %. Specimens were mixed, compacted and tested at each of these RAC values.

f. Curing
The first procedure (referred to as "design curing") was used to assist in determination of the mechanical and volumetric properties during the mixture design procedure, i.e. to assess the influence of variations in pre-wetting water content (PWwc) and total liquid content (TLC) values.

Design Curing for mix design purposes, when determining Optimum Residual Asphalt Content is carried out in two stages:

- Design Curing Stage A; Oven Curing Compacted Samples for Dry Stability Test.
  This conditioning procedure consisted of keeping the samples for one day in their moulds after compaction. The samples are then extruded and kept for one day in an oven at 40 °C, they were then removed from the oven and stored for one day at room temperature (24 °C). Some of the samples are subsequently tested for Marshall Stability at room temperature and the results obtained are referred to as Dry Stability.
- Design Curing Stage B; Water Conditioning (capillary soaking) Samples for Soaked Stability Test.
  After having been subjected to oven curing as explained earlier in Design Curing stage A, the dry samples are water conditioned (capillary soaking). In this procedure half the thickness of each compacted specimen is soaked in water at room temperature for 24 h, the specimen is then inverted and the other half was soaked for a further 24 h. During soaking, the samples would rest on a bed of approximately 15 to 20 mm coarse sand. The samples are subsequently towel dried then tested for Water Absorption and Marshall Stability at room temperature. The Marshall Stability test results obtained are referred to as Soaked Stability values. At this condition the samples have not yet achieved full curing, i.e. still contain some amount of water.

g. Determination of Optimum Residual Asphalt Content (ORAC)
This is achieved by optimizing the following parameters from samples of all residual asphalt content (RAC) variation:
- Soaked Stability
- Retained Stability (ratio of Soaked/Dry Stability)
- Dry Bulk Density/SG (values obtained from Design Curing Stage A, taking into account the remaining water content in the samples at the time of testing),
- Porosity (values obtained from Design Curing Stage A),
- Water Absorption (values obtained from Design Curing Stage B),

The main parameters considered are the maximum soaked stability and the maximum dry density, meanwhile other parameters should meet the specification at the proposed ORAC.

CAEMs Design Procedures of the Asphalt Institutes MS 19, 1997 [6]

The Asphalt Institutes MS 19, 1997 [6], largely follows its predecessor MS 14, 1989 [5], but with main addition and modification as below.

Adhesion Testing Procedure

In this additional procedure, the coated loose CAEMs shall be cured in oven at 60 °C for 24 hours,

and then it is boiled and stirred (with one revolution per second) for three minutes. After that the loose mixture is air dried, and evaluated for its degree of coating. If the degree of coating remains satisfactory, the asphalt emulsion can be used, otherwise other type or grade of emulsion should be used.

Compaction Procedure and Curing

There are modifications for compacting the samples compare to the Asphalt Institute MS 14, 1989 [5]. There is no requirement for Optimum Total Liquid Content at Compaction (OTLC), but the mixtures shall be air dried until neither too wet nor two dry for compaction. When the mixtures are too wet, and drop hammer compaction is applied, the hammer may bounces. If it is too dry, the mixtures become too stiff. The specimens are compacted at medium compaction (the same as in MS 14, 1989 [5]).

The other modification is on the curing of the samples. After compaction the samples are cured including its mould in oven at 60 °C for 48 hours. After that, while the samples are still at that temperature, the samples are given additional compaction by using double plunger from both top and bottom of the specimen. The load applied is 178 kN for one minute. The samples are then cooled down, de-moulded then tested.

The modifications above will require changes to the existing testing procedure and requires additional equipment compared with the one that had been practiced in Indonesia.

CAEMs Design Procedures of the Ministry of Public Works of Indonesia [2]

The design procedure adopted by the Ministry of Public Works Republic of Indonesia: "The Paving Specifications Utilizing Asphalt Emulsions" [2] is basically the same with the one from the Asphalt Institute Manual Series (MS) 14 1989 [5], therefore it is not described further. But, there are two main differences on the specification (Table 1), i.e. the there is a requirement for porosity of 5-10%, and a minimum bitumen film thickness of 8 micron on the Indonesian specification [2], while there are no such requirement on the Asphalt Institute MS 14 [5].

LIMITATIONS ON THE DESIGN PROCEDURES REVIEWED

Limitation on the Design Procedures of the Asphalt Institute MS 14, 1989 [5]

After carrying out intensive laboratory works, it had been experienced and felt by the author that there are some limitations (problems) on the design procedures mentioned in the previous related sections. Those limitations are described below.

Determination of Optimum Total Liquid Content at Compaction (OTLC)

The procedure is of a sound principle. However it is unlikely practicable and difficult to control on site particularly when involving low skill labor and conventional equipment in mass mixture production. This can be described by referring to an example in Figure 1.

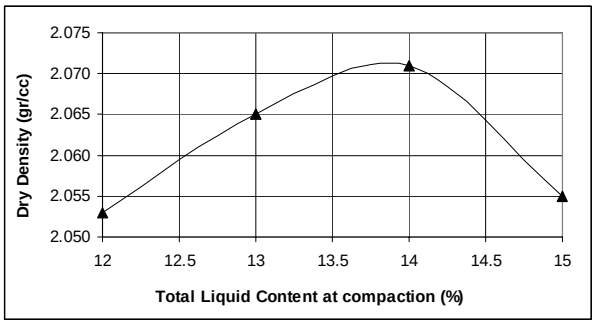

Figure 1. Total Liquid Content (TLC) at Compaction.

Data in Figure 1 was based on 6% initial residual asphalt content (IRAC). Four batches of samples were produced at the same total liquid content (TLC), i.e. emulsion + pre-wetting water, of 15% by weight of total mixture obtained from the coating test result. One batch was compacted at 15% TLC (straight away after mixing), and three batches of samples were air dried and each was compacted after achieving TLC of 14%, 13%, and 12% as shown in Figure 1. The optimum total liquid content (OTLC) at compaction was found at 14%, which gave maximum density 2.072 gr/cm3.

This procedure is practicable in laboratory, but requires a good care by regularly weighing the air dried mixture until achieving certain OTLC that give maximum density. This is the particular part that is unlikely practicable on site.

The Pre-determined Compaction Effort

The compaction effort is pre-determined at 50 blows Marshall hammer on each side of the specimen (medium level of compaction). There is no porosity requirement in the Asphalt Institute MS 14, 1989 [5]. This level of compaction level had been found could meet the Soaked Stability specifications of 2.225 kN [5], but could hardly achieve achieve porosity less than 10% require in the Indonesian specification where the porosity target is: 5-10 % [2].

In term of porosity, even at heavy compaction level (75 blows on each side of the specimen), the porosity was still higher than the target [11, 14] as shown in Table 1. Another thing to be considered is that, although the compaction level is the same, there can be a significant difference in porosity. This could be due to the quality hence workability of the emulsion (Table 1).

Table 1. CAEMs Properties at Optimum Residual Asphalt Content (ORAC) subjected to Design Curing Condition at room temperature 24°C, compared with Specifications.

Description	Characteristics of CAEMs (Average values)					
	Soaked Stability (kN)	Retained Stability (%)	Dry Bulk Density (gr/cc)	Porosity (%)	Water Abs. (%)	AFT * Micron (μm)
CAEMs using Total Emulsion (100pen) [14]:						
Medium Compaction						
ORAC = 6 % (soaked sample)	15.125	92.137	2.073	12.575	0.647	14.98
Heavy Compaction						
ORAC = 6 % (soaked sample)	17.556	90.676	2.155	9.155	0.494	14.98
Dense Emulsified Bitumen Macadam (100pen) [11]:						
Medium Compaction 2 × 50 blows Marshall Hammer	-	-	-	18.73	-	-
Heavy Compaction 2 × 75 blows Marshall Hammer	-	-	-	16.31	-	-
Summary of Specifications [2,5]:						
The Asphalt Institute, 1989, 1997, at 22°C	2.225	50 (min)	-	-	-	-
The MPW-RI, 1990 at room temp.	3.0	50 (min)	-	5 – 10	4 (max)	8 (min)
Compactor: Marshall Hammer	2 × 50 blows Marshall Blows (Medium Compaction)					

* AFT: Asphalt Film Thickness

After carrying out sufficient trials, it was found that the mix requires Extra Heavy Compaction (up to two times heavy compaction effort) to safely meet porosity target 5-10% in line with the Indonesian Specification [2]. This is another problem on CAEMs as there is no universally accepted specification available regarding porosity requirements on CAEMs.

The Retained Stability: (Soaked Stability/Dry Stability)

These parameters are taken from samples with all variation of residual asphalt content based on Design Curing Stage A and B of the Asphalt Institute MS 14, 1989 [5]. Marshall Stability test is a destructive test, therefore it requires the production of too many samples, i.e. Soaked samples and Un-Soaked samples. This is felt unnecessary. It will be more efficient if this parameter only to be determined at ORAC only. It also had been experienced by the author that the un-soaked stability test results at lower asphalt content then the ORAC can scatter [14]. This situation may be because of the compacted mixtures had not yet achieved full curing condition or still contain some trapped water.

The Ultimate Strength of the CAEMs

The Asphalt Institute MS14 design procedure does not mention the ultimate strength requirements. The soaked stability value recommended is based on the Design Curing of the Asphalt Institute MS 14, 1989 [5] previously described. At this condition the samples still contain water or have not yet achieved full curing condition.

Limitation on the Design Procedures of the Asphalt Institute MS 19, 1997 [6]

Referring to the Design Procedures of the Asphalt Institutes MS 19, 1997 [6], the modification and additional equipment required would cause difficulties in implementing the design procedure in Indonesia.

Limitation on the Design Procedures of the Ministry of Public Works Republic of Indonesia [2]

The Design Procedures of the Ministry of Public Works Republic of Indonesia is basically the same with the design Procedure of the Asphalt Institute MS 14 1989 [5], therefore its limitations are also the same and had been described in the discussion on the limitation of on the Design Procedures of the Asphalt Institute MS 14 1989.

RECOMMENDATION FOR CAEMs DESIGN PROCEDURE

In addition to the limitations of the design procedures as mentioned in Section 3, experimental results conducted at Leeds University during the author's Ph.D. study [14] and previous publication [15] had given inspiration for the recommendation. Further consideration for recommending this design procedure is due to its simplicity and familiarity, without needing modification to the equipment already available in Indonesia.

As this recommendation is an adjustment to the existing methods reviewed, detail for a particular stage of the procedures should refer to the related section section previously described. The recommendation (adjustment) to the design procedure is briefly given as follow:

a) Determination of Aggregate Gradation.
The aggregate gradation can simply follow the national (Indonesian) specification. In the author's opinion, there is an advantage to adopt a continuously graded aggregate due to its aggregate interlock property that can support the weak early life strength of CAEMs. Continuous grading can also be obtained by using Cooper's Formula [12] as below:

$$P = \frac{(100 - F)(d^n - 0.075^n)}{D^n - 0.075^n} + F \qquad (3)$$

where P is the percentage material passing sieve size d (mm), D maximum aggregate size (mm), F the percentage of filler, and n an exponential value that dictates the concavity of the gradation line. Values of n between 0.50 or 0.45 have commonly been used for optimum packing. The value of D and F shall be pre-determined in line with any specification or based on experience. As an example, the application of Cooper's formula with D=14mm, F=4%, and n = 0.45 is presented in Figure 2, where it is very comparable to macadam aggregate grading in the British Standard (BS) 4987 in the UK [16].

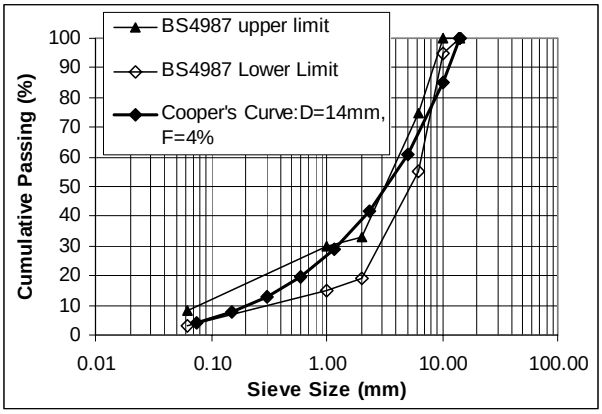

Figure 2. Cooper's Curve, Compared With Macadam Aggregate Grading of British Standard (BS) 4987.

b) Estimation of Initial Residual Asphalt Content (IRAC), and Initial Emulsion Content (IEC).
No recommendation is given for this procedure.

c) Coating Test
For laboratory work it is simpler to used dry aggregates although on site aggregates are mostly damp. The dry aggregates are pre-wetted with various percentage of water before adding emulsion.
Alternatively the dry aggregates can be dampen with an estimated certain amount of water then kept in a sealed container for 24 hours. This is with due consideration to the existing water content within the materials [6]. After that the remaining (varying) pre-wetting water needed is added for determining Optimum Pre-wetting Water Content (OPWc).
However, it had been experienced by the author that the two aggregate pre-wetting water methods above did not noticeably give different workability and degree of coating [14,15]. The target degree of coating is minimum 75 % [2].

d) Determination of Compaction Level to meet Porosity target , shall consider or based on:
- Storage Time for the loose mixture (considering time for preparation, transportation, etc.) and condition: sealed or unsealed container.
- Compaction by applying an initially judged compaction effort (preferably started with heavy compaction).
  At the Optimum Pre-wetting Water Content (OPWc) that gives best workability and coating, the loose mixture may be in a rather sloppy condition. In this case the loose mixture should be air dried, either by giving gentle air blows using a fan or a hair dryer (for lab experiment) before compaction. On site this can be done by laying and exposing the loose mixture to the environment.
  The compaction should be carried out when the loose mixture is neither too sloppy nor too dry. The compaction practicality should be assessed according to the compaction equipment used. Compactor with kneading motion (such as a gyratory compactor) can compact the loose mixture in a slightly sloppy condition, but impact type compactor (such as a Marshall hammer) requires less sloppy loose mixtures to avoid bouncing [14].
  As the porosity range targeted is wide: 5-10% [2] and compaction level was found to play significant role to meet porosity target [14, 15] the above procedure is simpler then the requirement for determining the optimum total liquid content for compaction (OTLC) as required in the Design Procedures of the Asphalt Institute MS 14, 1989 [5].
- Curing for Dry Density determination.
  Dry Density can be obtained from samples after undergoing Design curing Stage A (see Section 2.1.f), where the sample is then tested for Dry Marshall Stability Test. At this stage the sample still contains some amount of water. The failed samples shall be broken down and used for taking Water Content at testing. After that the Dry Density can be determined.
- Determination of SG Mix and Porosity value after obtaining Dry Density data.
- Adjustment of compaction effort and Determination of Compaction Effort which meet Porosity target. Some useful formulas for determining the porosity of the CAEMs is given below [7, 8, 9]:
  - $$SGmix = \frac{100}{\frac{\%CA}{SGCA} + \frac{\%FA}{SGFA} + \frac{\%F}{SGF} + \frac{\%Binder}{SGBinder}},$$
    by weight of total mix (4)

- Bulk Density = $\left(\frac{\text{Weight.in.air}}{(\text{Weight.SSD} - \text{Weight.in.water})}\right), \text{gr/cm3}$ (5)

  Weight saturated surface dry (SSD) is obtained by towel drying the samples after weighing in water, until no air bubble occurs (when the samples are of high porosity).

- $\text{Porosity}\,(\text{P} - \%) = \left(1 - \frac{\text{BulkDensity}}{\text{SGmix}}\right) \times 100\%$ (6)

e) Variation of Residual Asphalt Content (RAC)
Using the determined compaction effort from step d above, samples are manufacture and cured according to the Design Curing Procedure [5] followed by Marshall Stability Test of the Soaked Samples only.

f) Determination of Optimum Residual Asphalt Content (ORAC).
Based on Soaked Samples by optimizing all parameters previously mentioned in the discussion of the limitation of the Design Procedure of the Asphalt Institute MS 14, 1989 [5], with reference to (Indonesian) specification, all parameters are plotted into graphs against the RAC. Evaluate the soaked stability values against the specification (minimum 3 kN) [2]. If unsatisfactory, the compaction level shall be increased, although the porosity target had been met.

g) Calculation of Asphalt Film Thickness (AFT) at ORAC.
The Asphalt Film Thickness–AFT can be calculated using the formula below [10]:

$$\text{AFT} = \frac{\%.\text{Binder}}{100 - \%.\text{Binder}} \times \frac{1}{\text{SG.Binder}} \times \frac{1}{\text{ASA}} \qquad (7)$$

where ASA is the aggregate surface area that can be determine with reference to Asphalt Institute [5]. Calculation of ASA requires surface area factor (SAF) as given in Table 2. The ASA is calculated by multiplying the total percent passing each sieve size by the appropriate SAF, and adding up altogether (Table 3). Using the ASA with unit as shown in Table 3, the AFT value obtained had been found to be equal to a unit of mm, then to be converted to micron where 1 mm = 1000 micron. The minimum AFT targeted is 8 micron [2].

Table 2. Surface Area Factor [5].

Particle / Sieve Sizes	Surface Area Factor (m2/kg)
Maximum size (all sizes grater than 4.75mm)	0.41
4.75 mm (No.4)	0.41
2.36 mm (No.8)	0.82
1.18 mm (No.16)	1.64
600 µm (No.30)	2.87
300 µm (No.50)	6.14
150 µm (No.100)	12.29
75 µm (No.200)	32.77

The Surface Area Factor shown in Table 2 should be used in accordance to the related sieve/ aggregate particle sizes. If different sieve sizes are used when sieving and proportioning the aggregates for the mixtures, when calculating the ASA, the total percentage of aggregates passing the related sieve size in line with those in Table 2, can graphically be estimated from the mixture's aggregate gradation graph. An example of ASA calculation for this case is given in Table 3.

Table 3. Calculation of aggregate surface area (ASA) [5].

Sieve		ASA Calculation		
Inch/ No.	mm *	Estimated Total Pass (%) **	SAF	ASA (m2/kg)
		a	b	c = a x b
¼"	19.0	100	0.41	0.4100
3/8"	9.5	-		
No. 4	4.75	58	0.41	0.2378
No. 8	2.36	41.5	0.82	0.3403
No. 16	1.18	28.8	1.64	0.4723
No. 30	600 µm	19.6	2.87	0.5625
No. 50	300 µm	12.7	6.14	0.7798
No. 100	150 µm	7.7	12.29	0.9463
No. 200	75 µm	4	32.77	1.3108
ASA (sum)				5.50598

* in line with particle size/sieve as in Table 2

** estimated based on the mixture's aggregate grading curve as in Figure 2 (from Cooper's formula/curve).

h) Determination of Retained Stability of the mixture at ORAC only, according to the Design Curing procedure.

i) Determination of the Ultimate Strength (at full curing condition) of the samples at ORAC only.
Strength of CAEMs develops with time to achieve ultimate values at full curing condition. This is the reason why it is necessary to cure CAEMs to full curing. In order to achieve full curing condition the specimens shall be left in their compaction moulds for 1 day at room temperature then extruded, and followed by several days in an oven at 40 °C (until a constant mass is achieved). At this condition all water content within the samples should have been evaporated (full curing condition). Finally the samples shall be left to cool down at room temperature (24 °C) for one day.
At the end of this curing procedure the specimens can be tested either for Marshal Stability at 60 °C or for Indirect Tensile Stiffness Modulus (ITSM) at 20 °C. ITSM can be tested either using Materials Testing Apparatus (MATTA) or Nottingham Asphalt Tester (NAT). The test is principally applying dynamic vertical stress, and detecting the horizontal deformation of the samples for obtaining the ITSM. A minimum ITSM of 2000 MPa is targeted. This curing is only applied to the mixtures having Optimum

Residual Asphalt Contents to evaluate the mixture's ultimate performance.

Specifications in the United Kingdom (UK) require the strength of the CAEMs (in term of ITSM) [13] which should equal to similar Hot Mix of the same based asphalt and the same maximum nominal aggregates size.

The adopted ITSM specification on the ultimate strength of the sample was based on UK Specifications: Indirect Tensile Stiffness Modulus (ITSM) of min 2000 MPa [3,4] for cold mixes with 100 pen based asphalt, in other word to be comparable to hot mixes of similar based asphalt and maximum nominal aggregates size. This property is not mentioned within the American based Specification such as AASHTO or Asphalt Institute.

j). When considered necessary, improvement on the performance the CAEMs can easily be obtained by incorporating about 1% to 2% cement by mass of aggregates.

CLOSING REMARK

The following conclusions are the key outcomes from the investigation:

a) Porosity of cold asphalt emulsion mixtures can be reduced to meet a pre-selected target simply by increasing the compaction effort.
b) Compaction effort is a significant variable that needs to be determined depending on the target porosity, mixture type, storage conditions (sealed or unsealed) and storage time prior to compaction.
c) The Recommended CAEMs Design Procedure at the end of the paper was found simpler than the design procedure reviewed.

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