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Chinese Society of Pavement Engineering

International Journal of Pavement Research and Technology 11 (2018) 888-898

http://www.ijprt.org.tw/

Effect of binder type on Full Depth Reclamation material behaviour

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Received 19 February 2018; received in revised form 13 July 2018; accepted 29 August 2018

Abstract

The present study aims to evaluate the potential use of both foamed asphalt and emulsified asphalt on Full Depth Reclamation (FDR) mixtures to have better performance with four different types of FDR mixtures. Different binder combinations of adding procedures were tested to find the optimum mix design procedure. The scope of work for this research consisted of determining the optimal mixing procedure according to moisture sensitivity tests, determining the complex modulus (E^*) at different loading frequencies and testing temperatures. It was concluded that the better performance can be achieved with double coating practices. In particular, mixing procedure showed that first coating the coarse aggregate with foamed asphalt and second coating the fine aggregate with emulsified asphalt ensure the best results in terms of performance based tests. The complex modulus showed that with the use of both binders it was possible to produce a mixture with a higher modulus than mixtures characterized by a single coating.

Keywords: Full Depth Reclamation; Emulsified asphalt; Foamed asphalt; Complex modulus; Double coating

1. Introduction

Full Depth Reclamation (FDR) is a popular rehabilitation technique for flexible pavements, in which the old asphalt pavement and predetermined portion of granular base are recycled at the same time to lay down a new single layer [1–3]. The FDR is a cost effective and environmentally sustainable approach for construction of pavements compared to conventional Hot Mix Asphalt (HMA) [3,4]. FDR can be done with two different techniques, (a) FDR with emulsified asphalt (EA) and (b) FDR with foamed asphalt (FA) [5]. Over the years, both the technologies are fully consolidated in practice [6], and few studies have been conducted on the combined usage of FDR-EA and FDR-FA techniques. It is believed that with emulsified asphalt, most particles are well coated, which is not the case with foamed asphalt. However, foamed asphalt does work as a binding agent in Cold recycled asphalt materials. As of now, there have been no precise mix design specifications to understand the double coating (combined) technology. It can be achieved using the proper approach to develop the mix design and validate the probability of using EA and FA together on FDR mixtures to have superior mechanical characteristics.

Double coating is an innovative technology that consists in splitting the production process into two parts (Coarse and fine aggregates) in order to obtain the optimal combination in terms of aggregates coating and rupture (Breaking) time. The present study was done in two steps. The first step of the study focused on the determination of the laboratory optimum mix design procedure by varying each of the components involved: emulsified asphalt, foamed asphalt, an emulsion/emulsion double coating mixture, emulsion/foam double coating mixture and aggregates' gradation curve. And in the second step, which is a part of the validation effort to assess the consistency of the

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Peer review under responsibility of Chinese Society of Pavement Engineering.

https://doi.org/10.1016/j.ijprt.2018.08.005
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developed optimum mix design procedure, the Complex modulus tests were conducted on FDR mixtures (50% of Reclaimed Asphalt Pavement (RAP) and 50% of Virgin Aggregates) of four different combinations of the binders: FDR emulsified asphalt mixture (Mix-A), FDR foamed asphalt mixture (Mix-B), FDR emulsified asphalt – emulsified asphalt double coating mixture (Mix-C), and FDR emulsified asphalt - foamed asphalt double coating mixture (Mix-D). The results obtained from the complex modulus test were analysed to characterize the double coated FDR materials.

2. Background

2.1. Bitumen stabilized cold recycled asphalt mixtures

All over the world, bitumen stabilized material(s) (BSM) such as emulsified asphalt and foamed asphalt mixture usage is gradually increased in road construction and rehabilitation. However, it has created a need for sound guidelines to be established for the laboratory mix design procedures for FDR materials. Typical normally contains water (25% to 60%), bitumen (40% to 75%), and emulsifier (0,1% to 2,5%), depending on the specific type of emulsified asphalt and the necessary viscosity [7]. The role of EA in cold in-place recycling method delivers a robust binding through the recycled asphalt pavement material. In the last two decades, efforts have been employed on the emulsion-based technologies for road construction and repair, as well as significant improvements were achieved over the emulsion system [7], for instance the addition of polymers to increase the performance of final mixes [8]. Foamed asphalt is a process in which water is injected in to the expansion chamber containing hot bitumen at 170 °C to 180 °C, resulting in spontaneous foaming, which produces the foamed or expanded asphalt [9].

According to literature, FDR-EA and FDR-FA techniques signify an effective solution for old asphalt pavements; however, a detailed comparison between the two gives in depth advantages and disadvantages of each technique and helps in understanding one of the objectives of the present study. Primarily, it is very important to understand that these two technologies have the different forms of distribution of binder. Essentially, the EA acts as a lubricant in the process of the compaction stage and, prior to it starts breaking, the coarse aggregates and fine aggregates are totally being covered by the binder [10]. The difference is also visual, in fact, in the case of emulsion the binder distribution is more homogenous into the material, instead for foamed bitumen black spots appear.

As demonstrated by recent studies [11], given the same compaction effort, cold recycled emulsified asphalt specimens showed lesser density than cold recycled foamed asphalt specimens. Both Indirect tensile strength and Marshall Stability of cold recycled emulsified asphalt specimens were about same as those of cold recycled foamed asphalt specimens [12]. With respect to curing, EA mixtures have a lower dynamic modulus than the FA mixtures; it could be due to the inferior moisture content. In addition, ITS results are affected by the RAP percentage and type of bitumen grade [13].

2.2. State of the art on Full Depth Reclamation material mechanical properties

Until now, numerous studies concluded that, at early periods, the FDR material behaviour seems to be like a granular material, nevertheless, when the curing is done the FDR material's behaviour is close to HMA. As a result, it is considered that FDR-EA and FDR-FA materials have a time-dependent behaviour [14]. Locander (2009), explained that granular and FDR materials have a distinctive behaviour due to the presence of the binder, and coating FDR's aggregates. Molenaar [16] concluded that, in comparison to an equivalent granular material, the inclusion of a binder (foamed asphalt) in cold recycled mixes resulted in better cohesion. Jenkins stated that, foamed bitumen mixtures with 2% binder content perform similarly to granular materials. Whereas, with less than 4% binder content foamed bitumen mixtures shows stress dependent behaviour [17]. Santagata, Chiappinelli, Riviera, and Baglieri [18] reported that when properly designed CRM, in the long-term, can achieve stiffness values comparable to those obtained for an HMA mixture. Therefore, Pérez [14] explained that treating FDR materials, which are stabilized with a binder, as a granular material is unrealistic. Moreover, there is a persistent gap between the predicted life as a result of pavement design simulation and the observation in the field with respect to FDR layers in flexible pavement structures.

Cizkova and Suda [19] studied the mechanical behaviour of Cold recycled asphalt mixtures with foamed asphalt and emulsified asphalt. They concluded that the CRM are sensitive to thermo-mechanical behaviour. However, these materials are less dependent on temperature and frequency than traditional HMA mixtures. Particularly, at lower temperatures and higher frequencies, these materials show elastic behaviour. Carter, Bueche, and Perraton [20] investigated complex modulus of cold recycled asphalt materials treated with EA and FA. Based on laboratory test results they concluded that, for full depth reclaimed asphalt materials, at higher temperature and lower frequency foamed asphalt treated mixtures are higher modulus values then emulsified asphalt treated mixtures. Godenzoni, Graziani, and Bocci [21] studied the cold recycled emulsified asphalt materials with different percentages of RAP (0%, 50% and 80%) contents. They concluded based on the complex modulus test results that the cold recycled emulsified asphalt materials with RAP showed as asphalt-like behaviour than without RAP mixtures. Godenzoni, Graziani, and Perraton [22] studied the Linear Viscoelastic region (LVE) response of cold recycled asphalt mixtures treated with foamed asphalt. They revealed based on results that the values of the phase angle and stiffness modulus are lower than the traditional hot mix asphalt mixtures. Gandi, Carter, and Singh [23] investigated the complex modulus of cold recycled materials treated with those emulsified with different RAP contents. Fig. 1 represents the cole–cole diagram of the 2S2P1D model of the respected mixtures. They concluded that at lower frequency and higher temperature of 100 percentage of RAP shows high stiffness values.

Despite the recent efforts employed for the investigation of the FDR mechanical behaviour, few studies have been conducted on the combined usage of FDR-EA and FDR-FA – techniques (Double Coating). The present study was undertaken to provide additional information on the rheological properties of FDR materials using both emulsified asphalt and foamed asphalt. That emulsified asphalt allows an appropriate coating of the aggregates while foamed asphalt does not reach the same efficiency as a binding agent, thus a mix of both techniques could result in higher level quality mixes [6,36].

3. Objectives

The objectives of the present study were to:

(a) Determine the mix design procedure for double coating Full Depth Reclamation materials with the addition of four different combinations of the binders.
(b) To evaluate the complex modulus of the double coated Full Depth Reclamation materials with the addition of four different combinations of the binders.

4. Experimental plan

4.1. Materials

In this study, the Full Depth Reclamation (FDR) samples like 50 percent of Reclaimed Asphalt Pavement (RAP) and 50 percent of Virgin Aggregate (MG20) were fabricated in the laboratory with VA, RAP, Emulsified Asphalt (EA), Foamed Asphalt (FA), water and Portland cement. The RAP used in this research was acquired from a stockpile in the Montreal city. The RAP was homogenized to confirm that all representative samples have likely similar gradation. The VA was the nominal maximum aggregate size (NMAS) of 20 mm (MG20), which is the aggregate usually used in Quebec as a base material for highway construction. The FDR asphalt mix gradation is according to TG 2 [26] as shown in Table 1. Intended for the mixes with emulsified asphalt, two different types of binders (CSS-1S and CSS-1P) were employed as mentioned as shown in Table1. Foamed Asphalt was produced in the laboratory based foaming plant as shown in Fig. 2. Foamed bitumen is produced by injection of a small amount of tap water into hot bitumen at different air pressures (Table 1). The FDR mix gradation and other properties of the mixtures used in the experiments are presented in (Table 1).

4.2. Mix design

The compaction ability of the double coating mixture emulsion/foam was studied performing four series of tests, which are directly related to four types of mixtures: FDR emulsified asphalt mixture (Mix-A), FDR foamed asphalt mixture (Mix-B), FDR emulsified asphalt - emulsified asphalt double coating mixture (Mix-C), and FDR emulsified asphalt - foamed asphalt double coating mixture (Mix-D). The latter has been compared to the first three reference mixes with Mix-D. Furthermore, the addition of coarse aggregates and fine aggregates to the Foamed Asphalt and/or Emulsified Asphalt in the mix design has been distributed in two parts. To test the Indirect Tensile Strength (ITS) and Marshall Stability 10 replicates were compacted for each mix.

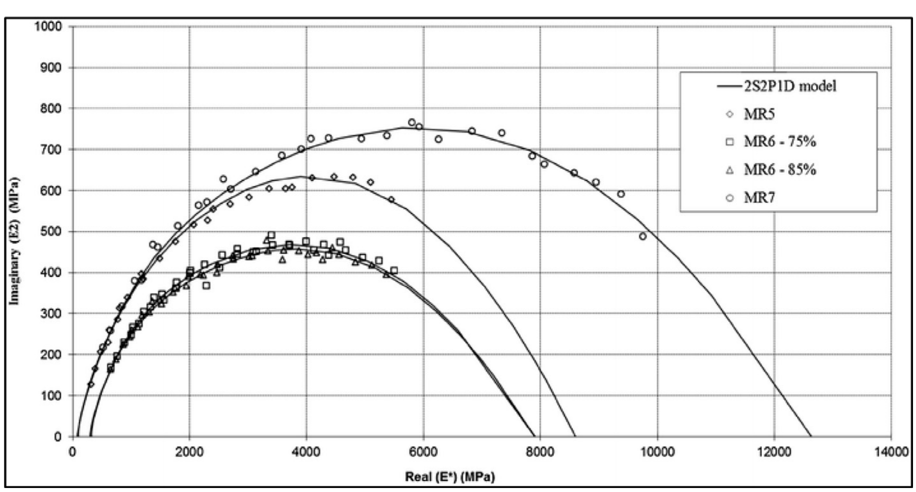

Fig. 1. Complex modulus of Cole–Cole diagram with 2S2P1D model [24].

Table 1
Full Depth Reclamation mixture gradation and its properties.

	Percent of passing sieve	
Sieve size (mm)	Requirements	FDR mix gradation
28	80–100	100
20	–	95
14	50–90	89
10	52–75	74
5	25–55	48.5
2.5	–	29.1
1.25	–	23.9
0.630	–	12.2
0.315	5–20	6.4
0.16	–	3.7
0.080	3–10	2.3
% of residual binder in RAP (According to ASTM D6307-10(27))		6.38
AC of Emulsified Asphalt CSS-1S (%)		65.2
AC of Emulsified Asphalt CSS-1P (%)		61.6
Compaction		Marshall and Superpave gyratory Compaction
Curing Time (days)		10 days at 38 ± 2 °C
PCC (%)		1.0
Water content (%)		6.5
Targeted Air Voids V_a (%)		13 ± 1
Foamed Asphalt Production		
Bitumen Grade		PG 58-28
Water Content (%)		3.25
Expansion ratio		15
Half-life		12 seconds at 170 °C temperature.

Note: V_a = Air voids of the mixture; AC = Asphalt Content; PCC = Portland Cement Content; CSS-1S = Cationic Slow-Setting with soft bitumen emulsion; CSS1P = Cationic Slow Setting 1 with Polymer; PG = Penetration Grade.

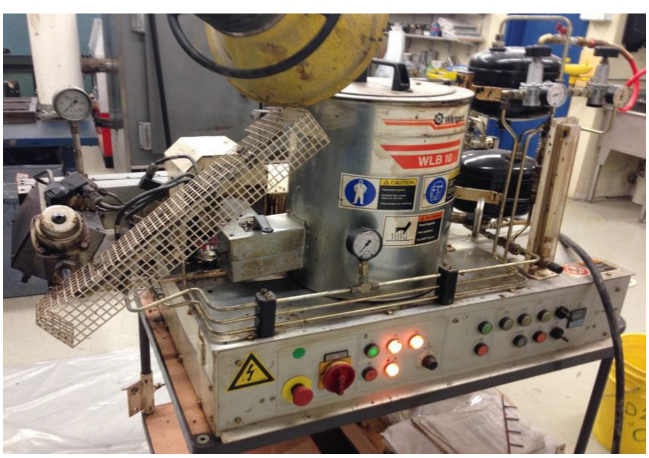

Fig. 2. Writgen laboratory foaming plant.

4.2.1. Single coating and double coating of emulsified asphalt mixtures

Single coating of emulsified asphalt mix design has been done with respect to Quebec standard LC 26-002 [28]. The pre-mix optimum water content was fixed at 6.5% by weight on the dry aggregates, including cement. The rate of pre-mix water can lead to several advantages, such as higher RAP content, virgin aggregate coating, increased lubrication during compaction, and accelerating the cement hydration process [29]. The exact dosages of water and cement are added to aggregates and thoroughly mixed for one minute. Then, CSS-1S emulsified asphalt is poured according to proportions, and the mix is blended for one more minute.

The same process is applied to double coating emulsified asphalt mixes, but the entire mixing process is split in to two phases. Initially, an aggregate fraction is mixed with Portland cement and water and for one minute. Then, half portion of the first emulsified asphalt (CSS-1S) is added and mixed again for one minute. Before performing the second coating, the emulsified asphalt needs to break first. After that, the second fraction of the aggregates and second emulsified asphalt (CSS-1P) is poured and mixed well for one minute duration.

4.2.2. Double coating of emulsified and foamed asphalt mixtures

Double coating of emulsified asphalt and foamed asphalt mixtures mix design follows the similar process as mentioned in Section 4.2.1, even though it has two separate stages in the mixing procedure. The initial aggregate fraction is mixed with 50% of water content and the necessary amount of emulsified asphalt (CSS-1P) for one minute. Then, immediately after the emulsified asphalt breaks, the mixture and the second fraction of aggregate are added directly into the laboratory foam mixer. Afterwards, the remaining 50% of water content and 1% of cement are poured, whereas foamed asphalt was added according to mix design proportions.

4.3. Sample preparation

To determine the mix design of FDR materials in this study, a Marshall compactor was used to produce specimens at targeted percentage of air voids, applying 50 blows on each face. The following curing process was performed at one day at ambient temperature with mould and one day at 38 ± 2 °C in demoulded state. In particular, curing humidity was not controlled, even though laboratory relative humidity resulted being always around 50%. The air voids of all FDR mixtures were measured and presented in Table 2, before putting instrumentation in place; each sample is weighed to determine its bulk specific gravity (G_{mb}). After, with G_{mb} and maximum theoretical specific gravity (G_{mm}) values, the actual level of air voids (V_a) is calculated according to LC 26-320 [39]. The bulk specific gravity can be measured by calculating the mass of the specimen in its dry condition, when it is submerged in water tank, and when it is in its saturated surface dry (SSD) condition. Measured air voids are calculated with: $V_a = (1 - (G_{mb}/G_{mm})) * 100$.

In addition to that, to evaluate the rheological characteristics of the double coated Full Depth Reclamation materials with the complex modulus test, cylindrical specimens were produced by means of a gyratory compactor fixing the targeted air voids content. Specimens were immediately demoulded after compaction and cured for 10 days at 38 ± 2 °C. At the end of the curing process, samples of 75 mm × 120 mm prepared with the help of coring and sawing.

Table 2
Percentage of air voids of FDR Mixtures.

S. No.	Mix type	Percentage of air voids (%)
1	Mix-A	10.62
2	Mix-B	11.36
3	Mix-C	11.64
4	Mix-D	12.24

4.4. Testing

4.4.1. Marshall stability test

Marshall Stability and flow test results along with density and other parameters are normally utilized to compare and evaluate the laboratory mix designs of asphalt mixtures. In addition, it evaluates the properties of conditioning such as with water [30]. For Marshall Stability and flow, the cured specimens are tested with laboratory Marshall testing equipment at room temperature, and it reaches failure under a constant load (Fig. 3). The maximum load linked to failure is named Marshall Stability, which needs to be corrected according to the sample height.

4.4.2. Indirect tensile strength test

The Indirect Tensile Strength (ITS) test values can be used to evaluate the moisture damage and quality of asphalt mixtures [31] (Fig. 4). The ITS test was performed at room temperature. The following Eq. (1) is used to obtain the ITS value, which is calculated dividing the maximum compressive strength by the specimen's geometrical properties [31]:

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \tag{1}$$

where

S_t: Indirect Tensile Strength, kPa;
P: Maximum load, N;
D: Specimen diameter, mm, and
T: Specimen height immediately before test, mm.

4.4.3. Complex modulus test

The structural performance of flexible pavement is significantly influenced by the rheological properties of the

Fig. 3. Compacted Marshall Specimens and Marshall Testing setup.

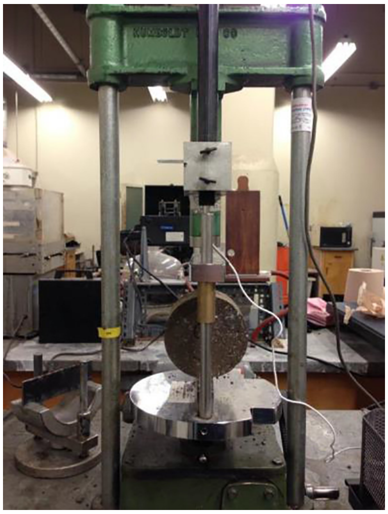

Fig. 4. Indirect Tensile Strength Test loading.

asphalt mix layers. Therefore, the rheological analysis aims at defining the constitutive laws of road materials in order to associate their specific mechanical properties with the performance of road materials in exercise and the expectations of the pavement service life.

During the pavement design phase of road structure, it is necessary to consider that the temperatures are normally between 0 °C and 60 °C while the loads from vehicular traffic have a short time application but not sufficiently short to induce purely elastic behaviour in the bituminous material. FDR materials, containing bitumen, should be studied referring to models and principles used in the rheological analysis of the viscoelastic material. This means that the application of a constant effort (σ) produces both an instantaneous deformation and a deferred deformation that grows during the entire period of the load application, i.e. elastic and viscous contributions coexist. An identical behaviour is observed when the load is removed. The elastic deformation returns instantly, followed by a delayed recovery delayed while a rate of irreversible deformation due to viscous flows represents a plastic deformation. In the Linear Viscoelstic region (LVE) only the first two components are taken into account. Therefore, the complex modulus for asphalt concrete is defined by the following Eq. (2):

$$|E^*| = \sqrt{E'^2} + E''^2 \tag{2}$$

where

E'' = loss modulus, viscous contribution [Pa]
E' = storage modulus, elastic contribution [Pa]

The phase angle (δ) represents the distributions of the elastic and viscous contributions (Eq. (3)):

$$\delta = arctg\left(\frac{E''}{E'}\right) \tag{3}$$

The rheological properties become important input parameter to implement mechanistic-empirical pavement design models [32]. The complex modulus and phase angle depend on the mixture characteristics, the loading frequencies, and pavement temperature profile. Clearly, a lack or fragmentary information regarding the rheological behaviour of FDR has become a source of reluctance to use this type of alternative as pavement base materials [33]. As of today, attempts to characterize the stiffness of FDR materials through a tri-axial test, by measuring the resilient modulus (MR), or through a complex modulus (E^*) test have been undertaken.

The experimental results obtained from the complex modulus test are analysed through the 2S2P1D (2S: two Springs, 2P: two Parabolic elements, 1D: one Dashpot) model and graphical representation of the model is in Fig. 5 [34].

It is extensively used to model the LVE unidimensional or tridimensional behaviour of bituminous materials which includes binders, mastics and mixes [35]. The 2S2P1D analytical expression of the Complex Young's Modulus, at a specific temperature, as expressed by Eq. (4):

$$E^*(i\omega\varpi\tau) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\varpi\omega\tau)^{-k} + (i\varpi\omega\tau)^{-h} + (i\varpi\omega\beta\tau)^{-1}} \tag{4}$$

The temperature (τ) change is dependent by means of the shift factor at temperature (T) as presented in the Eq. (5):

$$\tau_E(T) = \ a_T(T) \times \tau\ _{0E} \tag{5}$$

where aTref (T) is the shift factor at temperature T and $\tau_E = \tau_{0E}$ at reference temperature T_{ref}. Seven constants (E_{00}, E_0, δ, k, h, β and τ_{0E}) are required to completely characterize the linear viscoelastic properties of the tested material at a given temperature. The evolutions of τ_E were approximated by the William-Landel-Ferry (WLF) model [36] (Eq. (6). τ_{0E} was determined at the chosen reference temperature T_{ref}. When the temperature effect is considered, the number of constants becomes nine, including the two WLF constants (C1 and C2 calculated at the reference temperature).

$$\log(a_T) = \frac{-C_1(T - T_{ref})}{C_2 + T - T_{ref}} \tag{6}$$

All the experimental and analytical results fit on a single curve in the Cole–Cole plan of the model, if the material

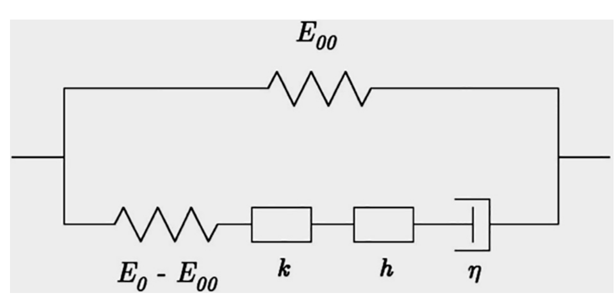

Fig. 5. The graphical representation of the 2S2P1D model [34].

has linear viscoelastic behaviour. Furthermore, for reference temperature, with considerations to the principle of time and temperature equivalency, master curves are deducted from the test results and highlight the evolution of the dynamic modulus with regard to a constant reference temperature and a changing frequency.

Coefficient of evolution C^*_{CE} is introduced, in order to compare objectively the experimental results of complex modulus of mixtures with different binders. The calculation of the RAP coefficient of evolution (C^*_{RCE}) was proposed by Di Benedetto [37]. It is defined as the ratio between the complex modulus of a specific mix at the equivalent frequency (f_e) and complex modulus of a reference mixture at the same frequency (f_e) as mentioned in Eq. (7).

$$C^*_{RCE}(f_e) = \frac{E^*_{mix}}{E^*_{ref-mix}} = |C^*_{RCE}|e^{i\Phi RCE} \tag{7}$$

C^*_{RCE} is a complex number, as shown in Eq. (7). It is standard the ratio of the norms of the complex modulus of the recycled mixture to the one of the reference is calculated by Eq. (8). Its phase angle is the difference between the phase angle of the recycled mixture and the one of the reference as determined by Eq. (9).

$$|C^*_{RCE}| = \left|\frac{E^*_{mix}}{E^*_{ref-mix}}\right| \tag{8}$$

$$\Phi_{REC} = \Phi_{E^*_{mix}} - \Phi_{E^*_{ref-mix}} \tag{9}$$

It is important to note that the $|C^*_{RCE}|$ value is calculated in the reference mixture.

The complex modulus was measured with a servo-hydraulic testing system (MTS 810). The axial strain was measured on the centre portion of the testing specimen with the help of three 50 mm extensometers, placed 120° apart as shown in Fig. 6. Each sample was subjected to haversine compression loading (stress controlled) along the axial direction. Experiments were performed under strain control with target amplitude of 50 μdef. The test was performed at eight temperatures (−25 °C, −15 °C, −5 °C, 5 °C, 15 °C, 25 °C, 35 °C, and 45 °C) and five frequencies (0.03, 0.10, 0.30, 1.00, and 3.00 Hz). After each temperature change, 6 h of conditioning period has been applied.

5. Results and discussions

5.1. Marshall Stability

Fig. 7 presents the test results of all mixtures starting form Mix-A to Mix-D in dry condition and wet condition. According to Ministry of transportation Quebec, minimum of 8 kN of Marshall Stability is required [28], which is satisfied by all the mixtures. As anticipated, the Marshall Stability of Mix-A and Mix-B are lower than Mix-C and Mix-D. Furthermore, in saturated conditions, all formulations showed almost the same resistance value.

Overall, Marshall Moisture susceptibility results were not satisfactory enough. Fig. 8 shows that double coating mixes are the most influenced by the presence of water. On the contrary, Mix-A has the lowest stability loss (11.35%), due to the optimal coating action provided by the single film of emulsified asphalt. On the other hand, higher moisture sensitivity was obtained by foamed asphalt mixtures, probably due to the tendency of foamed asphalt to merge mainly with the fine fraction, leading to a lower coating. However, it was expected Mix-D to reach lower moisture sensitivity than Mix-B (single foamed asphalt).

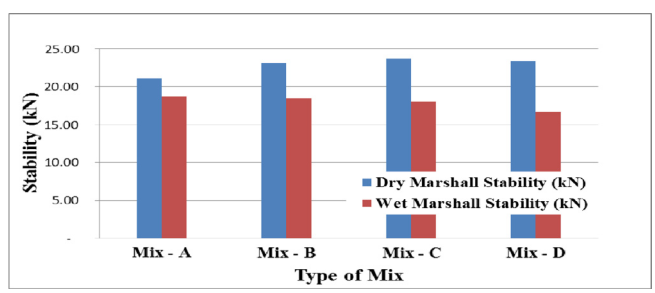

Fig. 7. Marshall stability of FDR materials.

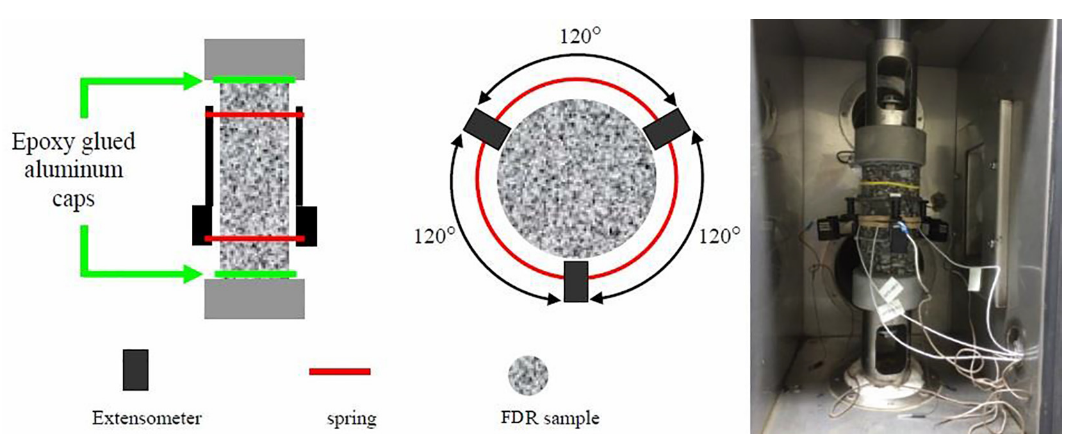

Fig. 6. Complex Modulus Test setup and MTS Machine [38].

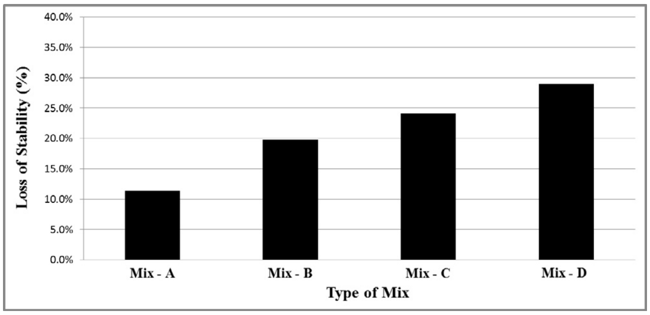

Fig. 8. Loss of stability of FDR Materials.

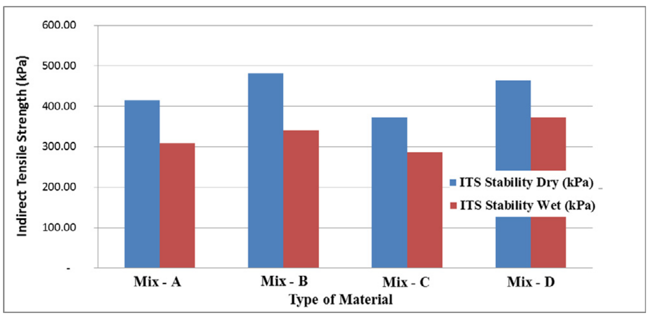

Fig. 9. Indirect Tensile strength test results of FDR materials.

5.2. Indirect tensile strength

Fig. 9 shows both ITS-Dry and ITS-wet experimental results. As for Marshall Stability values, no particular gain in strength is visible among the four formulations, especially between single and double coating. The Mix-B and the Mix-D show good results. Mix-B is very similar to the latter.

ITS moisture sensitivity results are more comprehensible, if compared to the Marshall Test ones. As expected, double coating FDR mixtures are the most performant, with Mix-D reaching the highest value (81%) (Fig. 10). Since moisture susceptibility is considered one the important parameters in this study, it is fundamental that double coating mixtures respect the Wirtgen reference criterion. Such good results for Mix-C and Mix-D indicate a good and suitable coating of aggregates and demonstrate the effectiveness of the formulation used for the double coating. In particular, for detailed mixing procedure refer Gandi et al. [25].

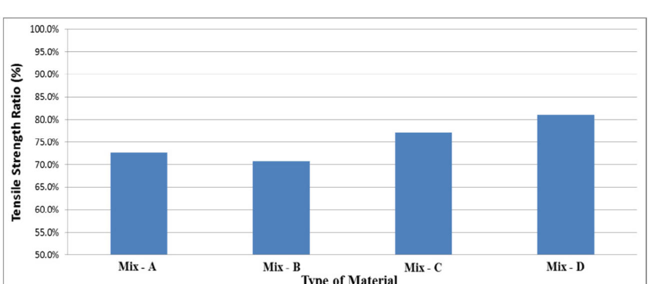

Fig. 10. Various tensile strength ratios of FDR materials.

5.3. Complex modulus

As mentioned before, complex modulus test was performed on samples in a range of eight different temperatures and five different frequencies. The 2S2P1D rheological model was used as a tool to analyse results obtained from the laboratory investigation.

5.3.1. The Cole–Cole diagram and Black space diagram with 2S2P1D model

The 2S2P1D model is generally used to explain both behaviours of the asphalt mixtures and binder [35]. The complex modulus tests were carried out on four different asphalt mixtures (Mix-A through Mix-D) at eight temperatures and five frequencies; this allows to determine accurately the modelling parameters (E_0, E_∞, k, h, β, δ, C1, and C2) to be employed in the 2S2P1D model to characterize the linear viscoelastic response of the asphalt mixture. The modelling parameters are listed in Table 3 at a reference temperature. Such parameters are determined by the best-fitting curve for all the measured complex modulus data plotted in the Cole–Cole and Black space diagrams of the 2S2P1D models. Figs. 11 and 12 represent the Cole–Cole and Black space diagrams respectively. The binder rheology is represented by the k, h, δ and β parameters. These parameters are nearly same for single and double-coated mixtures separately, which means a double coating of the asphalt mixtures could lead to a change in the binder rheology. For what concerns the other parameters, E_0 is the static modulus (E when $\omega \to 0$), and E_∞ is the glassy modulus (E when $\omega \to \infty$), which is normally related to the air void content and aggregate skeleton [39]. However, it should be noted that the targeted percentage of air voids and the aggregate gradation is the same for all mixtures. Our results show that the binder type affected the glassy modulus, which is moderately higher for mixtures treated with foamed asphalt (Mix-B and Mix-D).

Fig. 12 illustrates the black space diagram of 2S2P1D model, in which the complex modulus norm is linked to the phase angle (φ). As the experimental data suggest, the phase angle, which is the loss coefficient of the material, varies between 3.85° (low temperature/high frequency) and 33.18° (high temperature/low frequency). In general, if the material has high φ values, it is supposed to be highly viscoelastic and to absorb more cyclic loading energy as a consequence; on contrary, with less φ value it absorbs less energy. However, values of both E_0 and φ for all tested cold recycled asphalt mixtures are below those normally measured on HMA [22,40]. Fig. 12 shows that phase angle is significantly attenuated at higher temperatures with respect to Mix-B. It can be seen that the Mix-B has relatively high φ values than the other mixtures. This can suggest that the Mix-B exhibits viscoelastic behaviour and in

Table 3
Parameters of the 2S2P1D model for the FDR mixtures ($T_{ref} = 5$ °C).

Mixture	E0 (MPa)	E∞ (MPa)	k	h	δ	β	C1	C2
Mix-A	80	8750	0.18	0.5	4.8	1000	16.24	108.38
Mix-B	41	9600	0.17	0.5	3.6	375	21.56	150.15
Mix-C	26	3800	0.16	0.5	2.5	1200	20	136.88
Mix-D	75	7500	0.16	0.4	3.0	1200	19.08	137.01

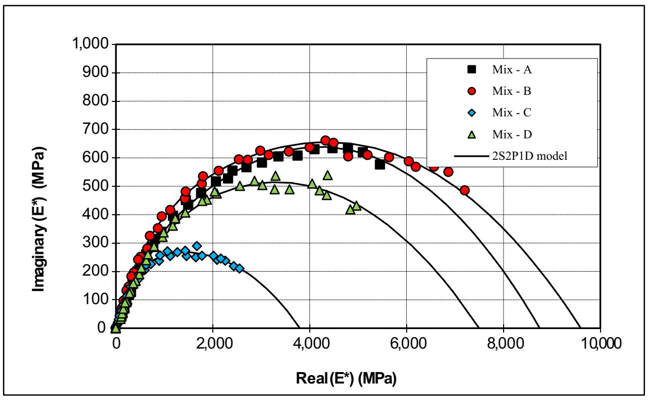

Fig.11. Complex modulus' master curve in Cole & Cole axes.

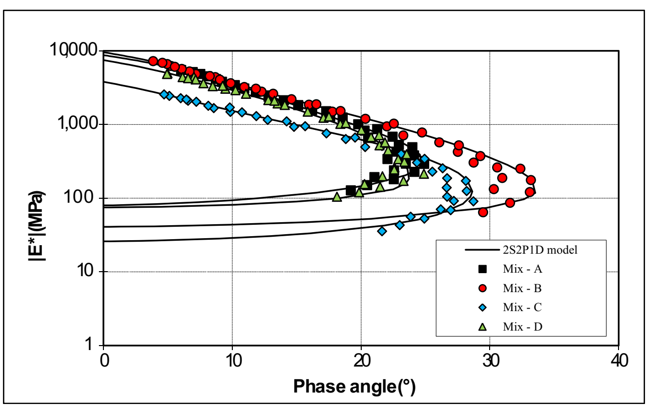

Fig. 12. Complex modulus' master curve in Black space diagram.

addition to this, double coating does have a higher impact on elastic response rather than on viscous behaviour.

5.3.2. Master curves of the tested FDR asphalt mixtures

An optimal tool to understand the complex modulus test results is to plot them as a master curve. If the hypothesis that the asphalt mixture satisfies the Time-Temperature Superposition Principle (TTSP) is assumed, the master curve can be plotted as a function of an equivalent frequency. Initially, the reference temperature is selected ($T_{ref} = 5$ °C), and then, all data at different temperatures need to be shifted with respect to time in order to obtain a single smooth master curve. The build-up of the master curve requires the determination of the shift factors for each testing temperature T, named $a_T(T)$, that can be done by means of Eq. (6). However, to achieve a complete understanding of the rate and temperature effects, both the master curve and the shift factor $a_T(T)$ are needed [41]. Fig. 13 illustrates the master curves (complex modulus norm as a function of a frequency of the material) of the four mixtures at the reference temperature $T_{ref} = 5$ °C.

In Fig. 13, the top right portion of the $|E^*|$ master curves at a higher frequency or low temperature approach asymptotically to a maximum value which describes a maximum stiffness value of the corresponding asphalt mixtures (Mix-A and Mix-B). At the bottom left quarter of the graph, which means at lower frequencies or high temperatures, $|E^*|$ master curves approach a minimum value which describes the minimum stiffness value of the corresponding asphalt mixture (Mix-C). In addition to this, at the lower frequency and higher temperature, the other two mixtures (Mix-A and Mix-D) represent the maximum stiffness value. In particular, FDR asphalt mixtures treated with foamed asphalt are representing high stiffness values at lower frequencies which are characterized by an improved cohesion with respect to unbound granular materials. It should be noted that Mix-C showed relatively low stiffness at both lower frequency – higher temperature and high frequency – low temperature. A hypothesis could be the less cohesion presents in between double coated emulsified asphalt materials (Mix-C).

Fig. 14 represents the shift factors for the norm of the complex modulus at 5 °C. Both the master curve and the shift factor $a_T(T)$ are needed for a complete depiction of the rate and temperature effects [41]. From Fig. 14, Mix-A has higher thermal susceptibility in the entire temperature domain. In addition to this the double-coated mixtures (Mix-C and Mix-D) have lower thermal susceptibility. In other words, double coated asphalt mixtures could be less sensitive to temperature. This aspect needs further research and other laboratory tests.

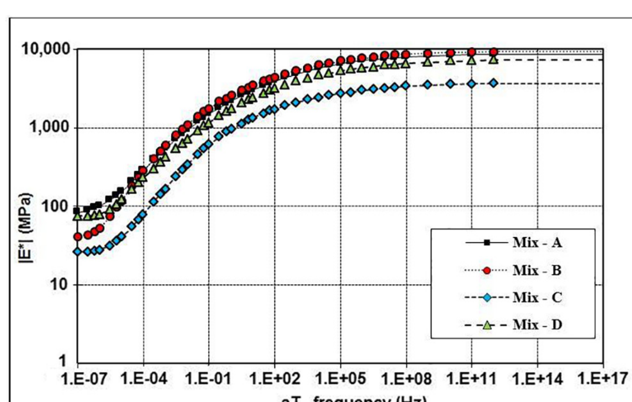

Fig.13. Master curves of the norm of complex modulus.

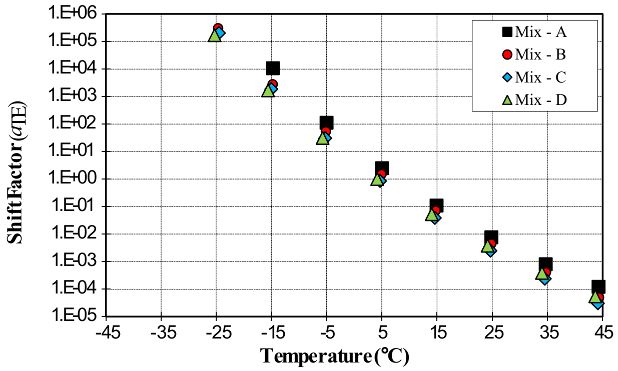

Fig.14. Master curves and shift factors of complex modulus norm at ($T_{ref} = 5$ °C).

6. Conclusions

The present study was carried out to determine the mix design procedure for double coating FDR materials and evaluate its rheological characteristics of four different combinations of the binders like FDR EA mixture (Mix-A), FDR FA mixture (Mix-B), FDR EA-EA double coating mixture (Mix-C), and FDR EA-FA double coating mixture (Mix-D). The following conclusions can be drawn based on the results.

- Prior to mechanical testing, two-stage mixing procedure was done to produce specimens with uniform binder percent and same volumetric properties. This new two-stage mixing technique is primarily based on pre-coating a portion of the aggregate with the suitable quantity of optimum binder content. Based on the ITS and Marshall stability test the Mix-D results indicated better performance. Nonetheless, with respect to moisture content some developments remain to be made.
- This indicates that mixes containing a high content of bitumen in the form of EA or separating the fine aggregates and coarse aggregates appear to be better solutions to deal with the inadequate coating. Enhancing the aggregates coating, should effect in a lower water sensitive asphalt mixture. Furthermore, these developments in the mix design and including production process could increase resistance which is already enhanced with respect to the conventional formulations. If the mixing procedure is optimized taking into account results for Tensile Strength Ratio (Fig. 10), the first coating should be performed on coarse aggregates with foamed asphalt, whereas fine aggregates should be coated by emulsified asphalt afterwards. An adequate time gap between the two coatings is one minute. However, to reach better performance further investigations are needed.
- The laboratory based complex modulus experimental results are considered satisfactory since they respect the 2S2P1D rheological model. As well as a master curves are plotted using a shifting procedure at a reference temperature of 5 °C. FDR single coated (Mix-A and Mix-B) and FDR double-coated (Mix-C and Mix-D) asphalt mixes are satisfies the Time – Temperature Superposition Principle (TTSP).
- The results confirm that for the study of FDR it is necessary to refer to models and principles used in the rheological analysis of viscoelastic material. It should be noted that, the binder type had an influence on the glassy modulus that is moderately higher for mixtures treated with foamed asphalt (Mix-B and Mix-D). In addition to this, Mix-C showed relatively low values of complex modulus over all the range of temperatures and frequencies tested. This may be due to less cohesion that characterizes the FDR emulsion-emulsion double coating mixture (Mix-C).
- The hypothesis is that the residual water trapped in the mixture, after the first emulsion coating step, reduces the adhesion of the bitumen once the second coating step takes place. This may result in a non-homogeneous distribution of the bitumen film thickness, and consequently the formation of weaker points that decrease the mechanical performance of the mixture. Indeed, it should be considered that the bitumen film thickness has an important influence on the rheology. In this case, it means that the time-span between the first and second coating should be handled in a way to remove or evacuate the residual moisture. Therefore, additional work is needed to study and apply a possible solution during the mixing phase.
- The results revealed also that, FDR double coated foam – emulsion asphalt mixture (Mix-D) increases stiffness approximately 49.32 % when comparing with the FDR double coated emulsion – emulsion asphalt mixture (Mix-C). In this case, the problem of the residual moisture is overpassed because foam technology application (first step of coating) reduces significantly the amount of total water in the whole process. From the shift factors' point of view, double coated mixtures could be reflected in a lower thermal susceptibility.
- After having solved the limits developed during this research, it will be required to validate the results obtained in the laboratory when the mixtures are produced in the Central mixing plant as well.

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