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Laboratory characterization of CIR and FDR materials

Alan Carter, Nicolas Bueche, Daniel Perraton

Abstract: Nowadays, the pavement industry revolves more around rehabilitation projects than around new constructions. Cold In-Place recycling (CIR) and Full Depth Reclamation (FDR) are two rehabilitation techniques that are getting more and more popular. However, the lack of knowledge regarding their rheological behaviour makes the optimized use of those techniques hard to grasp. In this study, CIR and FDR materials, made in laboratory with both asphalt emulsion and foamed bitumen were tested in complex modulus. The results have shown very little difference between the results for a given type of mix, CIR or FDR, if emulsion or foam is used. However, CIR moduli are always higher than those measured for FDR. In both cases, their modulus is around one third of what is normally measured for HMA. Based on these results, some pavement design considerations are also proposed.

1 Introduction

Cold In-Place (CIR) recycling and Full Depth Reclamation (FDR) are two pavement rehabilitations techniques that are used around the world. In both cases, bitumen can be added as an asphalt emulsion or as foamed asphalt. However, the variability of the performances obtained with those techniques in the fields has limited their usage. For some, CIR and FDR can be used on highways, but for others, they should only be used on low volume roads. This is unfortunate since it has been shown to be a cost-effective, environmentally friendly solution to pavement rehabilitation.

2 Background

Cold In-Place recycling (CIR) is a rehabilitation technique in which only the asphalt layer is milled, that has environmental, economic and structural benefits (Martinez et al., 2007). As for Full Depth Reclamation (FDR), it has basically the same benefits, but in this case, part of the underlying granular base is also recycled (Smith et al., 2008).

According to the MTQ (Bergeron, 2007), stabilized FDR improves the ride quality (IRI, rutting) from 10% to 48%, which is the best result for a cold rehabilitation technique. But in their study, which was done on 450km of cold rehabilitated project over 12 years, they also found out that CIR does not improve the ride quality as much, but the technique has the best price/advantage ratio (initial price + user cost / ride quality improvement). It has been shown (Alkins et al., 2008) that those pavement rehabilitation techniques, compare to the others techniques, are good options in terms of lowering Greenhouse Gases (GHG) emissions, reusing existing nonrenewable resources, minimizing use of new material, reducing costs, minimizing disruption to motorists and residences and reducing transportation of construction materials.

2.1 FDR and CIR

The choice between FDR and CIR depends on the depth that needs to be treated. If there are only superficial defects, only the Hot-Mix Asphalt (HMA) is milled to get CIR. This is done to a depth between

75mm and 150mm. When the degradations are due to a structural problem, FDR can be used. In this case, the HMA and part of the aggregate base can be milled to obtain FDR. It is usually done for depth between 100mm and 300mm (ARRA, 2001). CIR and FDR layer are then typically overlaid by HMA to protect them from water and traffic load. Depending on the amount of Reclaimed Asphalt Pavement (RAP) in the mix and because of the gradation and the binder content, CIR and FDR are believed to have different mechanical properties. For example, in Quebec, pavement design is done with a modified version of AASHTO 93 design guide. The structural coefficients, and the related resilient modulus, used in the software CHAUSSÉE 2 are shown in table 1. It should be noted that the FDR here is a 50%-50% mix of asphalt and granular base. The values shown in table 1 are low compared with other values found in the literature. For example, according to Wirtgen (Wirtgen, 2004), the resilient modulus of CIR should be between 1 000 and 2 500 MPa and FDR (50-50) between 800 and 2 000 MPa when they have reach their peak value.

The values shown in table 1 were obtained from FWD tests done on Quebec's road network by the Ministry of Transportation (MTQ). As it can be seen, there is a wide range of value between each technique. It should be noted that, in Quebec, there is only the possibility to choose CIR with cement. Cement is always added to CIR in order to meet the criteria from test method LC26-002: Mix design of cold recycled materials stabilized with asphalt emulsion (in French). In the LC26-002 test method, the mix must have a minimum of dry Marshall stability of 8 000 Newton after a cure of 24 hours in the mold at room temperature followed by a cure in a draft oven at 38°C for another 24 hours. The minimum retained stability is 60%. Without cement, the retained stability was rarely achieved; so cement is now added to every mix in order to meet this criterion. A study by Carter et al. (2008) has shown that without cement, it takes a few days to reach a rutting resistance equivalent of one achieved with 1% cement after only 4 hours.

Table 1. Structural coefficient for FDR and CIR used in CHAUSSÉE 2 in Quebec

Material	Resilient modulus MR, MPa	Structural coefficient, a_i
CIR emulsion + 0,5% cement	1400	0,30
FDR no emulsion no cement	84	0,04
FDR emulsion no cement	136	0,09
FDR emulsion + 0,8% cement	337	0,19
FDR emulsion + 1,5% cement	569	0,25

Cement is the most common additives for CIR and usually around 1 % is used. The use of cement can increase the early resistance to damage of CIR and accelerate the cure (AASHTO, 1998). According to Eckan et al. (2008), it takes 2 % of cement to increase the dry resistance of CIR, but even 1 % can significantly increase the wet resistance.

CIR and FDR can both be stabilized with asphalt emulsion or foamed asphalt. In Quebec, CIR is done only with emulsion, but in other provinces, like in Ontario, foamed asphalt is used for CIR. The main advantage they found when comparing CIR (with emulsion) and CIREAM (CIR with expanded asphalt) is the overlaying HMA can be applied after a three days curing period instead of a 14 days curing period required for CIR (Lane et al., 2009). With emulsion, the material cannot be covered until the emulsion is set which means all the water is gone from the mix. If the CIR or FDR with emulsion is overlaid before complete setting of the emulsion, the trapped water may cause delamination or stripping. The cement mentioned earlier serves as a dewatering agent which accelerates the cure of the emulsion.

2.2 Complex modulus

For pavement design purposes, Indirect tensile test (ITS) or Marshall stability are not relevant. With the availability of different mechanistic-empirical pavement design method, like DARWIN-ME, to do a proper pavement design, complex modulus values are needed. Dynamic modulus, which is the norm of the complex modulus, can be obtained with mathematical relations with CBR or even from the mix design with the Witczak equations (Garcia and Thompson, 2007) as used in DARWIN-ME.

Complex modulus tests are performed to determine the viscoelastic behavior of asphalt mixtures at various temperatures and different loading speeds. Those tests are performed within the linear portion of the material behaviour, which means that the rigidity is independent from the stress or the strain (Di Benedetto and Corté, 2005). For viscoelastic materials, such as asphalt mixes, the stress-strain relationship under a continous sinusoidal loading can be defined by the complex modulus E^*. The complex stiffness is defined as the ratio of the sinusoidal stress of pulsation *at a given frequency* ω applied to the material $\sigma = \sigma_o \sin(\omega t)$ and the amplitude of the sinusoidal strain $\varepsilon(t) = \varepsilon_o \sin(\omega t - \phi)$ that results in a steady state (Pellinen and Witczak 2002; Di Benedetto et al. 2001):

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_o e^{i\omega t}}{\varepsilon_o e^{i(\omega t - \phi)}} = E_1 + iE_2 \qquad [1]$$

where E_1 is the storage modulus and E_2 is the loss modulus.

The modulus (length of vector) of the complex number is defined as the dynamic modulus $|E^*|$, the norm of the complex modulus, where σ_o is the maximum stress amplitude and ε_o is the peak recoverable strain amplitude:

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \qquad [2]$$

With the application of the time-temperature superposition principle, it is possible to draw all the results on a single curve; the master curve (Di Benedetto and Corté, 2005). The master curve is the representation of the dynamic modulus at a given temperature over a wide range of frequencies that are not practical or possible to test.

Complex modulus tests on CIR and FDR were performed by some researchers. Example of results obtained for CIR are shown in figure 1. As it can be seen, there seems to be a big difference between the results obtained for CIR with foam and CIR with emulsion. It should be noted that the CIR emulsion results from Lacombe and Lupien (2007), were obtained with mixes containing cement and Lee and Im (2008) mixes did not. In all cases, the results shown are for the longest curing time in each study, which are: 72 hours at 40°C for Lee and Im, 2007; 90 hours at room temperature for Lee and Im, 2008; and 20 days at room temprature for Lacombe and Lupien, 2007. It should be précised that for the CIR of Lacombe and Lupien, the cure was done in seal container in which the water content was maintained at 3%.

There are very few papers on the rheological behavior of FDR materials. Since FDR is a combination of granular and bituminous materials, it is sometimes treated as a granular base for pavement design purposes.

3 Objectives

The choice between treating FDR and CIR with emulsion or foamed asphalt is in most case economical. In Quebec, like in many other regions, the choice of how asphalt is added to those materials is for the contractor to make since either method are considered equivalent.

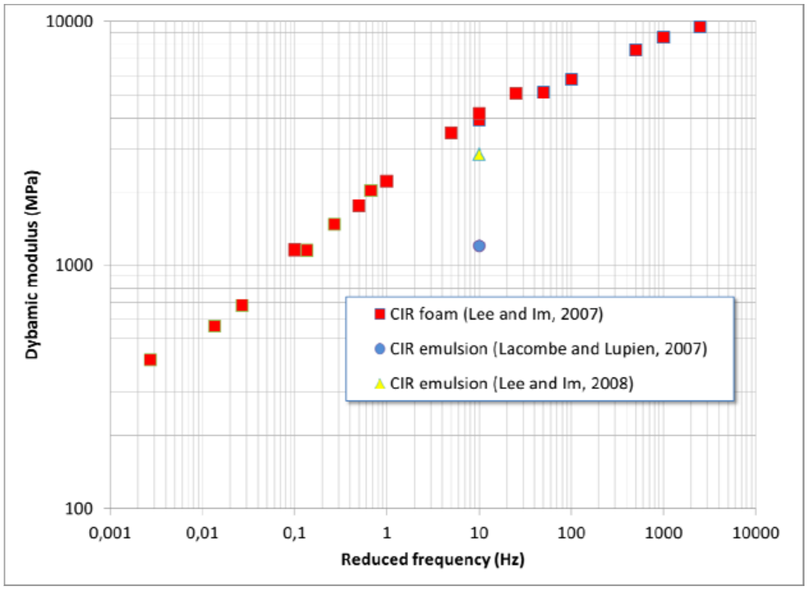

Figure 1. Example of results of dynamic modulus for CIR with foamed asphalt or emulsion at 21°C (adapted from Lee and I, 2007 and 2008 and Lacombe and Lupien, 2007)

The main objective of this paper is to compare the rheological properties of CIR and FDR treated with asphalt emulsion or foamed asphalt. This comparison is achieved with the use of complex modulus testing.

4 Experimental programme and procedures

4.1 Materials

Mix design for all four mixes was done in accordance with Quebec's standard LC26-002. The mixes designs are shown in table 2. The Portland cement content, set at 1%, is calculated by reference to the dry mass of (RAP + virgin aggregates). Other contents, like binder content, are calculated by reference to the dry mass of (RAP + virgin aggregates + Portland cement).

Table 2. Design of mixtures for the different mixes tested

Mix	Added residual bitumen (%)	Portland Cement (%)	Water (%)
FDR emulsion	2,3	1,0	5,5
CIR emulsion	1,1	1,0	6,0
FDR foam	2,6	1,0	5,5
CIR foam	2,1	1,0	5,4

The emulsion that was used is a CSS1-P with a bitumen content of 62,5%. For the foam mixes, a non-modified PG58-28, heated at 170°C, in a Wirtgen foam lab was used. The RAP used for all four mixes was sampled from a CIR job near Montreal and it contains 3,6% asphalt cement. The gradations of the RAP, as well as the gradation of the CIR and FDR mixes are shown in Figure 2.

In order to prepare FDR mixes with 50% RAP and 50% aggregates, virgin aggregates with a nominal maximal aggregate size of 20mm (MG-20) was used. This MG-20 gradation was chosen because it's usually used as base materials for highways in Quebec. In order to achieve a good blend of the virgin aggregates and the RAP, both materials were placed in a concrete mixer and mixed for 2 minutes. The end result is a mix with a gradation similar to those observed on site for FDR materials and with some virgin aggregates stained with bitumen.

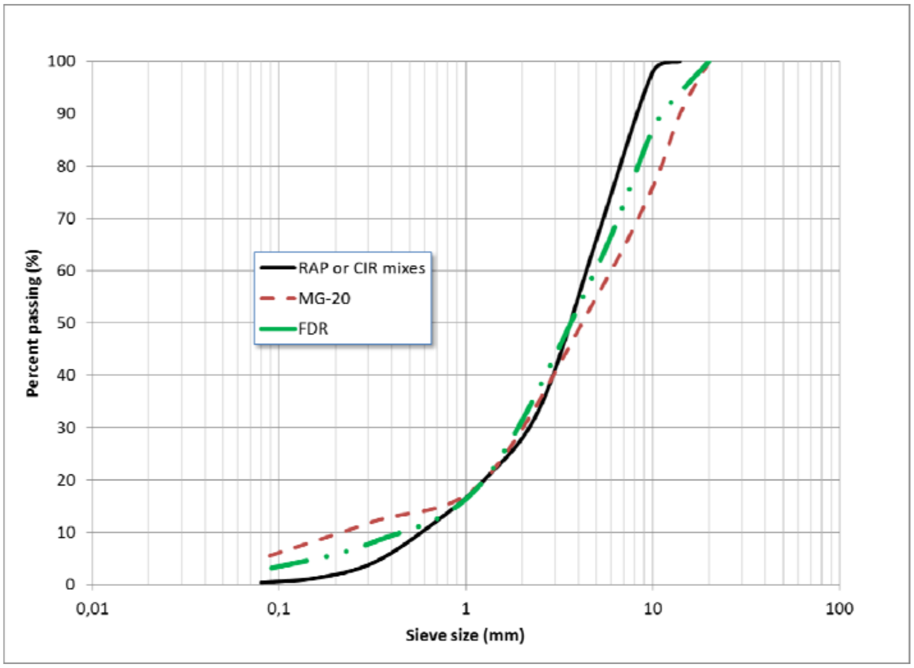

Figure 2. Gradations of the RAP, virgin aggregates (MG-20) and of the CIR and FDR mixes

After that, samples were prepared, using Marshall hammer (50 blows on each side) to determine the bulk specific gravity, the maximum specific gravity and the dry and wet Marshall stability. For all mixes, aggregates, RAP and emulsion were at room temperature and the mixes were compacted right after mixing was completed. The results are shown in table 3.

Table 3. Dry and wet Marshall Stability and air voids for all four mixes

Mix	**Dry Marshall Stability (N)**	**Soaked Marshall Stability (N)**	**Retained stability (%)**	**Air voids (%)**
FDR emulsion	20 076	14 824	74	14,7
CIR emulsion	17 274	13 071	76	13,2
FDR foam	18 435	14 563	79	12,7
CIR foam	19 337	15 663	81	12,3

As it can be seen, all mixes have good retained stability, which is the ratio of wet over dry Marshall stability, and there is no clear trend showing that CIR of FDR has higher Marshall stability or if the uses of asphalt emulsion gives better or worse results than the uses of foamed asphalt.

4.2 Samples preparation

Slabs (100*180*500mm) were also prepared, using LCPC slab compactor, to have representative samples which can be cored for complex modulus tests. The slab compactor is commonly used for hot mix asphalt (HMA). For cold and wet materials, the procedure had to be modified. First, the targeted air voids level is 13% instead of the usual 5% for HMA. Like for HMA, a total of 36 passes of the pneumatic, with a wheel pressure of 6 bar, was done, but the 6 passes with the steel wheel were not done. During previous tests with CIR materials, raveling was observed when the steel wheel was used to finish the compaction.

Once the slabs were compacted, they cured at room temperature for two weeks before being cored. Samples of 80mm of diameter were cored in the thickness of the slabs perpendicular to the path of the compacting wheel, and saw cut to a length of 120mm. After being cored, the samples were cured for another two weeks at room temperature. This two times two weeks curing period is the same procedure that is used for HMA.

For HMA, when complex modulus tests are performed in uniaxial tension-compression, aluminum caps are glued to each end of the samples in order to be able to apply traction on them. However, after several tests with CIR and FDR samples, it appears that those materials have very little tension resistance, therefore resulting in a breakage of the samples in the majority of the trials. Because of this, it was decided to test the samples in compression only; which means that gluing aluminum caps on the samples is not necessary.

Complex modulus (E*) was evaluated using un-confined uniaxial cyclic compression tests. A servo-hydraulic testing system (MTS 810, TestStar II) was used. The specimens were subjected to sinusoidal oscillating axial loading in compression at constant amplitude (30*10-6 m/m). Three extensometers placed at 120° apart were used during complex modulus testing to improve accuracy of results. The tests were performed at six different temperatures (-25,-15,-5, 5, 15, 25°C), and at each temperature, a frequency sweep of five frequencies (1, 0.3, 0.1, 0.03, 0.01 Hz) was done. A wider frequency sweep would have been beneficial, but at higher frequencies than those tested, we ended up breaking samples. Two specimens were tested for each asphalt mixture for all 6 test temperatures and 5 frequencies. The norm of complex modulus |E*(ω)|, and phase angle, ϕ (ω) were obtained.

5 Results

Master curves are often used to present complex modulus test results. To build a master curves, the isothermal curves are transformed in a single curve by following the time-temperature superposition principal. The master curves presented in Figure 3 are the representation, with the 2S2P1D model, of the average of two replicates, of the complex modulus tests performed on each mixes.

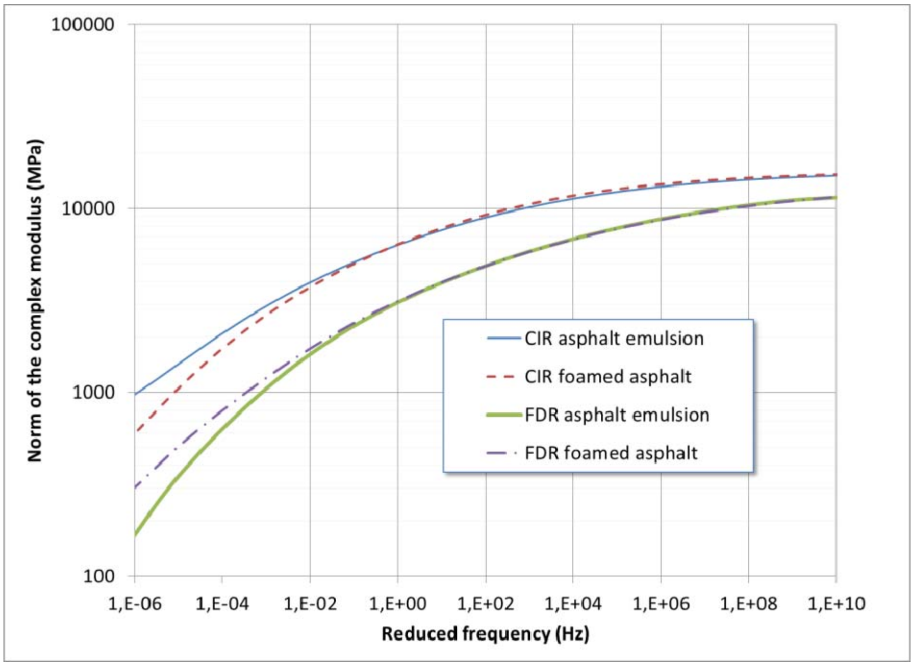

Figure 3. Master curves at 10^{o}C modeled with 2S2P1D

The 2S2P1D complex modulus model, which was developed by Di Benedetto et al. (2003), was used to model the results. The 2S2P1D model is a generalization of the Huet-Sayegh model (Olard and Di Benedetto, 2003).

As it can be seen on Figure 3, both CIR materials have higher modulus than the FDR at every frequency. This is in accordance with the literature review. However, at frequencies higher than 1Hz (low temperature domain), there seems to be no difference between mixes with asphalt emulsion or foamed asphalt for CIR and FDR. Under 1Hz (high temperature domain), CIR mixes with asphalt emulsion have higher modulus than those with foamed asphalt, and it's the other way around for FDR. In any cases, the values shown in figure 7 are about one third of the value we normally have for HMA when tested in the same manner.

In order to better compare complex modulus results, Delaporte et al. (2007) have proposed the use of coefficients that can quantify the differences between mixes. For this research, it's simply called the complex modulus coefficient (C^*_E). The complex modulus coefficient (C^*_E) is defined as the ratio between the complex modulus of the CIR-foam, FDR-emulsion or FDR-foam, at the equivalent frequency f_e and the complex modulus of CIR-emulsion at the same frequency f_e as written in Equation [4]:

$$C_E^*(f_e) = \frac{E^*_{mix}}{E^*_{CIR-E}} \qquad [4]$$

C_E^* is a complex number, as shown in Equation 5, and its norm can be calculated with the equation 6.

$$C_E^* = \left|C_E^*\right| e^{i\phi_E} \qquad [5]$$

$$\left|C_E^*\right| = \left|\frac{E^*_{MIX}}{E^*_{CIR-E}}\right| \qquad [6]$$

The complex modulus coefficients are shown in figure 4.

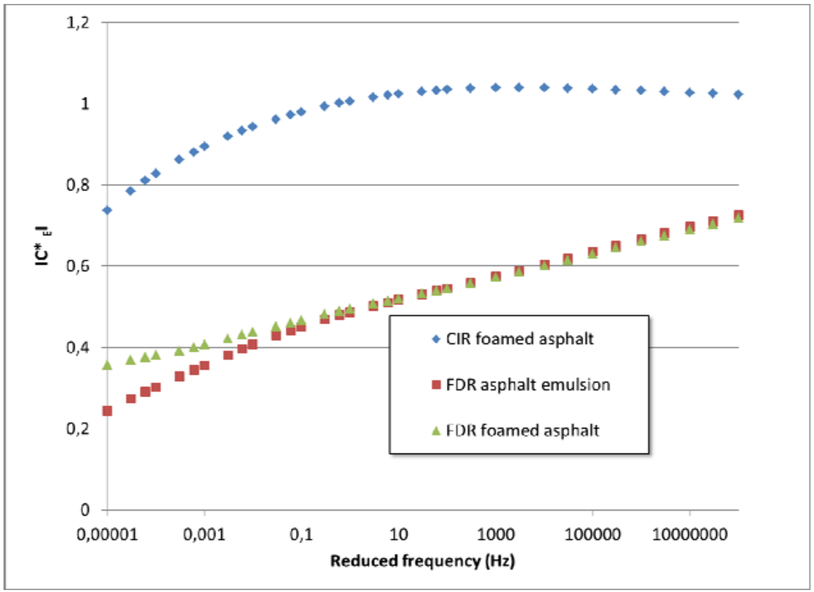

Figure 4. Complex modulus coefficients calculated at 10°C

When analyzing the complex modulus coefficient from figure 4, it can be concluded that at frequencies higher than 0,1Hz, the use of foamed asphalt or asphalt emulsion with FDR gives the same results, even if those two types of mixes look substantially different. This is in agreement with specifications of many agencies, like Transport Quebec, which consider the use of foamed asphalt or emulsion to be equivalent. However, at low frequency, or high temperature, the use of foamed asphalt gives a higher modulus. Over time, after a longer curing period, which mostly influence the behavior of mixes with emulsion; it's possible that the difference between those two mixes would be modified. As for the difference between CIR and FDR, the complex modulus coefficient of FDR mixes goes from 0,70 to around 0,30. This means that at 10^{o}C, the complex modulus of FDR is worth 30% to 70% of the modulus of a CIR mix with asphalt emulsion. This difference is also in agreement with what is currently used as resilient modulus values for those materials in Quebec (table 1).

As for CIR, over 1Hz, mixes with foamed asphalt have higher modulus than those with asphalt emulsion. This is basically the same trend as what was observed for FDR. However, the decrease in modulus is much more abrupt below 1 Hz for CIR than for FDR. The reason as to why foamed asphalt gives better results at high frequencies than emulsion has not been investigated at this time. The greater amount of asphalt in CIR mixes probably explains the higher modulus than those observed for FDR materials, since both type of mixes had similar gradations in this study.

According to Soltani (1998), complex modulus results can be represented by a single line, regardless of the temperature and the frequency, on a Cole-Cole plan, if the material has a linear viscoelastic behavior. On a Cole-Cole plan, the imaginary part (E_2) is plotted against the real part (E_1) of the complex modulus.

In figure 5, the average results of the different complex modulus tests are shown as well as the 2S2P1D models. As it can be seen for both FDR materials, the results fit very well on a single curve, meaning that their behavior is comparable to HMA. For CIR however, the fitting of the model is not as good. It is important to note that, even with the reduced numbers of frequencies and temperature, the lower strain level and the compression only cyclic test, many replicates were broken during the testing phase. In fact, most CIR samples were too damaged during coring to be tested. Dry coring, with no cooling water, was tried, but with no success. On the samples that survived coring, more than half broke after a few cycles of complex modulus test. This lack of cohesion explains why the results for CIR do not fit perfectly on a single curve. New tests with longer curing period are planned.

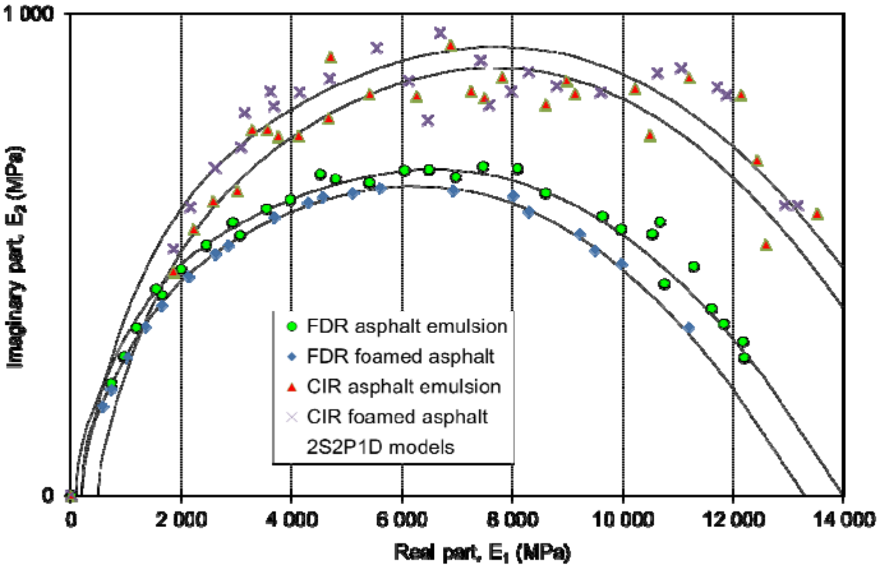

Figure 5. Complex modulus results and 2S2P1D models in a Cole-Cole plan

6 Pavement design

CIR and FDR are in-place rehabilitation methods that are used when the pavement is in bad shape. In most cases, there are no pavement designs done when it's decided to used CIR of FDR. For example, with CIR, it's usually done in 100mm thickness and covered with a surface layer. This means that the structural capacity of the rehabilitated pavement is not optimized. For example, with the AASHTO overlay design method (Huang, 1993), when a pavement is badly cracked, a structural condition factor of 0,6 is applied, which basically means that the modulus of the cracked section is reduced to 60% of its original value. As mentioned earlier, the moduli measured in this study are about 1/3 of typical values obtained for HMA. This means that if we were to replace a cracked HMA, with a modulus of 60% its original value, with a CIR, with a lower modulus, we are in fact creating a bigger problem by weakening the structure even more.

The fact is that on site, CIR and FDR performs really well and they do prolong pavement life. In a study done by Transport Quebec (Bergeron 2007), it has been shown that using CIR of FDR increases pavement life better than simply milling the surface and laying down a new overlay.

If a mechanistic-empirical pavement design method like DARWIN-ME is used, results are not very different. On paper, the use of CIR and FDR is only beneficial when the structural capacity of the pavement has been measured on-site, with a FWD for example, and the results have shown that CIR of FDR can increase the pavement remaining life because of their higher modulus than what is already in place.

7 Conclusions

The following conclusions are based on the experimental results obtained from the complex modulus tests performed on CIR and FDR treated with asphalt emulsion and with foamed asphalt:

- Both CIR and FDR complex modulus results can be modeled with the 2S2P1D model. This means that those materials do have a viscoelastic behavior.

- Regardless of the frequency, CIR norm of modulus is always higher than FDR.

- At high frequencies, or low temperature, there is no significant difference in the modulus of CIR treated with asphalt emulsion or with foamed asphalt. The same conclusion goes for FDR.

- For FDR, at low frequencies, or high temperature, mixes treated with foamed asphalt have higher modulus than mixes treated with asphalt emulsion. It's the other way around for CIR.

- To continue this research, more complex modulus tests will be done to validate the results, and fatigue tests are needed before a complete mechanistic-empirical pavement design can be done.

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