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Original Research Paper

Study of the impact of the compaction and curing temperature on the behavior of cold bituminous recycled materials

Apparao Gandi [a], *Alberto Cardenas* [a], *Djibril Sow* [b], *Alan Carter* [a,*], *Daniel Perraton* [a]

[a] *Department of Construction Engineering, École de Technologie Supérieure, Montreal, QC H3C 1K3, Canada*
[b] *Department of Construction Engineering, University of Thiès, Thiès, Senegal*

HIGHLIGHTS

- Cold temperature curing reduces ITS of CRM treated with foam or emulsion.
- CRM treated with emulsion are more sensitive to cure temperature than CRM treated with foamed asphalt.
- A secondary cure at room temperature has limited impact on ITS for emulsion treated CRM that were first cured at 0 °C.

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ABSTRACT

In most countries, there is a low temperature limit to lay down hot asphalt mixes because if it is too cold, it becomes impossible to get proper compaction. For cold recycled bituminous mixture (CRM), there is little information on the effect of the low temperature on their behavior. The goal of this study is to evaluate, in laboratory, the impact of the compaction and curing temperature on the behavior of CRM. To do so, CRM containing 50% reclaimed asphalt pavement (RAP) and 50% natural aggregates treated with foamed asphalt or bituminous emulsion were mixed and cured at different temperature between 0 °C and 23 °C for up to 10 days before being tested in indirect tension. The results show that for all mixes, a cure at lower temperature means lower tensile strength, but the decrease is more noticeable for emulsion treated materials than for foamed treated mixes. The trend is not as obvious for Marshall stability results. A second cure at ambient temperature was also done, and the analysis of the results showed that the decrease in mechanical performance remains important even after a second cure at higher temperature for all mixes treated with bituminous emulsion, but there is some mechanical gain for mixes treated with foamed asphalt.

* *Corresponding author*. Tel.: +1 514 396 8409.
E-mail address: alan.carter@etsmtl.ca (A. Carter).

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1. Introduction

In most countries, there is a low-temperature limit to lay down hot mix asphalt (HMA) because if it is too cold, it becomes impossible to get proper compaction. All over the world, various studies have been done to understand the compaction behavior of hot mix asphalt materials. However, limited research is available on low-temperature compaction of cold recycled bituminous mixtures (CRM).

Cold recycling of bituminous materials is a sustainable technology for pavement rehabilitation. Basically, it's the reuse of different percentage of reclaimed asphalt pavement (RAP) that is mixed with virgin or recycled aggregates, in different layers of pavement. In order to increase the strength of those mixes, different binders can be used. The most common one are bituminous emulsion and foamed asphalt.

The choice between foamed asphalt and bituminous emulsion is, in many regions, based on cost and availability. However, it has been shown that both binders can give similar results (Carter et al., 2013), even if the method in which the binder glues the particles together differs greatly.

2. Background

The compaction of CRM with bituminous emulsion or foamed asphalt is a very important factor to get good mechanical characteristics. It helps to position the particles of the material and redistribute the binder from separate globules to continuous films (Needham, 1996). The compaction quality has an impact on air voids of the CRM (Kassem, 2008; Lauter, 1998). Not only the quantity, but the level of uniformity of the air voids distribution considerably affects the behavior of the mixture (Castillo and Caro, 2013; Xu et al., 2012). However, too much compaction can also be detrimental. Quick and Guthrie (2011) stated that the severity level of compaction impacts strength development in emulsified asphalt mixture. Compaction can contribute to the initial damage of the emulsified asphalt but also lengthen the curing period within these mixtures.

Compaction can lead water to disperse from the asphalt bitumen and impact the mix curing time and cohesion (Asphalt Institute, 1997). Barbod and Shalaby (2014) studied the emulsified asphalt mixtures in cold regions, and they concluded that laboratory specimens prepared at low (5 °C) temperature have similar dry density than mixes prepared at 24 °C, but the strength of those mixes is much lower. For foamed asphalt, it has been shown that a compaction temperature between 13 °C and 23 °C is optimal and mixing below that will lead to poor quality mixes (Bowering and Martin, 1976).

Generally, the curing procedure of CRM has a significant impact on the final behavior of the mix. Due to that, curing has been considered an important parameter in the asphalt industry. Various definitions for the curing procedure of CRM can be found in the literature (Tebaldi et al., 2014; WIRTGEN GmbH, 2010). Jenkins (2000) defines the cure of CRM as the process in which the water is discharged of the specimen. The Asphalt Institute (1997) mentioned that insufficient curing may increase the chance of asphalt stripping along with a reduction of the rate of strength development when a hot mix asphalt (HMA) overlay is constructed. The curing process can be fairly fast in convenient weather conditions. However, it can be significantly impacted with relatively high humidity, lower temperatures, or when rainfall occurred after cold in-place recycling placement (Kim et al., 2011).

The World Road Association (PIARC, 2002) mentioned that the residual moisture has to be significantly evaporated prior to the application of the hot mix asphalt overlay. This period should not only depend on the weather conditions following cold in-place recycling construction, but also on the level of traffic. It's during this period that the material cures and forms some internal structure before being covered with a HMA layer (AASHTO, 1998; Bergeson and Barnes, 1998; The Barnhardt Group, 2016). Even though different curing protocols have been adopted in most countries, a universally accepted curing procedure is presently not available.

Marais and Tait (1989) recognized that the cold recycled emulsified asphalt mixture properties changed seasonally with considerable variation in the initial six months to two years. Another researcher, Leech (1994), concluded that full curing of CRM on construction site may happen between 2 months and 24 months depending only on the climatic conditions. However, a time period of 14 days is usually identified as an acceptable cure duration (Croteau and Lee, 1997; Kandhal and Mallick, 1998).

The lack of consensus in curing method (duration and temperature) can be seen in the different protocols that can be found in the literature. For example, SABITA (1999) used curing of 24 h at room temperature, 48 h at 40 °C with optimum moisture content (OMC) and 45 h at 60 °C. Robroch (2002) worked with 24 h at 40 °C (sealed) and 48 h at 40 °C (unsealed). Asphalt Academy (2003) conducted research at 24 h at ambient temperatures in mold and 3 days at 40 °C with sealed specimens. Lee et al. (2003) used 6 h at 60 °C to represent hot summer day and 24 h at 25 °C to represent cool summer night. Carter et al. (2007) used 24 h at 60 °C to accelerate curing, and the mix performances after that short period were satisfactory. Finally, WIRTGEN GmbH (2004) performed curing protocol at 24 h at ambient temperatures unsealed and 48 h at 40 °C sealed, and Gandi et al. (2017) studied laboratory prepared specimens that were cured for 10 days at 38 °C.

Some curing methodologies include periods in which the specimens are sealed. This is done to represent field conditions. Batista and Antunes (2003) sealed their specimens with a plastic film, except for the surface, in order to let the water evaporate. They mentioned that moisture content progression in the field would be in between the laboratory prepared CRM emulsified asphalt specimens with plastic film and without plastic films. The change in moisture content is greatly influenced by the temperature. Part of the water will evaporate, and the lower the temperature, the slower this process. Bocci et al. (2011) studied the temperature influence on three curing protocols (28 days at 40 °C, 63 days at 20 °C, and 56 days at 5 °C) on the indirect tensile stiffness modulus (ITSM) tests development of the mixture as illustrated in Fig. 1. They concluded that curing at 40 °C and 20 °C resulted in higher modulus, whereas at

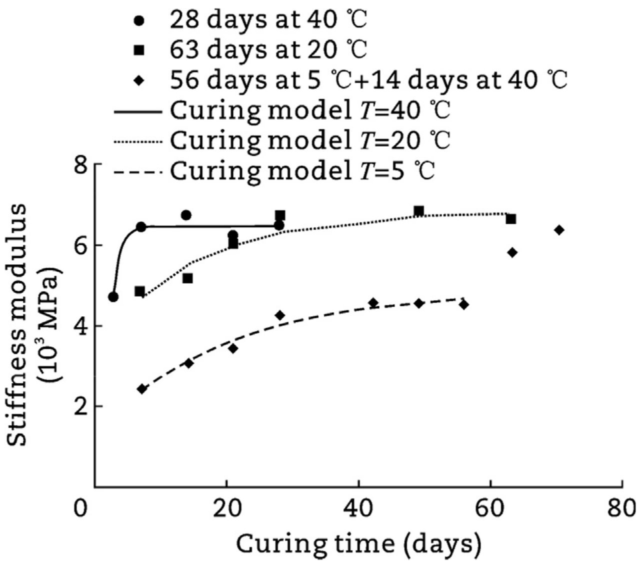

Fig. 1 – Development of stiffness modulus with different curing temperatures and time (Bocci et al., 2011).

lower temperatures, like 5 °C, the curing process is slower, and the stiffness reaches an asymptotic value lower than the one obtained at higher temperature.

3. Objective

In Canada, like in many other northern countries, the temperature dictates when pavement can be constructed. Since the paving season is relatively short, it is not uncommon to have to place CRM late in the season when the temperature is close to freezing. There is little information on the impact of the low temperature on the behavior of CRM except for WIRTGEN GmbH (2004) who advise against making treated cold recycling when the aggregate are below 10 °C.

Because of this, the main objective of this study is to evaluate the impact of the mixing, compaction and curing temperature on the mechanical properties of CRM. The specific objectives of this study are to evaluate the difference between the evolution of Marshall stability and indirect tensile strength (ITS) according to time and temperature, and also to compare the behavior of foamed asphalt treated CRM (CRM-foam) with bituminous emulsion treated CRM (CRM-emulsion).

4. Materials and methods

In order to reach the objectives, a single mix design of CRM was chosen. A 0–10 mm mix of 50% RAP with 50% virgin aggregates was prepared in laboratory with the same gradation for each mix. The gradation of the RAP, virgin aggregate and the final mix is shown in Fig. 2, and the mix design is shown in Table 1.

As it can be seen in Table 1, 1.0% of cement was used in all the mixes. The addition of small amount of cement does not affect the long term performance of CRM, but it helps speed up the cure. In this case, cement is used as a dewatering agent. The RAP used in this study comes from a single stockpile made of several RAPs. The extracted RAP bitumen performance grade (PG) is PG 76-28. This is not stiff RAP, which means that it's probably not very old. Depending on the binder used, foam or emulsion, different amount of water and total added residual bitumen was used. For the emulsion mix, a CSS1 bituminous emulsion containing 62% bitumen was used. The base bitumen for the emulsion is a PG 58-28. The total water shown in Table 1 includes the water that comes from the emulsion. The mix design for both binders (CRM-foam and CRM-emulsion) was done according to Quebec's method LC26-002 which is based on Marshall stability. Basically the amount of water and residual bitumen is a compromise between dry Marshall Stability, retained stability and air voids. It is however important to note that it is required to have a minimum 80% coating of the aggregate (virgin and RAP) with the binder (emulsion or foamed). The amount of added water is adjusted to ensure that coverage which is evaluated visually.

For the foam mixes, before making the mix design, the foamed asphalt design had to be done. Different water content and bitumen temperature (160 °C, 170 °C and 180 °C) were tested, and the optimum foam was obtained at 170 °C with 3.15% water. According to Jenkins (2000), the expansion and the half-life of the foamed asphalt are not sufficient to properly identify the optimum foam asphalt design. The foam index (FI), which is the area under the curve

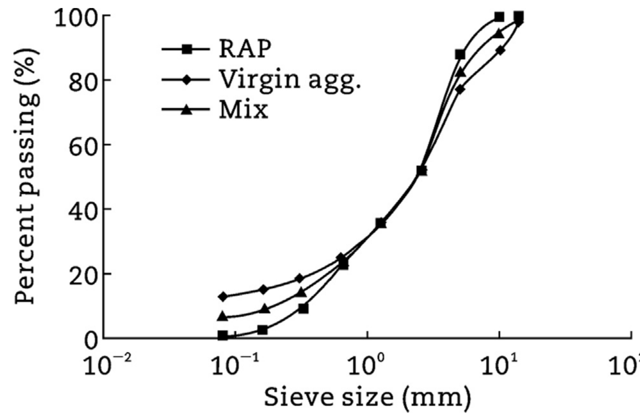

Fig. 2 – Gradation of the RAP, virgin aggregate and mix used in this study.

Table 1 – Mix design of CRM with foamed asphalt or bituminous emulsion.

	CRM foam mix	CRM emulsion mix
Aggregate	50% RAP (4.1% bitumen) 50% virgin aggregates	
Cement (%)	1.0	1.0
Total water[1] (%)	3.3	5.0
Added residual bitumen[1] (%)	3.0	2.0

Note: [1]percentage of the weight of the dried aggregates.

Table 2 – Testing methodology.

	Duration	Temperature
Storage of RAP-aggregates and mixing accessories	24 h	Variable (0 °C, 5 °C, 10 °C, and 23 °C)
Mixing	<5 min	Variable (0 °C, 5 °C, 10 °C, and 23 °C)
Compaction (Marshall 75 blows on each sides)	15–30 min	Variable (0 °C, 5 °C, 10 °C, and 23 °C)
Demoulding	3 min	Variable (0 °C, 5 °C, 10 °C, and 23 °C)
Cure	Variable (0–15 min, 1 and 3 h, 1, 3, 7 and 14 days)	Variable (0 °C, 5 °C, 10 °C, and 23 °C)
Tests (Marshall stability and ITS)	5 min	23 °C

expansion-time after the maximum (contraction surface), is a measured of the foam stored energy, and it can be used to select the optimum foam. The FI was used in this study to select the foaming temperature and water content.

The aggregate and the RAP were oven dried and pre-mixed beforehand. Water was added to the mixture 24 h before mixing to ensure absorption by the solid particles. During this first 24 h, the wet aggregate-RAP mixed is sealed in a plastic bag. Then the aggregate-RAP mix was stored for 24 h at different temperature, as shown in Table 2.

The chosen temperatures are 0 °C, 5 °C, 10 °C and 23 °C. 23 °C was the lab temperature when those experiments were performed, and the other temperatures represent possible field temperatures found in Canada. As shown on Fig. 3, for more than 50% of the year, the air average air temperatures in Montreal and Vancouver are below 10 °C, which is why those temperatures were selected. The relative humidity was not controlled during the cure or the tests. The measured relative humidity in the laboratory during this experiment was between 57% and 63%.

The mixing of the materials was done with a mechanical mixer, and the mixer's bowl as well as the beater was stored at the same temperature than the RAP mixtures. Just like it would be done in the field, the emulsion and the foam were not at those low temperatures. As mentioned before, the foam was produced at 170 °C, and the emulsion was stored at 40 °C as recommended by the supplier.

It is important to precise that in most studies done on the cure of cold recycled materials, only the cure temperature is controlled. Here, by controlling the temperature even during mixing, it is possible to ensure to be representative of field job site done late in the season. The mixing time was not adjusted for the different temperature, even if with lower temperature, the viscosity of the bitumen increases when in contact with the cold RAP-Aggregate mix. All mixes were considered well coated by the bitumen for the foam and emulsion mixes.

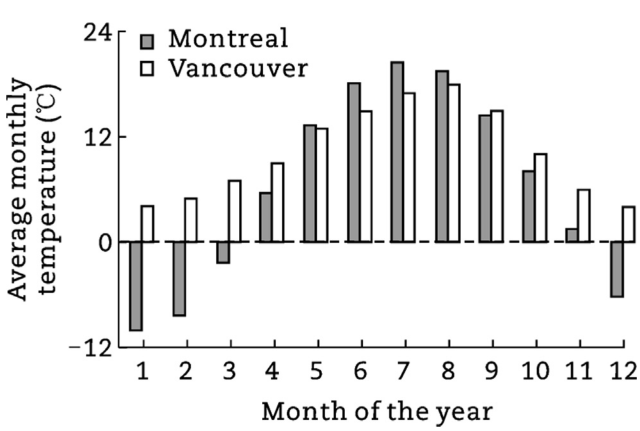

Fig. 3 – Average monthly air temperature in Montreal and Vancouver (Weather Network, 2017).

Once mixed, the specimens were compacted with a Marshall Hammer with 75 blows on each side. The Marshall moulds were kept at the cure temperature like all other equipment that went into contact with the mixes. The same energy was used for all the specimens, which can result in different air voids, and like it was done for mixing, the Marshall mould were stored at the same temperature as the RAP-aggregate mixture.

For the specimen to be tested during the first 15 min, the demoulding was done right after the compaction. For all the other specimens, the demoulding was done after 1 h. The demoulding right after compaction was not done since it resulted in the breakage of many specimens that did not have enough cohesion.

Once the different cure completed, the specimen were left 1 h at room temperature to be tested in Marshall stability or in indirect tensile strength (ITS), with the exception of the 0–15 min specimens which were tested right away. It's important to note that during compaction, the temperature of the specimen increases. So, for the 1 and 3 h cure, the specimen did not have time to stabilize at the cure temperature before being tested, but the surface of the specimens were at the right temperature.

Marshall stability was used for this research project because it's the specified method for CRM characterization according to Quebec's standard. Since ITS is used by many agencies and research center to evaluate CRM mechanical behavior, it was decided to use this method also. It is interesting to note that two mix designs were done; one with ITS and one with Marshall and the mix design were different. For example, for the Marshall mix design with foam, the optimum percent of added bitumen was 2.7% instead of 3.0% obtained with ITS. It was decided to select the ITS mix design because the trends (bulk specific gravity vs. total bitumen, wet stability vs. total bitumen, etc) of the impact of the amount of water and bitumen were not as clear with Marshall than with ITS.

Both tests were performed at the same loading rate (51 mm/min) and on the same apparatus (Fig. 4), but with a different loading setup. For ITS, a small loading strip curved for 100 mm samples was used at top and bottom, and for the Marshall stability, the usual Marshall breaking head was used. The Marshall stability test was done according to ASTM D6927, and the ITS test according to ASTM according to ASTM D6931.

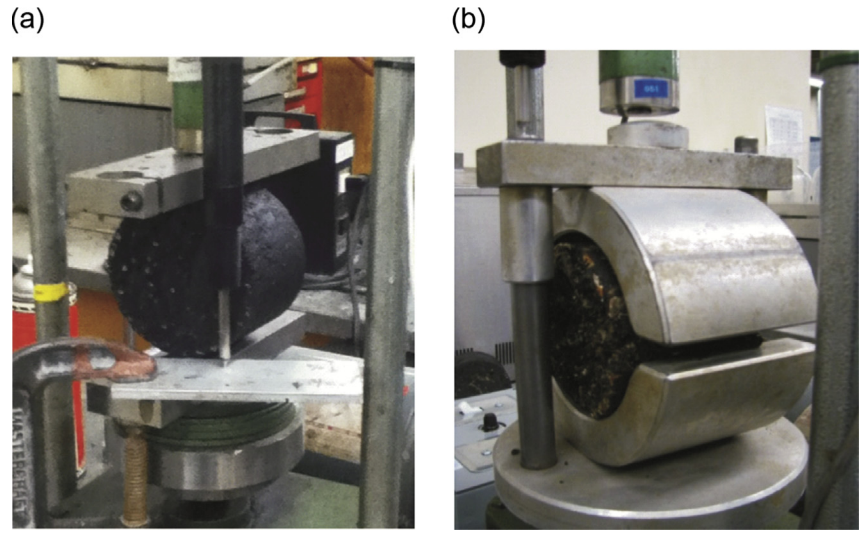

Fig. 4 – Indirect tensile strength (ITS) and Marshall stability test apparatus. (a) ITS. (b) Marshall stability test.

Those two tests give mechanical properties of CRM. The results of the tests can be associated with the cohesion of the materials, but not with their durability.

5. Results

For every mix, a minimum of three specimens were prepared for ITS tests and three more for dry Marshall stability. However, many specimens were broken during demoulding or handling, which resulted in having two specimens for most of the tests. The results shown are the averages of those two, or three when a third specimen was available. If the difference between two mechanical results were above 10%, new specimens were mixed, cured and tested. According to Fu et al. (2010), higher variability in the results is expected at cure temperature below 15 °C–25 °C. This can be due to the fact that when the bitumen, in the form or emulsion or foam, comes in contact with the cold RAP-aggregate mix, contracts and may not be spread homogeneously in the mix. Even if the mix looked properly coated, it was not possible to actually quantify the bitumen film thickness on each particle. It is possible that its heterogeneity increases with the decrease in temperature.

The Marshall dry stability results for different cure duration and conditioning temperature for foamed asphalt and bituminous emulsion treated CRM are presented in Fig. 5. As it can be seen, the results at 23 °C, for both types of CRM mixes (CRM-foam and CRM-emulsion), are similar. This shows, as mentioned in the literature, that both binders give similar properties with proper mix designs. Similar results are also seen at 10 °C, with maximum values between 30 and 35 kN at 14 days. However, it can be seen that the low mixing and cure temperature has a greater impact on CRM-emulsion mixes than on CRM-foam mixes. For example, at 14 days, the Marshall stability of the CRM-emulsion mix cured at 0 °C is about 20% of the Marshall stability of the CRM-foam mix, which is about the same difference that we got between a cure at 0 °C and 23 °C for the emulsion mix. Also, it should be noted that there are no Marshall stability in the first three hours for the emulsion mixes at 0 °C. This is due to the fact that the cohesion was too low to take the specimens out of the mould; all those specimens broke during demoulding.

The fact that the cohesion remained too low when cement is used as a co-binder is surprising. As mentioned before, cement was added only to speed up the cure process, to ensure that cohesion would reach an acceptable level within 3 days. In fact, in Quebec, for CRM, the quality control done in

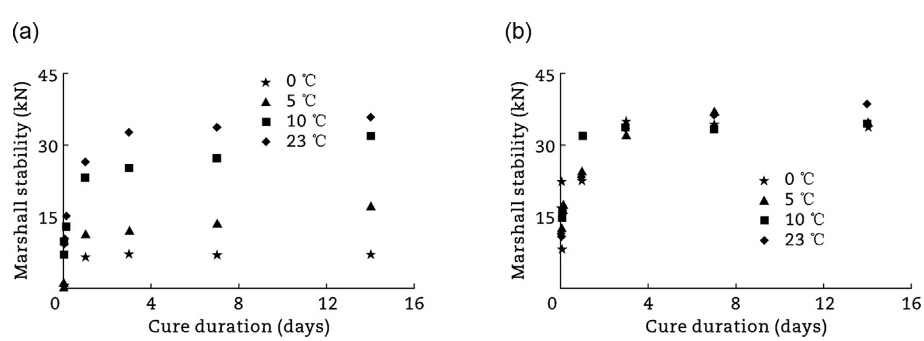

Fig. 5 – Average results of dry Marshall stability of different curing time and temperatures for all CRM mixes. (a) CRM-emulsion. (b) CRM-foam.

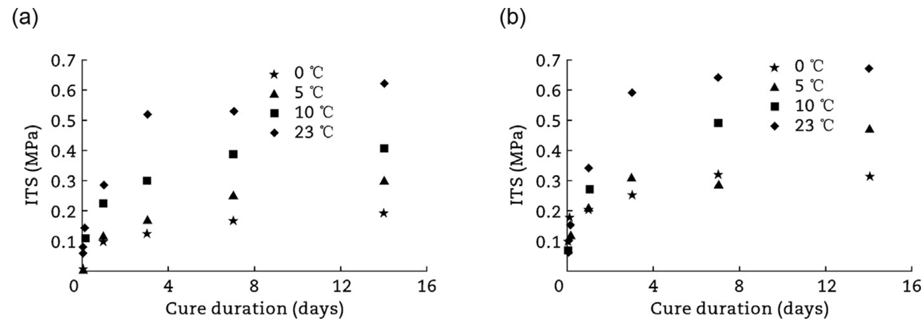

Fig. 6 – Average dry ITS results of different curing time and temperatures for all CRM mixes. (a) CRM-emulsion. (b) CRM-foam.

lab takes usually three days to complete. This means that if the temperature is adjusted for the QC testing, the mix at 0 °C would never reach, at least not in the first 14 days, the 8 kN required dry Marshall stability. Another aspect that is interesting is the rate of increase of the Marshall stability, which can be related to the rate of increase of the cohesion. The temperature has a very limited effect on the rate of cohesion increase for CRM-foam mixes, but it has a major impact for the CRM-emulsion mixes. At 23 °C, the rate is about the same for both types of CRM mixes, but at lower temperature, the cohesion increases at a much slower rate with emulsion. For example, at 0 °C, in the first three days, the increase of Marshall stability is 9 kN/day for foam mix, and only 2.4 kN/day for emulsion mix. If that trend was constant, it would take the emulsion mix would need around 13 days to reach the Marshall stability reached by the foam mix after 3 days. However, the trend is not constant, the maximum value for foamed is obtained after 3 days, after which it remains somewhat constant.

The results of the ITS are shown on Fig. 6. On the left side (Fig. 6(a)), we can see that, just like the results for the Marshall stability, there is a big difference between the results at low temperature than the results at room temperature for the emulsion mixes.

However, in the case of ITS results for the foam mixes (Fig. 6(b)), the trend in the results is different. For the Marshall stability, the temperature seems to have little influence on the results. For ITS, a clear difference is seen according to temperature. For example, at 14 days, there is barely over 10% of difference between the Marshall stability at 0 °C and 23 °C, but there's a 50% difference for ITS. More tests are needed, but it seems that ITS is more sensitive to the difference in the behavior of those materials. Because of this, we think that ITS should be used for CRM mix design and characterization instead of Marshall stability.

Contrary to the Marshall stability, the rate of increase in the cohesion, which is related to ITS this time, is affected by the temperature for both CRM-foam mixes and CRM-emulsion mixes. However, like for Marshall stability, the effect is greater for CRM-emulsion mixes.

As mentioned in the literature, the ITS or Marshall stability of CRM increases with the cure duration, but also with the decrease of moisture content in the specimens. The moisture content of each specimen was measured after the mechanical tests. However, the variability in the results is very high, up to 25%, due to material loss when handling the specimen, even if great care was taken. The results of the water loss for the CRM-foam mixes are shown on Fig. 7. The results for the emulsion mixes follow the same trend. On Fig. 7, it can be seen that the mix at 23 °C loose more water than at colder temperature, which is as expected. However, it was expected that there would less water loss at 0 °C due to limited evaporation, which is not shown here. Again, more tests are needed to precise those results, mostly because the highest variability of the measure was obtained at 0 °C. One hypothesis to explain the water loss at 0 °C is the fact that some water was actually turned into ice and it may have remained attached to the mould or to aggregate that were lost during manipulation of the specimens.

On Fig. 8, we can see the relation between ITS and water loss. This presentation of the results shows that the cohesion increase follows a linear trend at every temperature tested, but that this rate diminishes with the temperature. This is expected for CRM-emulsion mixes since the cohesion is directly linked with the breaking of the emulsion which is linked with the water content. However, for CRM-foam, the presence of water in the mix is not in the foam itself, but between particles. It is possible that this water keeps the bitumen to properly bind the particles together by being present between particles. This means that water loss could results in better packing, lower air voids. This aspect was not

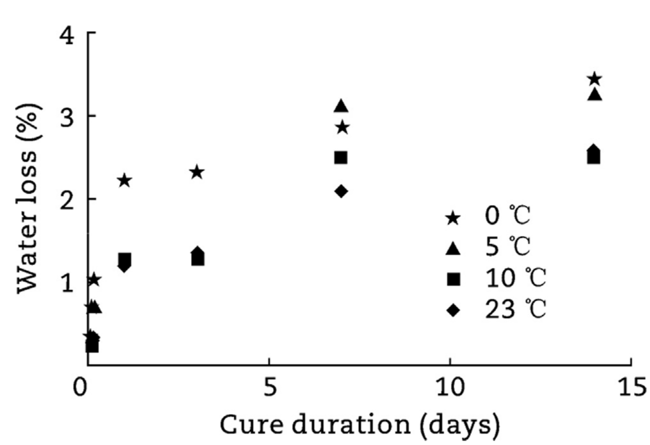

Fig. 7 – Water loss according to cure duration for foam CRM mixes.

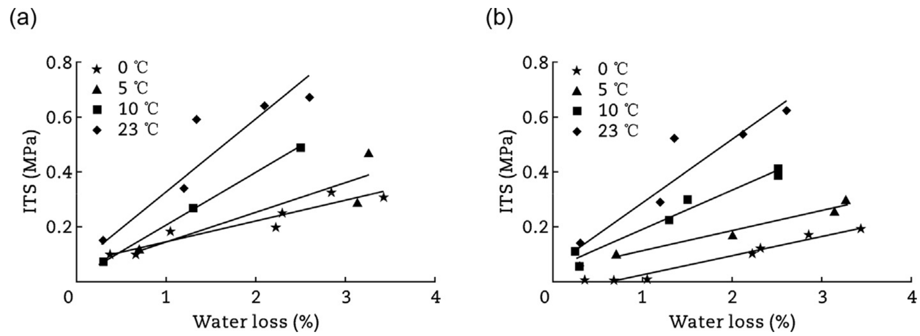

Fig. 8 — Average dry ITS results of different curing time and temperatures for all CRM mixes vs. water loss. (a) CRM-emulsion. (b) CRM-foam.

verified in this study. The rate of the cohesion increase is represented by the slope of the best fit curves (all $R^2 > 0.8$).

Another aspect of bituminous mixes, CRM or hot mix asphalt, that has a big impact on the mechanical performances, is the air voids. By mixing and compacting the specimens at different temperature but with the same energy, it was suspected that the air voids may be different according to the temperature. The air voids, calculated from the dry bulk specific gravity and the maximum specific gravity are shown on Fig. 9.

According to Quebec's specifications, the maximum acceptable air voids content in CRM is 18%. Even if the results respect the limit, the variation of the air voids is high for any given temperature. The error bars on the figures represent one standard deviation. However, at least two trends are visible here. First, the air voids are not statistically different at 0 °C, 5 °C and 10 °C, and are lower than at 23 °C. For either type of mix, the 2% difference in the air voids has to be related to the tackiness of the bitumen that is lower at low temperature, since all the other parameters (water and bitumen content) are the same in all mixes. Second, globally, the air voids of the emulsion mixes are higher than for the foam mixes. This is expected because of the higher water content in those mixes. During compaction, water serves as a lubricant, but it also creates voids. Lower water content can results in higher cohesion and mechanical properties, but it can also results in an incomplete coating, which can in turn results in poor retained stability, or high moisture sensitivity. Second, the air voids at low temperatures are lower than at room temperature. This can be explained by the black rock effect. At 23 °C, the bitumen of the RAP does not seem sticky, but with the pressure applied during compaction, it restrains movement of the particles since it increases the friction in the mix. At lower temperature, the same bitumen is stiffer, less sticky, so it does not increase the friction.

Lower air voids should mean higher ITS value and higher Marshall stability. This can lead us to think that if the specimens were compacted at equivalent air voids and not with equivalent energy, the ITS and the Marshall stability results would be even lower for the tested temperature below 23 °C. The fact that the measured mechanical performances are lower at lower temperature must be due to the repartition of the bitumen in the mix. For foamed asphalt, when the hot bitumen droplets come into contact with the cold aggregates, the temperature of the bitumen reduces very rapidly, which increases it's viscosity, and reduces its capacity to adhere properly to the fines. So instead of having homogeneous mastic around the aggregates, we can postulate that there are clusters of bitumen separated by fines particles, which creates weaker plane in the mix.

For the bituminous emulsion, the reduction in temperature has a direct impact on the coalescence of the bitumen droplets. In fact, at temperatures below 8 °C—10 °C, the flocculation of the bitumen droplets happens really fast when the emulsion comes in contact with the cold aggregates, but the coalescence is limited, and even impossible in some cases (Audeon, 1993). This could explain why very little cohesion, if any, was measured at short time for low temperature. Low temperature destabilizes the emulsion, just like a quick change in pH does. James (2006) mentions that solvent can be added to emulsion to accelerate coalescence at low temperature. This means that the manufacturer could design an emulsion that breaks normally at low temperature, but that emulsion would break too rapidly at normal temperature.

The obtained results clearly show that a reduction in mixing and curing temperature has a negative impact on the

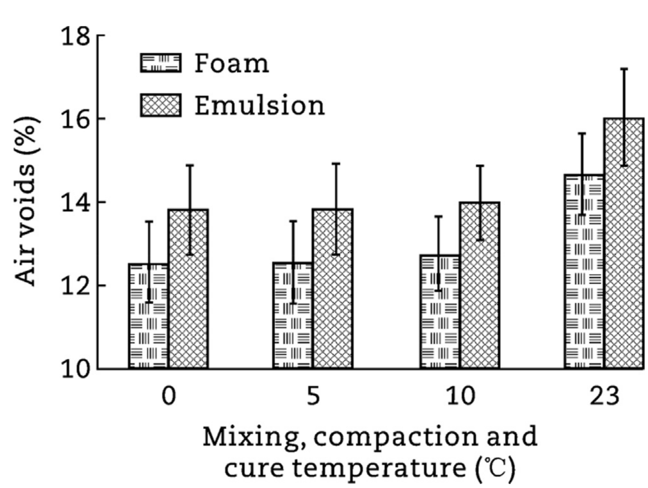

Fig. 9 — Air voids according to the mixing and compaction temperature.

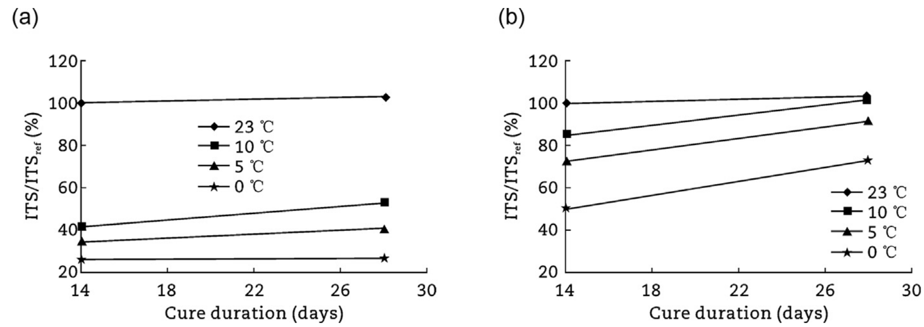

Fig. 10 – Average dry ITS results of different curing time and temperatures for all CRM mixes with an additional 14 days at 23 °C cure. (a) CRM-emulsion. (b) CRM-foam.

mechanical properties measured with ITS and Marshall stability for CRM-foam and CRM-emulsion mixes. The results do not, however, show if this decrease in performance is permanent or not. In order to study that aspect, new specimen were prepared with the same exact methodology, but with an added curing protocol after the initial 14 days. Once the 14 days at the various curing temperature was reached, the specimens were left for another 14 days at 23 °C before being tested in ITS. This was done to verify if the decrease in performance is permanent, or if it would correct itself after a temperature increase, which would be the equivalent of the next summer in the field. Results are shown in Fig. 10. The ITS results obtained at 28 days are divided by the ITS results obtained after 14 days at 23 °C (ratio $(ITS/ITS_{ref}) \times 100$) in order to better evaluate the change during this additional curing period. As for the first 14 days cure at different temperature, the relative humidity was not controlled. The specimens were left to cure in air at room temperature in the laboratory.

As it can be seen, for CRM-foam (Fig. 10(b)), with an additional 14 days at 23 °C, the ITS value increase significantly, but they still do not reach the values obtained after only 14 days at 23 °C. However, a longer curing period at that temperature should results in higher ITS value. Even at 0 °C, at the current ITS increase rate, it would take another 17 days to reach the same ITS value obtained at 23 °C. This is reasonable is the increase rate stays constant since in the field, the summer last longer than that. This means that the lower results obtained at lower temperature did not damage the specimen.

For the CRM-emulsion at 0 °C, the additional curing period did not have a significant effect (Fig. 10(a)). In this case, it seems that the cohesion measured through ITS at 14 days is the maximum that this mix will reach. This could be explained by the fact that at low temperature, as mentioned before, the emulsion did flocculate, but did not coalesce properly around the aggregate, which limited the cohesion. Even after increasing the temperature to intermediate level, the bitumen is not able to coat the aggregate correctly. It is possible that if the temperature was increased to decrease the viscosity enough to make the bitumen flow, the coating could increase with the help of a mechanical stress (traffic).

6. Conclusion and recommendation

The objective of this research was to evaluate the effect of cold temperature mixing and curing of cold recycled materials treated with foamed asphalt and bituminous emulsion. The CRM tested were made of 50% RAP and 50% virgin aggregates and they were mixed and cured at 0 °C, 5 °C, 10 °C and 23 °C for up to 28 days before being tested in Marshall stability and ITS. Not only was the cure done at lower temperature, but the mixing as well. The cure was separated into two distinctive parts: a first 14 days at different temperature to represent possible field conditions when the work is done late in the paving season, and a second 14 days at 23 °C to verify of the decrease in performance observed during the first 14 days can be recuperated if the temperature is increased.

Globally, it has been shown that low temperature for mixing and curing of CRM mixes do have a major impact on their mechanical performances. More specifically, the main conclusions that are drawn from this study are.

- Marshall and ITS results are related, but ITS results are less variable and more sensitive to mixing, compaction and curing temperature;
- CRM-foam and CRM-emulsion have similar Marshall stability and ITS when made and cured at room temperature;
- CRM-foam mixes are less sensitive to low temperature cure than CRM-emulsion. This can be explained in part because of the lower water content of CRM-foam mixes compared with CRM-emulsion mixes, and also because of the curing mechanisms of both mixes type;
- Mixing and compaction at 0 °C, 5 °C and 10 °C enables better compaction, so lower air voids, than at 23 °C. This shows that at low temperature, RAP has more a black rock behavior than at room temperature;
- An additional curing period at 23 °C does not have a significant impact for CRM-emulsion specimens that sustained initial low temperature cure. This additional cure does however help with CRM-foam mixes. For CRM-foam mixes, a second cure at 23 °C could potentially completely correct the results obtained at lower temperature given enough time.

In order to better understand the results obtained here, new tests should be done. The measurement of the complex modulus on the CRM at different mixing, compaction and curing temperatures would help to better grasp the impact of the lower temperature. It would also be beneficial to test strength of specimen at low temperature, like fatigue resistance, rutting resistance, or fracture energy in order to properly evaluate the impact of the end of season work done in the field. Another aspect to test is the emulsion-aggregate combination. Emulsion behavior is strongly linked with its chemistry and with its compactibility with the aggregate. It is possible that another emulsion and/or another aggregate source would give significantly different results. Finally, it would be helpful to test at longer curing period, and to test the moisture sensitivity.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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Dr. Alan Carter is a professor in the Department of Construction Engineering at École de Technologie Supérieure (ETS) in Montreal, and he's responsible of the Pavement and Bituminous Materials Laboratory (LCMB) at ETS. Professor Carter's research focuses mainly on cold recycling of bituminous materials, thermorheological characterization of bituminous materials and mechanistic-empirical pavement design.