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Simulation and Influence of Early-Life Traffic Curing for Cold In-Place Recycling and Full-Depth Reclamation Materials

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Abstract: Cold In-Place recycling (CIR) and Full-Depth Reclamation (FDR) of asphalt pavements are popular design alternatives for roads rehabilitation. These techniques are of great interest in road construction because they are environmentally friendly, economic, and efficient. These rehabilitation processes are used for more than twenty years in Quebec. But the behavior of these cold mixes is still not well known. The problem is that people tend to use a similar process to the Hot-Mix Asphalt (HMA), so additional investigations are needed to understand how these cold mixtures work. There are different kinds of mixtures depending on the proportions of Reclaimed Asphalt Pavement (RAP) and natural aggregates. In Quebec, it is common to work with two types of materials, RAP only for the CIR, half RAP and half natural aggregate for the FDR. It depends on multiple factors like budget, location but mainly on the type of rehabilitation (superficial or structural) you are looking for. The objective of this study is to analyze different ways to simulate the early-life traffic curing. In order to do that, we realized different cold mixes with Marshall hammer, slab compactor and gyratory compactor. We made them undergo a post compaction 6 hours after initial compaction and then determined their characteristics: bulk specific gravity, maximum specific gravity, water content after compaction, Marshall stability, and rutting resistance. The results have shown the benefits of early life post-compaction on the mechanical properties of CIR and FDR.

1 PROJECT INTRODUCTION

Cold in-place recycling (CIR) and Full-Depth Reclamation (FDR) are pavement rehabilitation techniques used to correct the defects of the road. To date, these two techniques are recognized in road construction for their environmental, economic, and structural benefits. A study on sustainable pavements (1) has shown that pavement rehabilitation compare to the others techniques is a good option 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.

The process is simple: we reuse the existing pavement material to a fixed depth, which is reclaimed and transformed into a bituminous aggregate. Then it is mixed with an asphalt emulsion, laid down and compacted to the specified density. This way, we can correct superficial or structural defects. It depends on the depth that we want to treat. If it is needed to correct the superficial defects, we just mill the Hot-Mix Asphalt (HMA) to get CIR. We are talking about a depth between 75mm and 150mm. Regarding the correction of the structural defects, we mill to a depth between 50mm and 200mm, so we take the HMA and part of the aggregate base to obtain FDR (2). Following the Bitume Québec Association and the Pavement, Roads and Bituminous Materials Laboratory (LUCREB) of the École de Technologie Supérieure (ETS) of Montreal, we call them respectively type I and type II. CIR and FDR layer are then typically overlaid by HMA to protect them from water and traffic load. The deeper we mill, the more we have natural aggregate in the mix. Therefore we have different cold mixes with different behaviors. A classification was defined by The Bureau de Normalisation du Québec (BNQ) for the different mixes according to the amount of aggregate, reclaimed asphalt pavement (RAP), and cement (2).

Cold mixes are sensitive to water. Indeed, we use asphalt emulsion which will have different properties dependent on the water content. The water content is influenced by the compaction and so by the obtained density. The higher the final density is, the higher the modulus and the cohesion of the mixture will be, so high-energy compaction equipment must be used (3). Like we know, water is incompressible, so during the compaction, the water has to be expulsed. What make this operation more difficult than for the HMA is that our mix has a higher void content, and that the voids size is smaller. Usually we have 4% to 5% of voids in field for a HMA (4) while we have around 14% of voids for a cold mix (5).

The objective of this project is to simulate traffic curing; which can be defined like the passage of cars on the cold mix at early-life coupled to the natural drying; by a post compaction. COLAS (6) did researches in which a post compaction, made with a slab compactor, 24 hours after initial compaction, allowed an increase of the level of compaction of 1.5% and a water content decrease of around 1%. In this case, we considered the possibility to simulate early-life traffic curing by post compaction for a MR7 with a Marshall hammer and for a MR5 with a gyratory compactor. We also wanted to evaluate the effects of post compaction on the rutting resistance of CIR and FDR materials. The aim was to be able to simulate early-life traffic curing.

2 METHODOLOGY

In order to compare several CIR materials and FDR materials, we decided to study the following mixtures: a) MR5: 50% of RAP, 50% of granular material, and b) MR7: 100% of RAP. First, all blends were made with the same raw materials, and the same blending processes. We always used:

- A RAP, milled on field and then stored in a quarry established in Montreal.
- Asphalt content: 3%.
- Portland cement.
- Asphalt Emulsion CSS1P, Cationic Slow Setting 1 with Polymer. Asphalt content: 67.4%.
- MG20, 100% crushed aggregates replacing natural aggregates from the granular base.

RAP was dried at 60°C before being mixed at room temperature. It was not heated at more than 60°C to limit bitumen oxidation. Finally, mixes were always made in this manner:

Total duration of the process was about 5 minutes. Mix design was first made to determine the optimal water content and the optimal added asphalt content. Based on documents of the Minister of Transport of Quebec (4) and of the Bitume Québec Association (7), it led us to retain these mixtures (TABLE 1):

TABLE 1 Mixes used for tests.

Mix	Added asphalt content (%)	Portland cement content (%)	Water content (%)	Total asphalt content (%)
MR5	1.8	1	6.5	3.3
MR7	0.8	1	5	3.8

The Portland cement content, set at 1%, is calculated by reference to the dry mass of (RAP + MG20). Other contents are calculated by reference to the dry mass of (RAP + MG20 + Portland cement). Below, the particle size distribution (FIGURE 1) of our materials. Sieve analysis was done only for MR7 (RAP) and MG20. Then, MR5 size grade was calculated.

Slabs (100*180*500mm) were also prepared, using LCPC plate compactor, to determiner rutting resistance. Some modifications had to be done for these cold and wet materials. The expected level of compaction was set at 87%. The rolling pattern was also adapted from the HMA rolling pattern because of their different behaviors. Whereas COLAS (6) waited 24 hours before to post compact, we waited only 6 hours to approach field conditions. Indeed, in Quebec, it is common to reopen road to traffic 6 hours after compaction (8). Finally, the slabs underwent an accelerated cure to increase their cohesion and avoid any risk of cracking during handling. This type of cure is generally achieved by controlling the temperature and humidity. Accordingly, our slabs cured 24 hours in the mould and then 10 days in oven at 38°C.

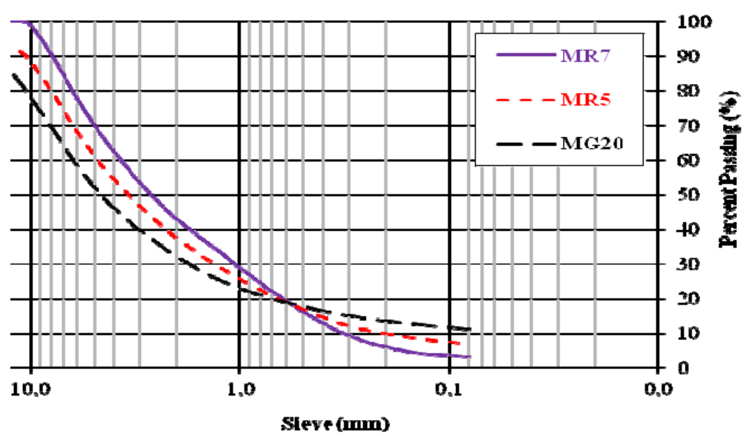

FIGURE 1 Particle size distribution of the various materials.

3 SIMULATION AND INFLUENCE OF EARLY-LIFE TRAFFIC CURING WITH MARSHALL HAMMER FOR CIR MATERIALS

The experimental work done for this part of the research is described in TABLE 2. For practical reasons, Marshall samples, which had to go through post compaction, were conserved inside the mould, with the absorbent papers. Also, to be able to determine the exact water content expulsed during post compaction, we measured the water content of non post compacted samples and conserved in the same conditions for 6 hours. It should be noted that the aim of the compaction WPC+ is to check if the initial compaction (WPC) is efficient enough to reach the maximum level of compaction. If it is, the voids content should be roughly the same for WPC and WPC+ compaction.

TABLE 2 Experimental work on Marshall samples.

	WPC	WPC+	PC
	Without Post Compaction	*Without Post Compaction +*	*Post Compaction*
Procedure	Standard compaction (50 blows on each side)	standard compaction (50 blows on each side) + additional compaction (25 blows on one side)	Post compaction (25 blows on one side), 6 hours after a standard compaction (50 blows on each side)
Tests done on samples	Bulk specific density - Maximum specific gravity - Water content after compaction Dry and wet Marshall stability - Water absorption		

The LC (Laboratoire des Chaussées) test method 26-002 (4) requires for Marshall stability samples a cure of 24h in the mould and 24h in oven at 38°C. This procedure was changed to approach the field conditions. So, our samples used for Marshall stability test cured 24 hours in the mould and then 29 hours in air.

4 Results and analysis

Main results are shown in TABLE 3. The difference between WPC and WPC +6h is that for WPC+6h, a 6 hours curing period at room temperature was done before testing. These data underline that with the WPC+, 0.3% of water is expulsed compared to post compaction. As for air voids content, the results are as expected. One thing to note is that if WPC and WPC+ are compared, it can be seen that with WPC, the initial compaction does not seem to be complete.

TABLE 3. Water content and air voids after compaction for MR7.

Mix	Water content after compaction (%)	Voids content (%)
MR7 - WPC	4.0	16.3
MR7 – WPC+	3.7	15.5
MR7 + 6h - WPC	3.2	-
MR7 + 6H - PC	2.9	14.6

Nevertheless, with the augmentation in the level compaction due to the post compaction, the mechanical properties of the MR7 material are affected. Marshall stability tests illustrate this phenomenon. Dry Marshall stability of the MR7-PC is higher by 23.4% when compared to the MR7-WPC (TABLE 4). As for the wet stability, the difference is 15.6%.

TABLE 4 Dry Marshall stability for MR7 with and without post-compaction.

Mélange	Sample A (N)	Sample B (N)	SampleC (N)	Average (N)	COV (%)
MR7 - WPC	17825	14573	13316	15238	15.3
MR7 - PC	18317	16398	21703	18806	14.3

COV: Coefficient of Variation

5 SIMULATION AND INFLUENCE OF EARLY-LIFE TRAFFIC CURING WITH GYRATORY COMPACTOR FOR FDR MATERIALS

The next step consisted in trying to simulate post-compaction in a manner more representatives of what the materials is submitted in the field. The gyratory compactor seems to be the way to go. Indeed the gyratory compactor works by kneading, which allows field like conditions to be achieved (9) (10). Moreover, the use of gyratory compactor with a mold of 100mm in diameter allows to prepared small specimens (materials economy) directly usable for Marshall stability test (fast).

One of the problems in this study was the compacting behavior of cold materials. Like explained in the project introduction, these mixes contain lot of water, so during the compaction, it has to be expulsed. The cold mixes voids contain at the same times water and air. Moutier has shown (11) that there are two characteristic inflexion points on the air voids vs number of gyration curve, which correspond to the departure of the air and water respectively. A study realized by COLAS displayed that the start of water leaving would match to the density obtained in field just after the compaction (C1), and the end of water leaving would match to the density obtained after the traffic action (C2) (FIGURE 2) (12).

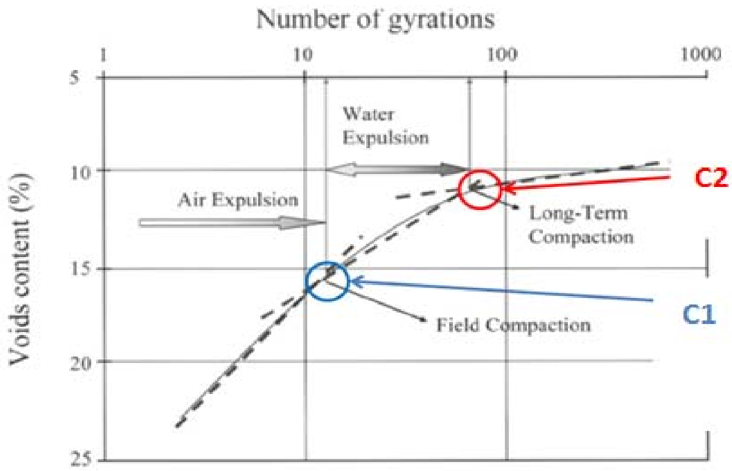

FIGURE 2 Gyratory compactor CIR behavior, early-life traffic simulation, adapted from (13)**.**

5.1 Experimental process

The goal of the study is the simulation of the traffic passage, six hours after the compaction by the wheel load pneumatic. Therefore, we compacted a first time our mix in order to reach the density of field compaction (C1). Then, after rest of 6 hours in air, we compacted again our specimen until a density equivalent to those after long-term compaction. After that, we compared specimens compacted twice (C1 and C2), and those compacted only once (C1).

For the first tests, porous stones were used in order to recuperate the water expulsed during the test and so to facilitate the compaction. The main goal would have been to measure the amount of water expulsed, like it can be done with the LCPC (Laboratoire central des ponts et chaussées) gyratory compactor 3 (15). Unfortunately, the porous stone broke during testing. It was decided to continue without the stones, and since there is not much water seeping out, the results are not affected.

Before starting the test, it was first necessary to establish C1 and C2. For that reason, we compacted several specimens to have a reference curve. With three linear regressions, we obtained our two characteristics and theoretical points C1 and C2 (FIGURE 3).

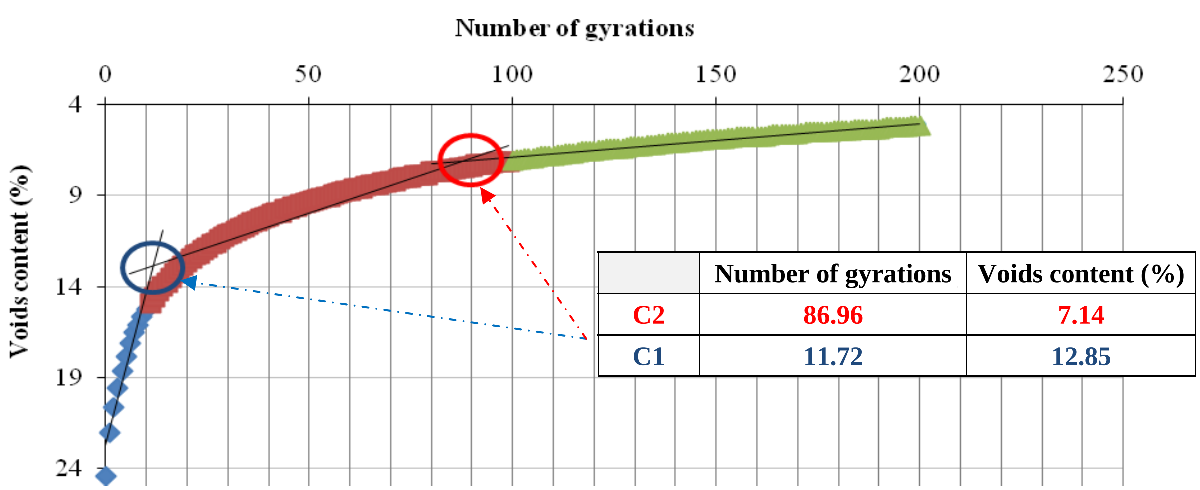

FIGURE 3 Mean evolution of the voids content in function of the number of gyrations for FDR materials.

For this study, materials used were MR5. The standard conditions for hot bituminous mixture compaction were used: 1.25°, 0.6 MPa, and 30 r/min (14) in order to have a good simulation of the field compaction. Indeed, a Spanish study about the experience with gyratory compactor in design and control of CIR, has shown that this conditions permit to obtain similar density to the final values of the placed and compacted mixture (3).

In France, level of compaction criteria for the cold mixes is generally a voids content inferior to 25% at 100 gyrations. In Norway, the current proposition is to have a level of compaction of 96% at 200 gyrations (16). In our case, we respect the French criteria and are close to the Norway criteria. In comparison to HMA, for GB20 we should have to be between 4% and 7% for 120 gyrations (4).

Now all the information are known to start the test. 12 specimens were manufactured with the gyratory compactor. The parameters of C1 and C2 were respectively rounded to 12 gyrations and 90 gyrations. 6 specimens were compacted only until C1: 12 gyrations in order to have about 13% of voids. 6 were compacted until C1 and six hours after, until C2: 12 gyrations and six hours after 78 additional gyrations to get about 7% of voids.

After the compaction, all specimens were oven cured at 38°C for 24 hours. We did this way in order to lose water and thus achieve the early-life field like conditions after the curing and hardening process subsequent to placement and compaction.

6 Results and analysis

The FIGURE 4 shows the behavior of our mix during the two compactions. It is the same that we have on the reference cure (FIGURE 2). Regarding the water loss (FIGURE 5), we can compare the behavior of post compacted (PC) and without post compaction specimens (WPC). The first compaction (C1) decreases the water content of 0.5%. Maybe the expulsion of water would have been better with the use of the porous stones. The post compaction decreases the water content about 1%. We noticed the presence of water over the mould. After the oven cure at 38°C during 24h, the loss of water is logically bigger for the specimens PC than for the specimens WPC.

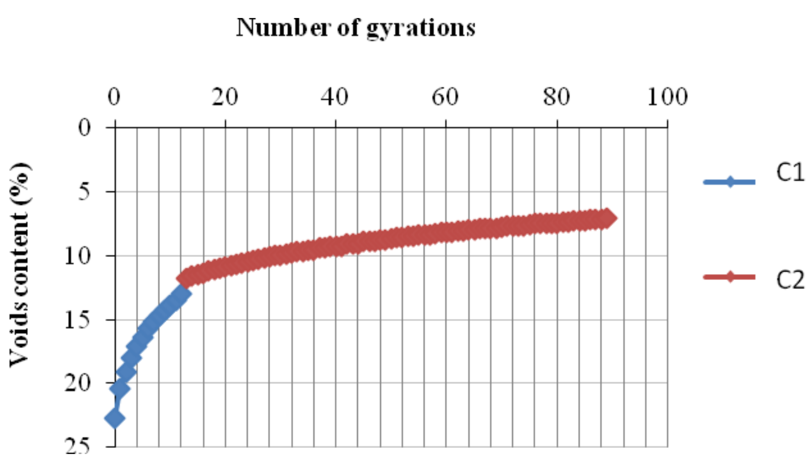

FIGURE 4 Evolution of the voids content during C1 and C2.

In order to evaluate the influence of the post compaction on the mechanical properties of our materials, Marshall stability of our specimens was measured. On the FIGURE 6, the benefits of the post compaction on the Marshall stability are shown. Dry Marshall stability improved by 67.4%, and wet stability by 62.1%. Regarding the loss of stability, it is higher for the PC specimens (33.7%) than those WPC (15.1%). We are under 40%, so the Quebec standard criterion is respected (4). Therefore, post compaction improved the early-life traffic mechanics resistance. Absorption tests showed that WPC specimens absorbed more (5.9%) than those PC (3.4%). It can be explain by the fact that PC specimens, having voids content lower WPC specimens, can not contain as much water.

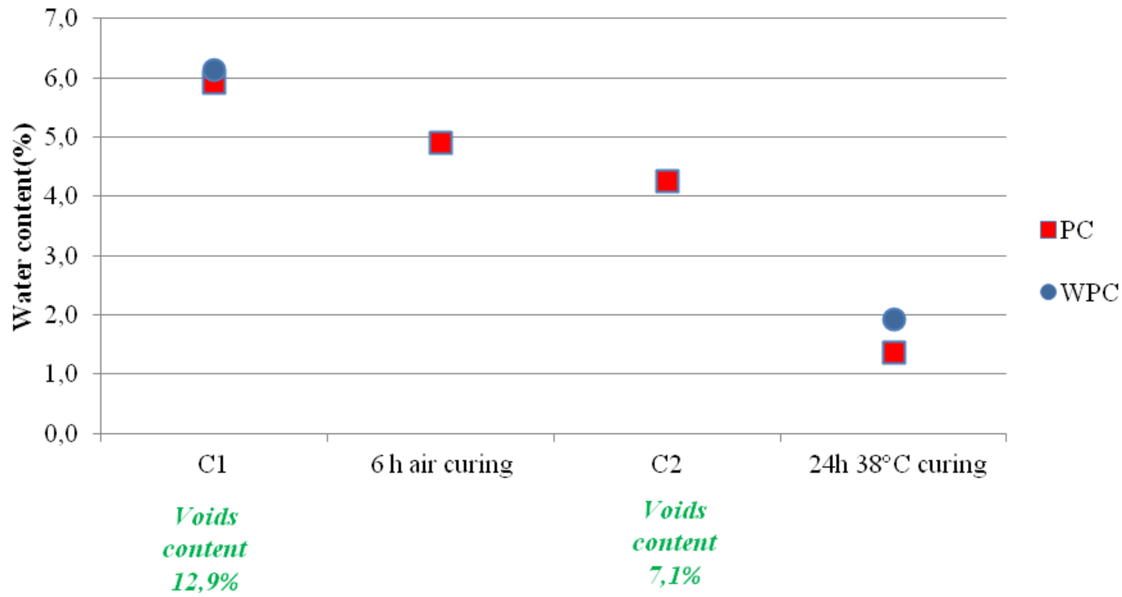

FIGURE 5 Water content before and after compaction.

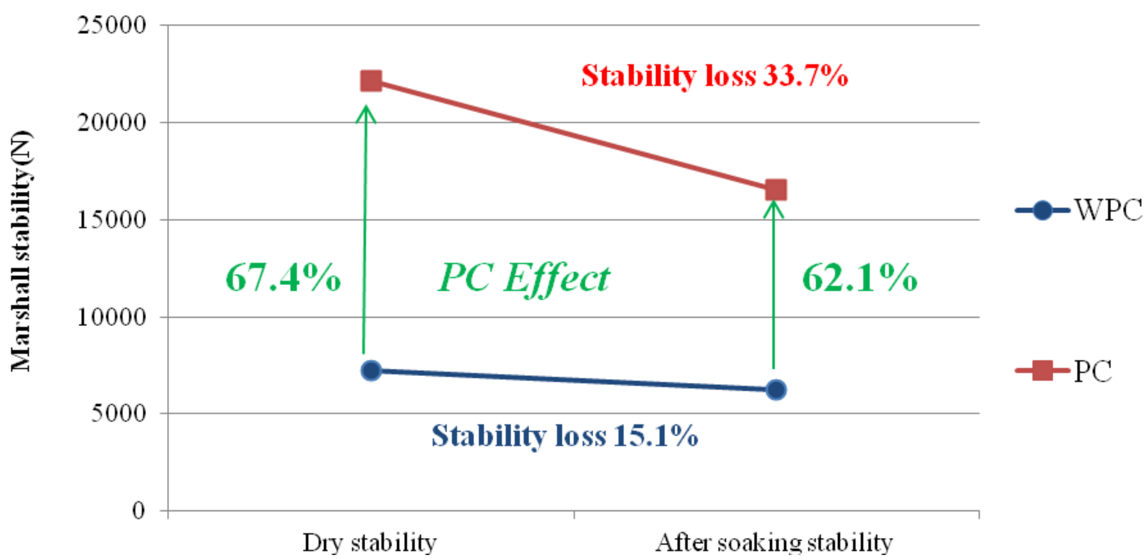

FIGURE 6 Post compaction effect according the Marshall stability.

7 SIMULATION OF THE TRAFIC CURING BY PLATE COMPACTOR POST COMPACTION FOR CIR AND FDR

The objective of this last part is to study the effects of post compaction on rutting resistance of cold mixes. In order to do that, we made 4 slabs whose dimensions are standard: (100*180*500) mm. 2 slabs of reference; MR7 and MR5 mixes; were just compacted according to the standard compaction pattern normally used with the LCPC slab compactor. 2 additional slabs were compacted according to the same initial compaction. But, 6 hours later, they underwent a post compaction whose pattern is based on COLAS documents.

However, the time between initial compaction and post compaction was reduced again. Whereas Colas waited 24 hours before to post compact, we waited only 6 hours to approach field conditions. Measurement of the slabs dimensions was done before and after post compaction. This way we were able to calculate the increase in the level of compaction of each one (TABLE 5).

TABLE 5 Level of compaction before and after post compaction.

	MR5	MR7
Level of compaction before PC (%)	88,8	85,8
Level of compaction after PC (%)	91,7	86,6
Increase (%)	2,9	0,8

It's known that fine aggregates and fines make easier the compaction of a mix by filling up the voids created by coarse aggregates (14). Indeed, gradation curves (FIGURE 1) show a bigger amount of fines in the MR5 than in the MR7. As a consequence, compaction and post compaction were more efficient for the MR5 than for the MR7. The expulsion of water, which happened only during the post compaction of the MR5 highlight this phenomenon.

Concerning the rutting resistance behavior, the procedure from the HMA (1000 cycles at room temperature, 30000 cycles at 60°C, pressure set at 5kN) was used. Raveling was observed at the beginning, due to the fact that we did not use a steel wheel to finish the compaction of the plates to avoid breaking aggregates at the surface. About the rutting performance of our cold-mixes, we see that all mixes have a rut depth below 10% (FIGURE 7). Therefore, meeting the standard of the Quebec MTQ (4). These good performances are doubtless due to the cure (10 days at 38°C in oven) and the cement addition. Then we notice, like the dry Marshall stability, that the rutting resistance increases when there is less asphalt in our mixes. The MR5 has the best resistance and the lowest total asphalt content but it has also the most continuous gradation, so a good size repartition of the aggregates which involves a better stones on stones contact. Finally, it is possible that rutting resistance testing at 60°C do not fasten the degradation, like it does for HMA, but on contrary, it might speed up the cure and so increase the cohesion of our materials.

As for the influence of the post-compaction, relying on COLAS documents (6), we were expecting an increase of the rutting resistance. On the other hand, the loss of rutting resistance is too small to underline the negative effect of post compaction. Manipulation or experimental conditions could be the reason of these insignificant results. However, if this effect was proved, an explication to this phenomenon could be given by the MTQ: the most rutting resistant mixes are those which have the more stones on stones contact, a high void content, and low total asphalt content. As a result, the increase in the level of compaction could be the reason to this sensible loss of rutting resistance.

8 CONCLUSION

Finally, these results led us to the following conclusions.

About Marshall post compaction: another way to simulate the traffic curing, on reduced size samples, has to be find out. A suggestion to study is the fabrication of a mould, which would allow compaction and post compaction of Marshall samples with the LCPC slab compactor.

About gyratory compactor use: results show that effects of the early-life traffic curing are not negligible. Early traffic opening allows clearly better mechanical resistance to cold mixes. Going further, opening the traffic earlier than 6 hours after initial compaction might further increase the level of compaction, therefore the performances.

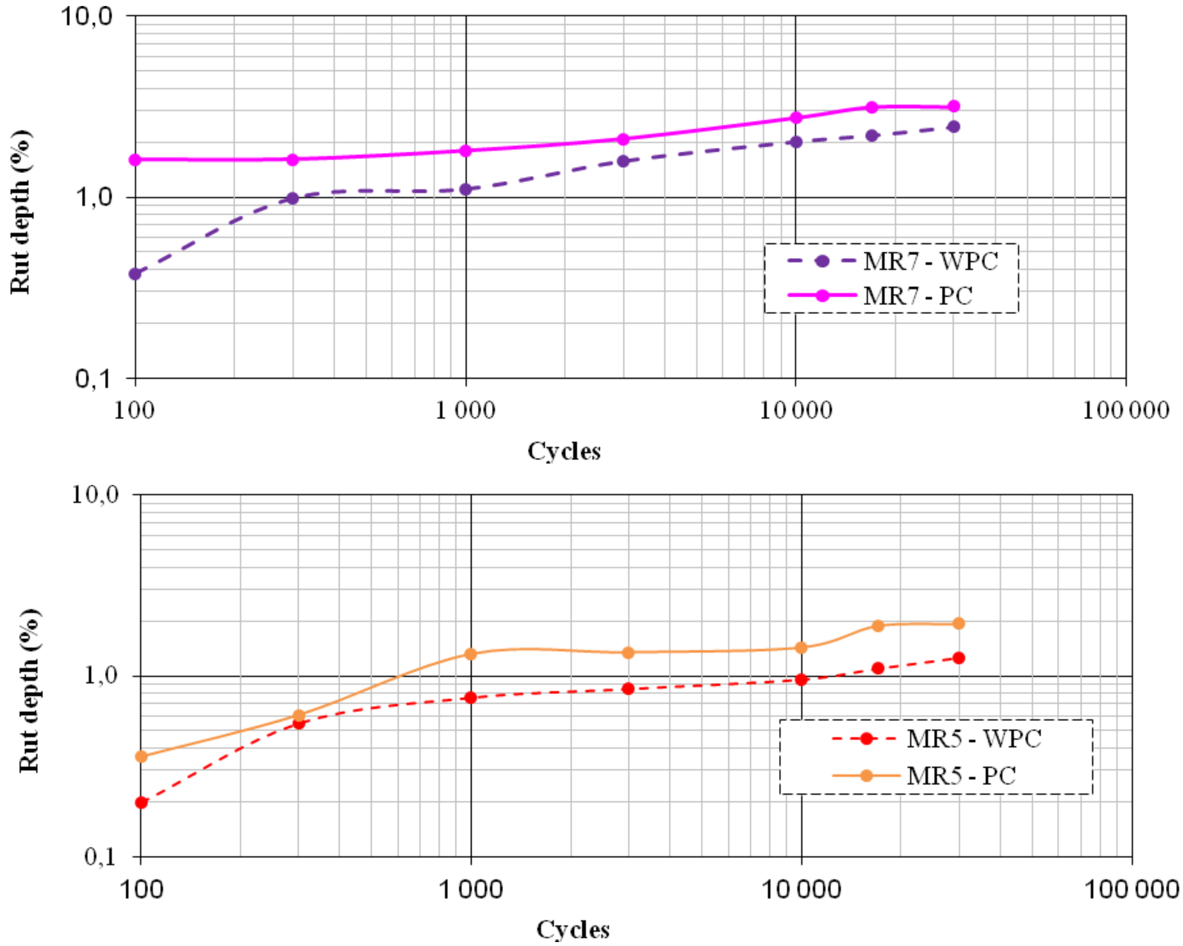

FIGURE 7 Rutting resistance before and after post compaction for MR5 and MR7.

About rutting resistance: considering that our materials underwent an accelerated cure, we conclude that the early-life traffic curing, simulated in this case by post compaction, could have a negligible effect but still damaging at long-term life for cold mixes. On the contrary, we believe that this traffic curing enhances the early-life rutting resistance for cold mixes. Complementary researches should be realized to characterize the behavior evolution of cold mixes according to rutting resistance.

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