Field compaction of thick recycled material layers

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Abstract

Full-depth reclamation techniques present numerous advantages in pavement rehabilitation. Typically, a thick layer of stabilized or unstabilized reclaimed materials is left behind the recycling machine, which is used as the base layer consisting of these latter recycled asphalt pavement material (RAP). The compaction of the thick layer, especially when unstabilized, is particularly critical for adequate performance. In Quebec, the smooth drum compaction is often used to compact the reclaimed materials. Previous studies demonstrated the difficulties associated with the convenient compaction of the reclaimed materials through its entire thickness, especially the presence of a vertical compaction gradient. Sheep or pad foot compactors are two common compaction machines used to ensure good densification during primary compaction of recycled materials. A research project was initiated to document and quantify the effects of compaction conditions and equipment on the response and performance of the reclaimed materials. An experimental embankment of reclaimed materials was built and divided in three sections compacted using different compaction procedures. Sheepsfoot roller, with and without vibration, was used in the first two sections, while the third section was compacted using a vibrating smooth drum roller. The density, stiffness and vertical density gradient were monitored with a nuclear gage, dynamic cone penetrometer and light weight deflectometer tests. Grain-size analysis was also performed on all experimental sections. The use of vibration along with Sheepsfoot roller improved both density and mechanical response of the compacted layer significantly. The penetration and density tests also revealed a significant difference in compaction throughout the thick layer of reclaimed materials. Using the sheepsfoot provided a stiffer base layer, and the smooth drum resulted in a vertical density gradient. Finally, significant differences in the grain-size distribution were found following the compaction when the sheepsfoot compactor was used.

1 Introduction

Full-depth reclamation (FDR) is a flexible pavement rehabilitation process where a recycling machine crushes and mixes the asphalt concrete layer and a part of the underlaying granular base, leaving behind the recycling machine an uncompacted thick layer of recycled materials. The recycling depth is typically in the range of 300 mm, but can reach approximately 400 mm with the appropriate equipment. FDR has many benefits, amongst others, the reuse of the aggregates used in the asphalt concrete and in the unbound granular base, and the elimination of the need to transport and manage construction residues and to purchase and transport new virgin aggregates to the construction site. It also allows the complete reset of the cracking pattern in the upper part of the pavement. In addition, when needed, the recycled materials can be stabilized with bitumen emulsion and/or cement, or the grain-size distribution can be adjusted as part of the process. After recycling, a new layer of unbound aggregates can also be added for strengthening or increasing frost protection.

The work from Depatie (2013) showed that adequate compaction of the thick layer of uncompacted recycled materials is difficult to achieve using standard compaction equipment, such as smooth drums. Amongst others, problems with unachieved compaction at the bottom of the recycled layer was observed. It is worth noting that this under compacted layer is typically difficult to detect, as it may be found at a depth of about 250 to 300 mm (or more) while standard nuclear gage rod reaches only a depth of 200 mm. Furthermore, since the nuclear gage output is an average density of the layer, the poorly compacted sublayers could be concealed by the dense top part of the layer. This lack of compaction energy at the bottom of the recycled layer and the resulting lower dry density are suspected to be partly responsible of rapid initial rutting encountered in some FDR projects in Quebec. This project was therefore initiated to document a compaction process widely used in the US for FDR projects where a sheepsfoot roller is used for initial compaction of the thick recycled layer. As a part of this project, an experimental embankment was built, and a comparative study between the properties of the sections compacted with smooth drum and sheepsfoot compactors was performed.

2 Methodology

As part of this research project, field tests were designed in order to assess the differences obtained in density, vertical gradient, stiffness and grain-size distribution, when thick layers of recycled materials were compacted using smooth drum and sheepsfoot equipment. Both rollers possessed the same size and weight. The recycled materials were produced by on-site mixing of two stock-piles; granitic aggregates meeting the requirements for granular base, and RAP aggregates. Equivalent volume of both materials were mixed in order to obtain a 50% RAP material. After laboratory analysis, it was concluded that the obtained mass percentage of RAP in the blend was 48%. Figure 1 shows the grain-size distribution of the virgin granular base, RAP and combined recycled material prior the compaction study. The grading envelope used in the Quebec standards for base granular materials (MG-20) is also shown for the reference purposes. The maximum dry density ($\rho_{d\text{-}max}$) (2190 kg m^{-3}) and optimum water content w_{opt} of (5%) for the combined recycled material was determined using the modified proctor test procedure.

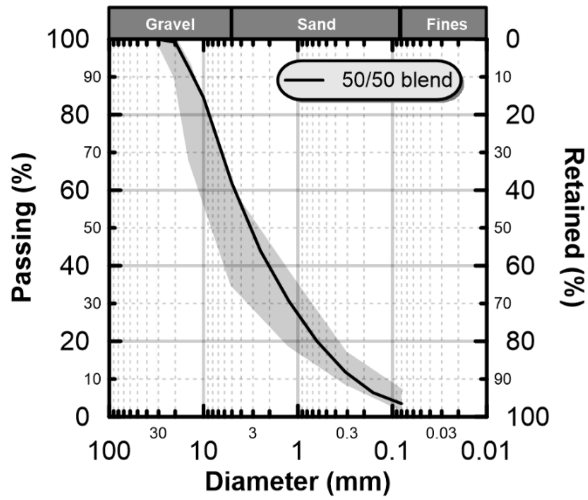

Figure 1. Grain-size distribution of the granular base material, RAP material and combined recycled material product

The tests were performed on the parking lot of a service centre of the Ministry of Transportation of Quebec in July 2018. The surface of the parking lot is covered with a thick dense-graded crushed stone surface; this material was used as the construction platform. For the project, it was overlaid by the experimental embankment of recycled materials. The elastic modulus of the crushed stone materials of the construction platform was equal to 300 MPa (determined from dynamic cone penetration tests). At the uncompacted state, the embankment was 350 mm thick after levelling and 2.5 m wide. For each section, regular linear spacing was fixed in order to perform after-compaction tests and samplings. The schematics presented in Figure 2 show that three different sections were as follows:

- Section PM - Sheepsfoot compaction with vibration
    - Length : 17.5 m
    - Number of samples collected : 15 (samples A1 to A15)

- Spacing between the tests and collected samples : 1.25 m

- Section PM-sv – Sheepsfoot compaction without vibration
  - Length : 5 m
  - Number of samples collected : 7 (B1 to B7)
  - Spacing between the tests and collected samples : 0.8 m
- Section RL – Smooth drum with vibration
  - Length : 17.5 m
  - Number of samples collected : 15 (C1 to C15)
  - Spacing between the tests and collected samples : 1.25 m

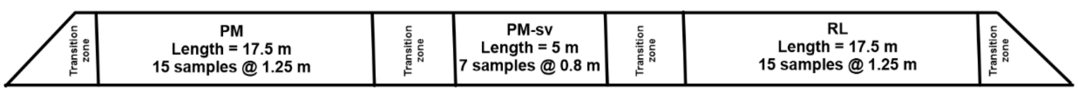

Figure 2. Test sections

In addition, a transition zone of 5 m was considered at the beginning and the end of the embankment as well as between the test sections, giving a total length of the embankment of 60 m. For each measurement points, Light weigth deflectometer (LWD), nuclear gage and Dynamic Cone Penetrometer (DCP) test were performed after compaction, prior to the final sampling for the grain-size analysis.

For the smooth drum section (RL), the compaction procedure consisted of rolling back and forth the recycled material until 98% of $\rho_{d\text{-}max}$ was achieved. For the PM sections, the compactor was first passed over the sections (PM and PM-sv), and the surface was leveled and finalized using a smooth drum pass in order to be able to take density measurements. In average, the final thickness of the layers was 275 mm.

3 Experimental test results

3.1 LWD

LWD tests were performed at the centre position in the transversal direction of the embankment as per the test spacing described in the test methodology section. A Prima100 test apparatus with a loading plate diameter of 300 mm was used. The results of one drop height were selected, which allowed to obtain a vertical stress of 120 kPa. This value was selected as it is representative of vertical stress conditions under standard loading conditions in the granular base for typical regional roads and typical temperatures in Quebec. For each drop location, after the application of three seating drops, four supplementary drops were used to obtain an average value. The average test results are presented in Figure 3 in terms of elastic modulus determined with the LWD (E_{LWD}). In a general manner, the LWD values are in the same range for the three test sections. When vibration was used, it can be noted that both sections reached greater and closer LWD values. The greatest LWD value (122 MPa) was obtained on the PM section, and the smallest value was obtained for the PM-sv section (109 MPa). The longest test sections are also the ones that show the greatest standard deviation. The values of the coefficients of variation were equal to 11, 10 and 16% for PM, PM-sv and RL test sections, respectively. A statistical Student's t-test analysis for a level of significance α= 0.05 reveals that the average value obtained in each section are all equal. Finally, it should also be kept in mind that depth of significant stress with a 300 mm LWD plate is about 1.5 to 2 times the plate diameter, therefore 450 to 600 mm. This investigation depth is much greater than the compacted layer thickness of 275 mm, leading to a possible significant contribution of the supporting layer to the average surface modulus measured using the LWD.

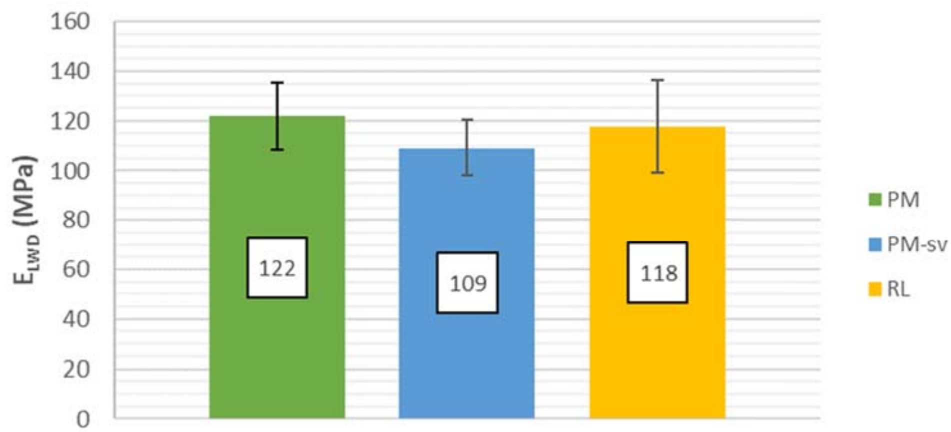

Figure 3. LWD test results

3.2 Density measurements using the nuclear gage

The dry density (ρ_d) of the compacted layer of recycled material was measured using a 200 mm Troxler nuclear gage. The dummy rod was first used to prepare a 200 mm deep 18 mm diameter hole in the compacted aggregates. Afterwards, density measurements were taken at a depth of 100 and 200 mm, and at additional depths of 50 and 150 for some locations. The nuclear gage used herein measures the average density between the tip of the rod at the investigation depth and the receiver in the apparatus located at the surface. The 200 mm measurement rod did not allow to reach the deepest sublayer of the compacted embankment, where possible density gain from using the sheepsfoot compactor was expected. The average density ratios ($\rho_d/\rho_{d\text{-}max}$) for the three studied test sections are presented in Figure 4. The variability along the longitudinal direction is presented along with the average values, which are expressed as obtained density ratio. In average, the results presented show different density patterns for both compaction equipments. When the sheepsfoot is used, the obtained density is greater at a depth of 200 mm in comparison with the depth of 100 mm, while it is the opposite for the smooth drum compactor. Taking the PM section as an example, as the measurements are average values over the investigation depth, the fact that the average density ratios of 97.1% and 98.4% are found at 100 mm 200 mm, respectively, reveals that the layer was most likely very well compacted deeper in the layer. Indeed, in order to reach an average density ratio of 98.4% at 200 mm while the average density ratio of the first 100 mm was equal to 97.1%, some sublayer had to possess a density ratio greater than 98.4%. Because the opposite trend is observed for the RL section, a similar but inverted principle can be considered. In other words, as discussed in the introduction section, the use of the sheepsfoot compactor allows obtaining denser materials lower in the compacted thick layer, while it is likely the opposite when the smooth drum is used. These observations are presented in Figure 5, using two measurement points in each section (PM and RL).

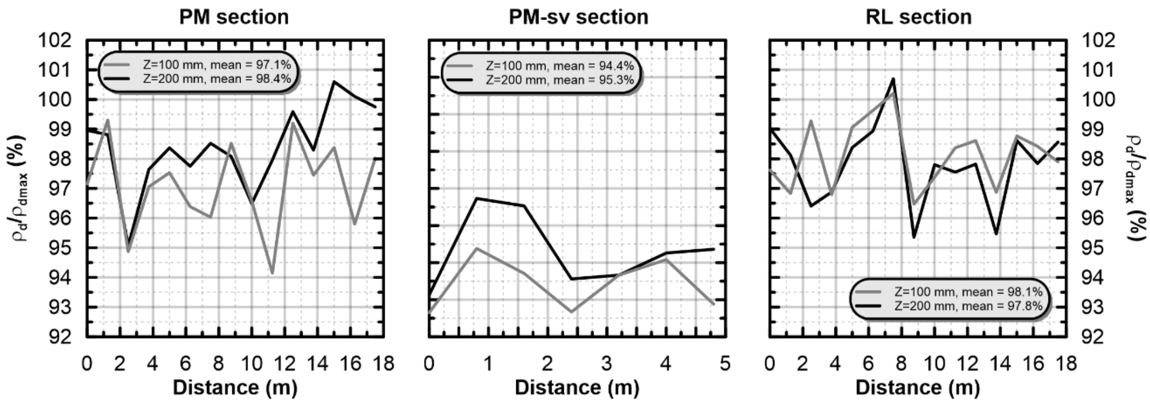

Figure 4. Nuclear gage test results for a) PM section and b) RL section

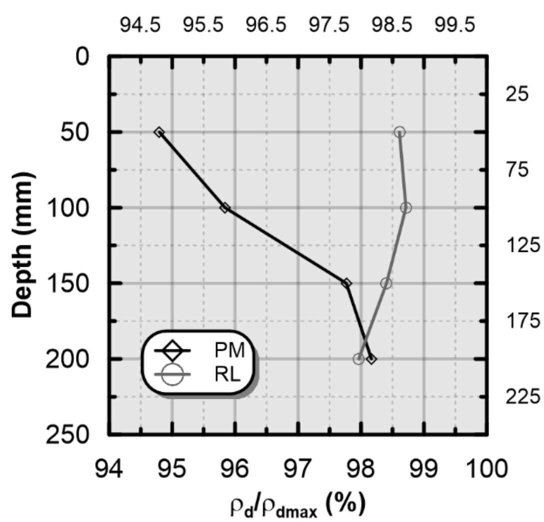

Figure 5. Examples of density ratios change with depth for PM and RL section

3.3 Dynamic cone penetration

Manual DCP tests were performed at all the test points identified in the methodology section. A depth of about 450 mm was aimed for these tests. Figure 6 and Figure 7 show the DCP test results.

Kriging interpolation was used to summarize the data in a plane representation, using DCP values averaged every 20 mm. The DCP values were also converted into elastic modulus (E) using

[1] $$E = 537.8 \times DCPI^{-0.664}$$

where DCPI is the dynamic cone penetration index in mm/blow and E is in MPa (Chen et al. 2005). According to Figure 6 and Figure 7, a significant difference in the mechanical properties of the layer between experimental sections compacted with and without vibration can be observed. In the middle of the embankment, the DCP values varied approximately from 4.5 to 7.5 for the PM-sv section, while it was approximately equal to 3.5 to 4.5 in the PM section. As for the RL section, the DCP values ranged from 4.5 to 6. When converted to elastic modulus, the observed ranges were approximately 210-230 MPa, 140-190 MPa and 180-200 MPa for the PM, PM-sv and RL sections, respectively.

The analysis of Figure 6 and Figure 7 also reveals some differences in the obtained mechanical properties at the bottom of the compacted layer. As a matter of fact, prior to the transition towards the underneath stiffer layer (depth of 250 mm) of the RL section (zones showing more orange and red in Figure 7), it is possible to observe several zones where the elastic modulus decreases (or DCP increases). This latter observation is also very obvious in the PM-sv test section. For the PM section, it is possible to state that the bottom of the layer shows less difference with the centre of the layer, which is associated with more compaction efficiency at the bottom of the layer. It also corroborates the main observations made for the density measurements, as generally stiffer material is associated with greater dry density.

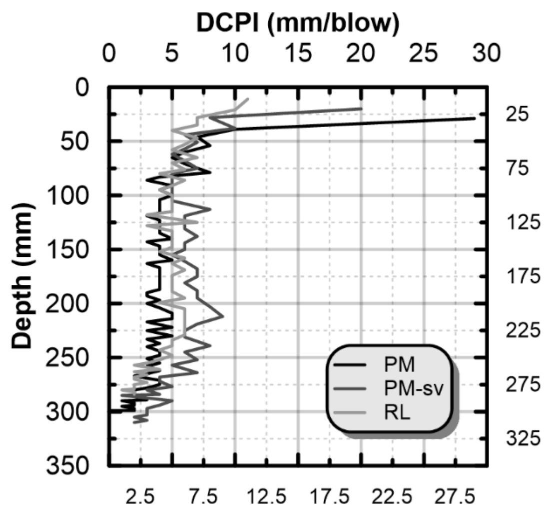

Figure 6. Typical DCP results for the three experimental test sections

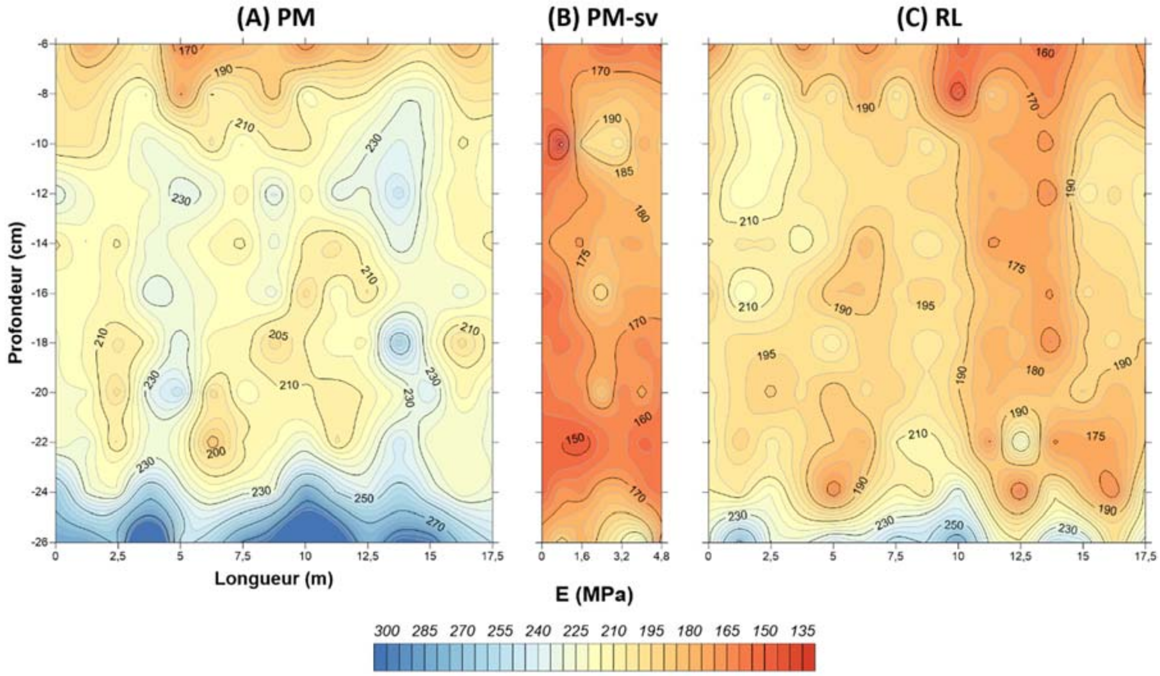

Figure 7. Interpolated values of estimated elastic modulus obtained from DCP tests for sections a) PM, b) RL

3.4 Materials analysis

For the vibrating sheepsfoot and smooth drum test sections samples of recycled materials were collected at each testing location after the compaction of the layer was completed. These samples were subjected to a grain-size analysis in order to document any possible material degradation associated with the compaction equipment. It is to be noted that no material was collected on the PM-sv test section considering that the material degradation was assumed to be more significant with the use of vibration during compaction. The results of this analysis are summarized in Figure 8 and Table 1. The results of the percent passing (%P) for each standard sieve was used for the comparison of the results prior compaction (%P_p) and after compaction (%P_a). The results show that the sheepsfoot compactor causes slightly more materials degradation than the smooth drum. For both compaction equipment, the increase in the percent passing was more pronounced for the sand-size aggregates. Comparing the %P values after and prior compaction (%P_a-%P_p), the average increase was about 1.17 % for the PM section and 0.15 % for the RL section.

Table 1. Results for grain-size distribution analysis prior compaction and after compaction for two test sections

	Gradation prior compaction		Gradation after compaction					
			PM section			RL section		
Diameter (mm)	%P_p (%)	SD* (%)	%P_a (%)	SD* (%)	%P_a-%P_p (%)	%P_a (%)	SD* (%)	%P_a-%P_p (%)
31.5	100.0	0.00	100.0	0.00	0.00	100.0	0.00	0.00
20	99.2	0.53	99.2	0.37	0.01	99.1	0.43	-0.05
14	91.9	1.12	92.8	1.28	0.92	91.8	1.39	-0.11
10	84.6	1.26	85.5	1.86	0.94	84.4	1.92	-0.23
5	61.7	1.23	62.8	2.03	1.08	62.1	2.31	0.41
2.5	44.5	2.08	46.1	1.93	1.57	44.4	1.87	-0.12
1.25	31.3	2.24	33.5	1.92	2.17	31.2	1.46	-0.14
0.63	20.8	2.03	23.1	1.92	2.37	21.2	1.19	0.44
0.315	12.4	1.62	14.3	1.26	1.86	13.1	0.93	0.64
0.16	6.9	1.28	8.1	1.27	1.24	7.4	0.73	0.58
0.08	3.8	0.91	4.5	1.08	0.70	4.0	0.59	0.26
N*	7		15			15		
Mean		1.30		1.36	1.17		1.17	0.15
Maximum		2.24		2.03	2.37		2.31	0.64
Minimum		0.53		0.37	0.01		0.43	-0.23

* N = Number of samples; SD = Standard deviation

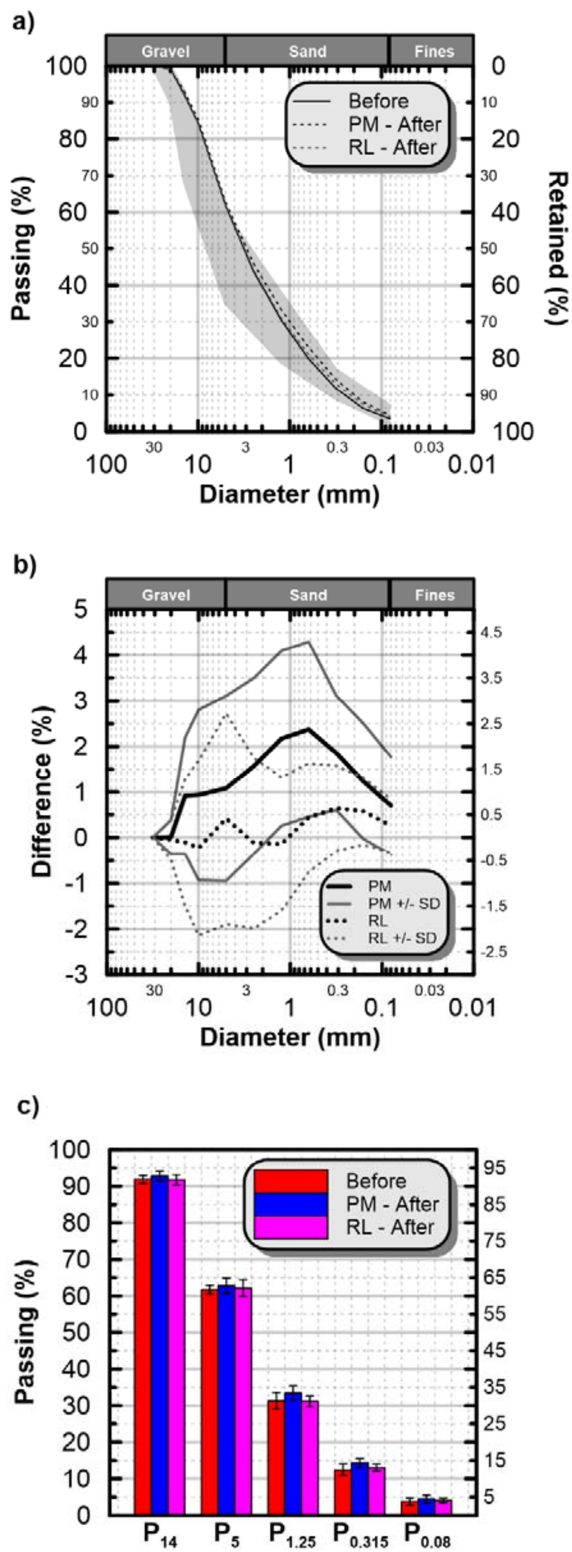

Figure 8. Results of grain-size distribution analysis, a) gradation curves before and after compaction; b) Differences in percent passing after vs before compaction for each sieve size; c) Percent passing before and after compaction for each regulated sieve sizes

4 Conclusion

A research project was initiated on the potential use of sheepsfoot compaction for construction of thick recycled materials layer produced by full-depth reclamation pavement recycling technique. As part of this real-scale embankment study, a comparison was made with a smooth drum roller, which is typically used for FDR projects in Quebec. An embankment of manufactured recycled materials was laid out at an uncompacted thickness of about 350 mm. The embankment was divided into three experimental sections. Two of these sections were submitted to initial compaction with the sheepsfoot roller (with and without vibration), while the third section was entirely compacted with the smooth drum roller. For each section, several sampling/testing points were considered. Density analysis with a nuclear gage, grain-size analysis, light weight deflectometer and dynamic cone penetrometer were among the main tests performed on the test sections. The results revealed that although surface modulus results did not show significant variations, dynamic cone penetration revealed a stiffer recycled materials layer when the sheepsfoot compactor was used for the initial compaction. In addition, and more importantly, this initial compaction allowed obtaining a more uniform modulus through the layer thickness. This was also emphasized by the density measurements, where denser material was observed deeper in the layer when the sheepsfoot was used. For the smooth drum section, a vertical gradient of density and modulus was inferred from the results. The tremendous importance of vibration was also concluded from the project. Finally, a slightly more important granular material degradation was observed when the sheepsfoot roller was used.

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