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Research Article

Laboratory Evaluation and Construction of Fully Recycled Low-Temperature Asphalt for Low-Volume Roads

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Growing economy and increasing pollution evoke the need for more environmentally friendly road construction techniques and the saving of natural resources. In this context, cold recycling plays an important role since, on the one hand, it allows to reduce CO_2 emissions drastically and, on the other hand, it offers a variety of opportunities for high percentages of recycling. Inspired by experience in Sweden, the international project "Optimal Recycling of Reclaimed Asphalts for low-traffic Pavement" (ORRAP) for low-volume roads in the Upper Rhine region aims to develop and establish a new strategy for 100% reclaimed asphalt pavement (RAP) at ambient temperature (20°C) without adding virgin bituminous binders or rejuvenators. The still ongoing research project involves laboratory experiments as well as in situ test sections. The link between small-scale laboratory experiments and in situ testing is provided by medium-scale traffic simulation in the laboratory. This paper describes results from medium-scale compaction in the laboratory using different methods as well as traffic simulation with a medium-scale mobile traffic load simulator. The results show that compaction in the laboratory at ambient temperature (20°) is very difficult to achieve. Nevertheless, it was found that compaction at a temperature of 60°C appears possible and provides promising results regarding stability and rutting enabling the in situ construction. The in situ pavement construction at ambient temperature on a low-volume road in Switzerland resulted in a visibly well-compacted and stable base course which was covered by a hot mix asphalt surface course the day after. The test section will be monitored closely over the next 12 months.

1. Introduction

For environmental reasons, recycling of reclaimed asphalt pavement (RAP) has become mandatory in many countries and regions worldwide. As a consequence, the accumulation of RAP may lead to enormous piles of RAP which create a problem for local authorities in terms of limited stockyards. This is particularly true, in regions with high-standard infrastructures, dense population, and busy regional road networks, where rehabilitation by far dominates new construction. One of these regions is the Upper Rhine area, combining parts of Germany, France, and Switzerland between the cities of Karlsruhe, Strasbourg, and Basel.

Nowadays, RAP is reused for both hot- and low-temperature asphalt mixtures by adding new material, either as single material components or as certain percentages of new asphalt mixture [1, 2]. In case of hot recycling, bituminous binders and/or rejuvenators are added whereas, for low-temperature recycling emulsions, foam bitumen and other components are used [3, 4]. However, adding new material means that one can only get close to 100% recycling of RAP.

By applying 100% recycling technology for low-volume roads using RAP at ambient temperature without adding new bituminous binder or other components, the current RAP recycling rate could be further increased, reducing road rehabilitation costs and minimizing environmental impacts, such as CO_2 emissions, energy consumption, and consumption of natural material resources. Thus, significant ecological and economic gains could be realized for the management bodies of low-traffic communal roads, which account for about 50% of the road network in the Upper Rhine region.

The application of such a method using cold recycling of reclaimed asphalt aggregates without binder addition is the aim of the ORRAP "Optimal Recycling of Reclaimed Asphalts for low-traffic Pavements" [5] project funded by ERDF-INTERREG V (3.1 ORRAP) [6], the Canton Aargau, and the Swiss confederation.

The ongoing project ORRAP is based on successful experiences in Sweden where the method was carried out in field trials on municipal roads and on low-traffic highways several years ago [7, 8]. Here, 100% RAP aggregates were used at ambient temperature for base courses, which were later covered with hot asphalt surface layers. According to the Swedish experience, the base courses constructed at ambient temperature require postcompaction by traffic as well as curing to settle and gain their ultimate strength. Therefore, they were left uncovered for at least 6 months. However, during this time, serious restrictions on the traffic regime, such as speed limits, had to be imposed. Since this long maturing process was not considered a feasible strategy for the 3 countries involved in ORRAP, the Swedish recycling technique was re-evaluated proposing an improved recycling and construction technique. In addition, for more homogeneous load distribution and avoiding early restrictions on traffic regimes, the 100% RAP base course of the realized in situ test section was covered with a hot mix surface course.

The ORRAP project includes a comprehensive study of the proposed recycling technique and its application. It consists of 6 work packages as shown in Figure 1.

Since the research is a collaboration between 3 different country regions, all work packages were distributed among the partners and RAP from the 3 different locations in Switzerland, France, and Germany was chosen and tested.

2. Objective

The objective of this paper is to present the results and conclusions of the medium-scale compaction evaluation in the laboratory with different compaction methods using different RAP materials provided by Switzerland, France, and Germany. Further, results from the traffic simulation with the medium-scale traffic load simulator and the large wheel rutting tester including all RAP materials from the different countries are shown and discussed. The last part of the paper describes the construction of the Swiss in situ test section, a road connecting the villages of Wahlen and Büsserach in the Canton Basel Landschaft.

3. Materials and Methods

The ORRAP project is composed of different work packages and tasks as shown earlier. Work package WP 2 "recipe design" includes material characterization, laboratory testing, and construction of a test section construction. Laboratory testing can be divided into two phases. In the first phase, small-scale laboratory testing was done [9, 10]. In a second phase, a medium-scale traffic simulation in the laboratory was carried out providing the connection to the next phase which aims at constructing an in situ low-traffic

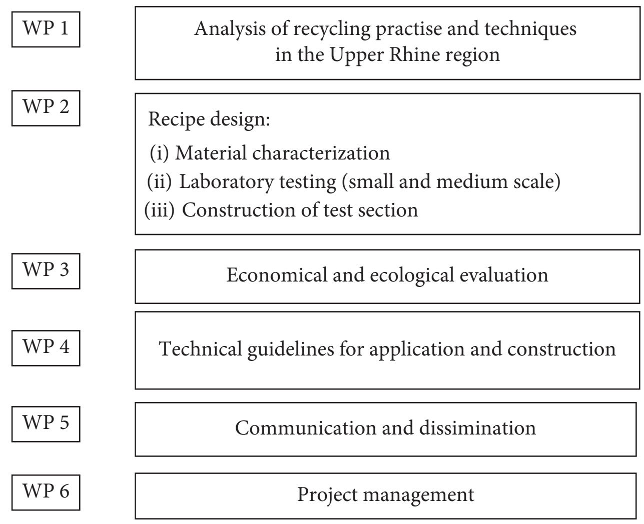


Figure 1: ORRAP work packages.

test section in Switzerland with 100% RAP. This test section will be closely inspected and assessed for at least one year, providing practical construction and performance information for producing a technical guideline for application and construction. In this context, the Swiss Federal Laboratories for Material Science and Technology (Empa) was given the task of the medium-scale traffic simulation in the laboratory.

A detailed flowchart of the experimental program of WP2 is depicted in Figure 2. The tasks shadowed in grey colour are those that will be discussed in the following. Hence, this paper mainly concentrates on the medium-scale laboratory compaction and testing as well as the first findings from the construction of the Swiss in situ test section.

3.1. Material. The material for laboratory testing was provided by the associate partners of the different countries, coming from 3 different RAP sources. It was taken from existing unprotected open-air piles of stored RAP as shown in Figure 3. The material was processed to the size of 0/16 mm and 0/22 mm (Swiss test section) and transported to the different laboratories in big bags.

Prior to the laboratory investigation and testing, the RAP aggregate material 0/16 mm was homogenized and portioned by pouring it through a riffle box as described in the European standard [11]. For the in situ test section between Wahlen and Büsserach, the Swiss RAP 0/22 aggregate material was taken as such.

Figure 4 and Table 1 present the material characteristics of RAP from different countries. All values including the presented grading curve in Figure 4 are mean values of two material characterizations. The results from the recovered bitumen are depicted in Table 2.

3.2. Methods. Testing was conducted in two steps. In the first step, the compatibility of small laboratory specimens was investigated. Then, based on these results, in the second step,

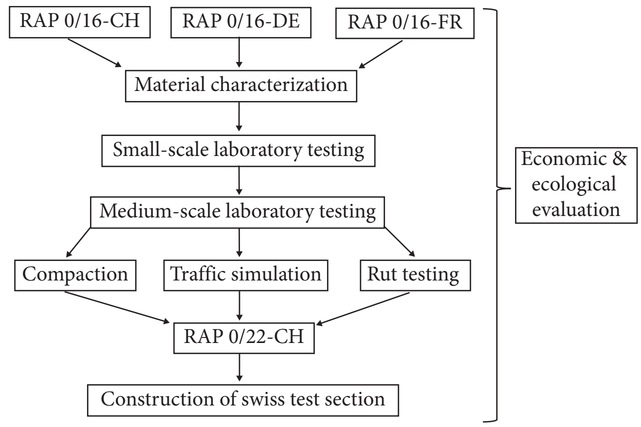


Figure 2: Flowchart of the experimental program of WP 2.

Figure 3: Pile of asphalt aggregates RAP-CH.

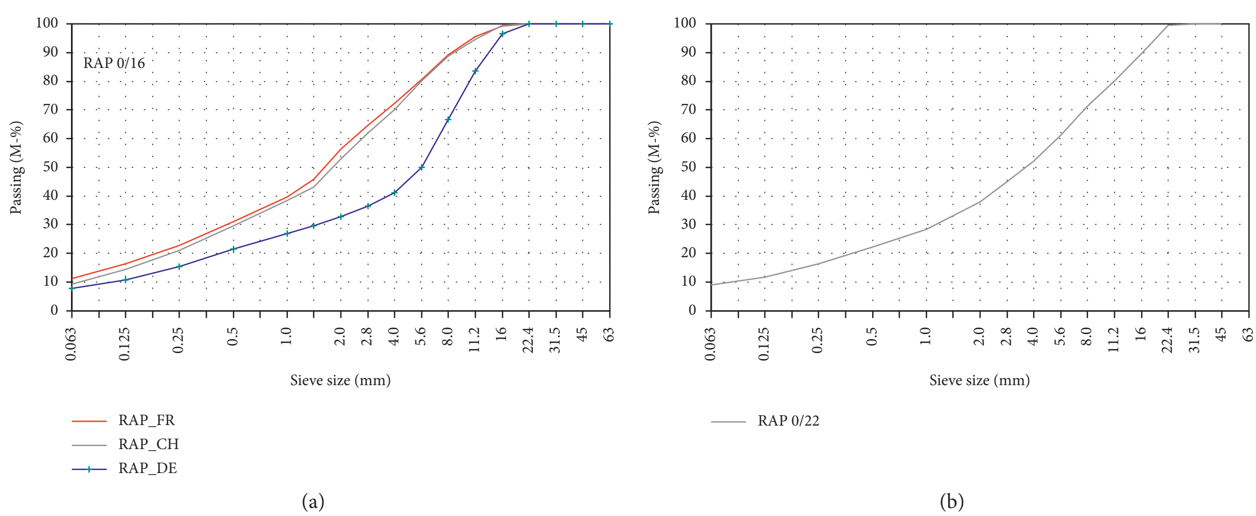


Figure 4: Gradation of asphalt aggregates. (a) 0/16 mm RAP. (b) Swiss RAP 0/22.

Table 1: RAP Material characteristics (mean values).

RAP source	Binder content (mass-%)	Density (kg/m^3)	Water content (mass-%)
RAP 0/16			
CH (Switzerland)	6.2	2.371	1.6
DE (Germany)	4.3	2.347	3.5
FR (France)	6.3	2.408	5.0
RAP 0/22 mm			
CH (Switzerland, test section)	4.0	2.387	4.4

the compaction of medium-size specimens was performed. These medium-size specimens were used for an investigation with the standardized, large wheel rutting tester as well as a medium-scale laboratory traffic simulator, the so-called model mobile load simulator MMLS3, for determining their stability and rutting performance.

Small-scale laboratory specimens were compacted using Marshall and gyratory compaction. From this, it became clear that producing stable specimens required increasing either the compaction effort (number of blows or gyrations) or the temperature. In fact, it was found that slightly

Table 2: RAP material characteristics (mean values).

RAP source	Penetration (0.1 mm)	Ring & Ball (°C)
CH (Switzerland)	17	69.0
DE (Germany)	17	68.4
FR (France)	16	69.4
CH (Switzerland, test section)	21	68.6

increasing the temperature (60°C instead of room temperature) changed compaction behaviour drastically [10].

For compacting medium-scale laboratory specimens, the following two methods were applied heating up the RAP material to 60°C [10, 12]:

(i) Medium-size specimens (500 mm × 180 mm, height 100 mm) for the large wheel rutting tester were produced with the compaction as required for the large wheel rutting tests modified with a modified steel roller instead of a pneumatic wheel [13].

(ii) Medium-size specimens (1300 mm × 430 mm × 65 mm) for the MMLS3 traffic simulator were produced using a special compactor consisting of a steel roller with a width of 90 mm and a diameter of 35 mm. The steel roller is mounted on a metal frame with rails for displacing the roller horizontally as depicted in [10]. A winder enables the steel roller to be moved in the vertical direction. During compaction, the steel roller is sprayed with water. The compaction was done manually by pushing the steel roller back and forth longitudinally in static compaction mode without vibration. A piece of concrete within the metal frame builds the base for compaction. Specimens were compacted using a wooden frame as lateral confinement. This method produced well-compacted specimens with a total aggregate loss of only about 0.1 mass-% and without in-plane inhomogeneities on the specimen surface [10].

Rutting tests were performed with the large wheel rutting tester at 60°C up to 30,000 cycles as required for heavy traffic roads.

For traffic simulation, the MMLS3 was used [14] applying a scaled tire load of 2.1 kN in one trafficking direction with four 1.05 m distant pneumatic 300 mm wheels that were inflated to 600 kPa (see Figure 5). The machine (length × width × height = 2.4 × 0.6 × 1.2 m^3) enables about 7200 load applications per hour at a speed of 2.6 m/s. This corresponds to a loading frequency of about 4 Hz for a measured tire-pavement contact length of 0.11 m. The first testing for the RAP 0/16 mm from Switzerland was performed during hot summer months at ambient temperature (25°C) up to 80,000 load passings without lateral wandering of the loading tires [10]. Later, another testing campaign for RAP from Switzerland, France, and Germany was conducted at a temperature of 20°C and up to 50,000 load passings. Rutting was measured with an automatic profilometer at 3 different points within the wheel path of the MMLS3, one in the middle and two others in 300 mm distance both ways from the middle.

Figure 5: Traffic load simulator MMLS3 situated on top of a specimen.

4. Laboratory Test Results

4.1. Rutting Test with Large Wheel Rutting Tester. The rutting test results of all specimens under laterally confined conditions are shown in Figures 6(a)–6(c). Generally, it appears appropriate to approximate the development of the rut depth d by a power law (equation (1)).

$$d = aN^q, \tag{1}$$

where N is the number of load cycles and a and q are constants.

This is confirmed by R^2 in the order of around 0.95 for the two replicas of RAP specimens from Switzerland (CH1 and CH2) and France (FR1 and FR2). In fact, as shown in Figure 6, the scatter between the replica of CH and FR is comparatively small. However, it is quite high for the DE mixture.

The reason for this is the different behaviour of the two DE specimens. As shown in the five longitudinal rutting profiles Prof. 1 until Prof. 5 in Figure 7(b), DE2 produced already after 30 load cycles on one side a comparatively high rut depth which migrated towards the middle after 100 load cycles. The reason for this sudden local structural collapse and loss of stability is not clear. However, it could be due to sudden reorientation and local breakage of RAP chunks that were unexpectedly large and concentrated on one side of the specimens. This would mean that these chunks did withstand the compaction process with the steel roller but not the repeated kneading loads of the pneumatic rutting wheel at 60°C. For DE1 in Figure 7(a), the rutting in Prof. 1 is generally a little bit lower than that in Prof. 5. Hence, rutting was not created totally symmetrical even in this case. This would mean that preparation and sieving are extremely crucial for this type of low-temperature RAP material.

Ignoring DE2 by assuming that these values were not representative due to this sudden rutting collapse on one side of the specimen, the comparison of the rutting behaviour of the RAP from different countries is shown in Figure 8.

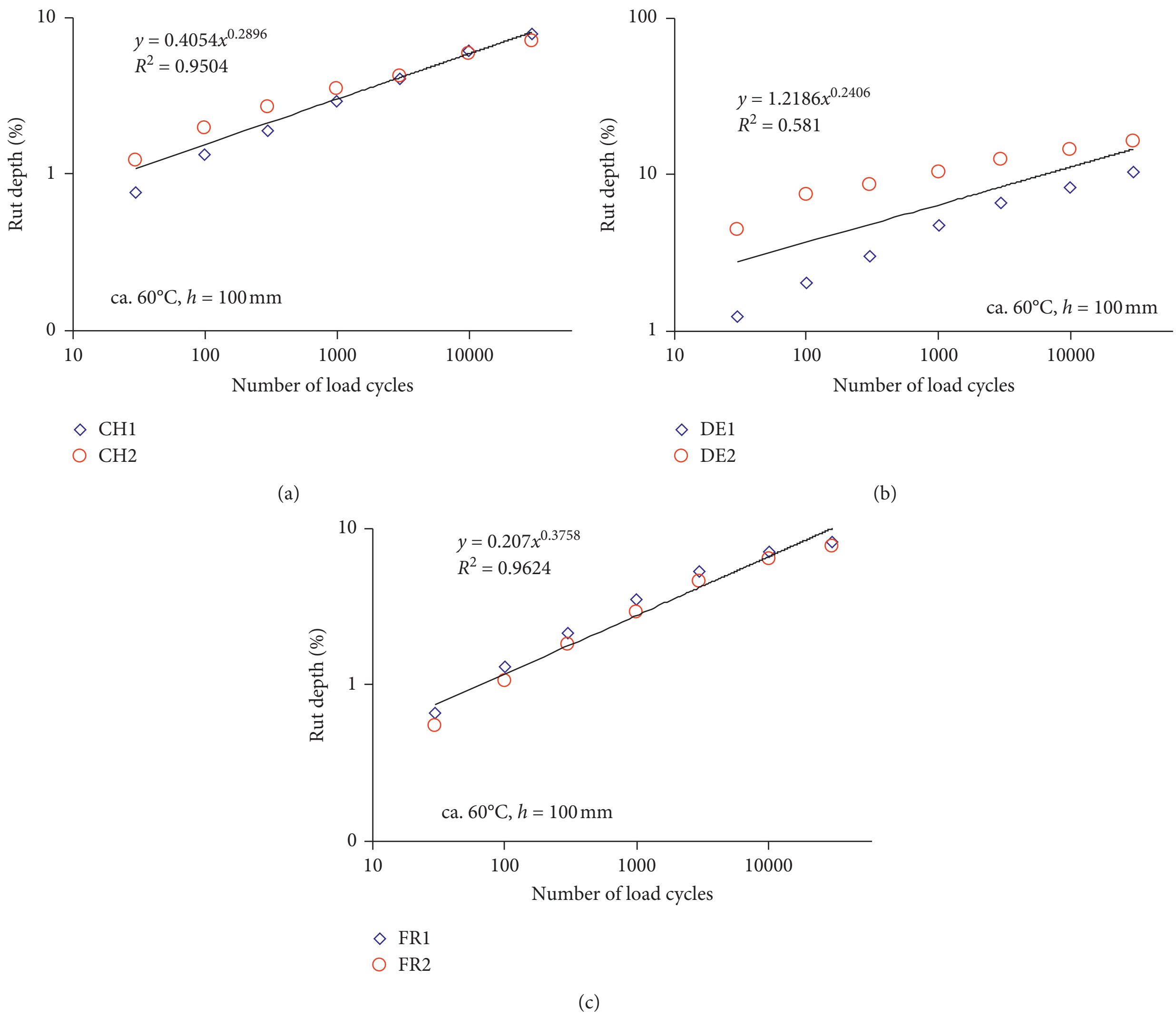


Figure 6: Rutting test results: single values and regression calculated from all individual data for each mixture. (a) CH. (b) DE. (c) FR.

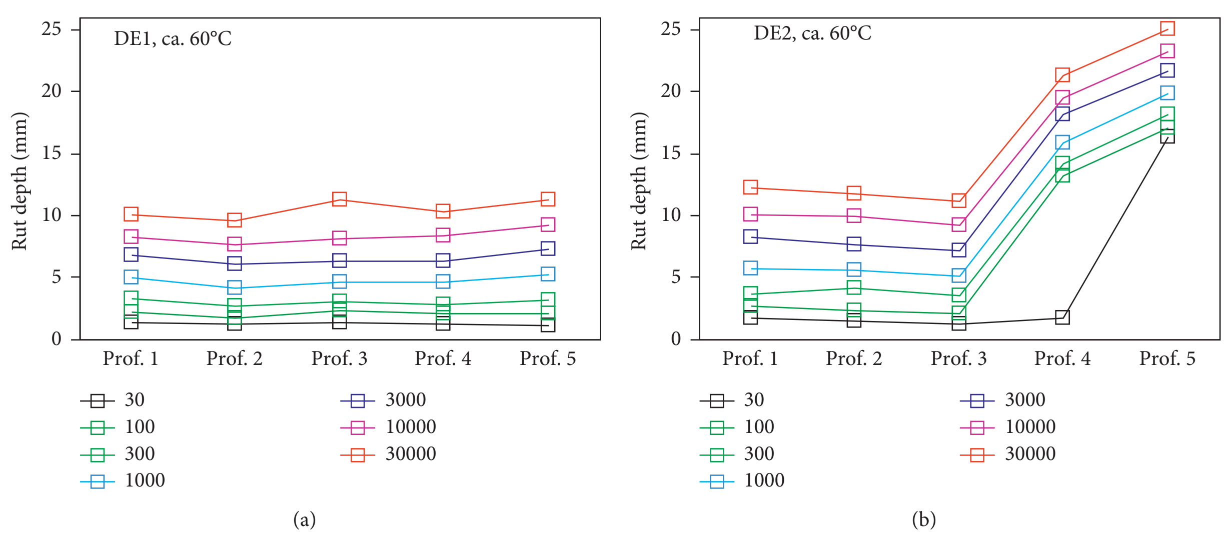


Figure 7: Development of length profiles of rutting test for both DE mixtures showing that DE2 behaved unexpectedly in Prof. 4 and Prof. 5 (a) DE1. (b) DE2.

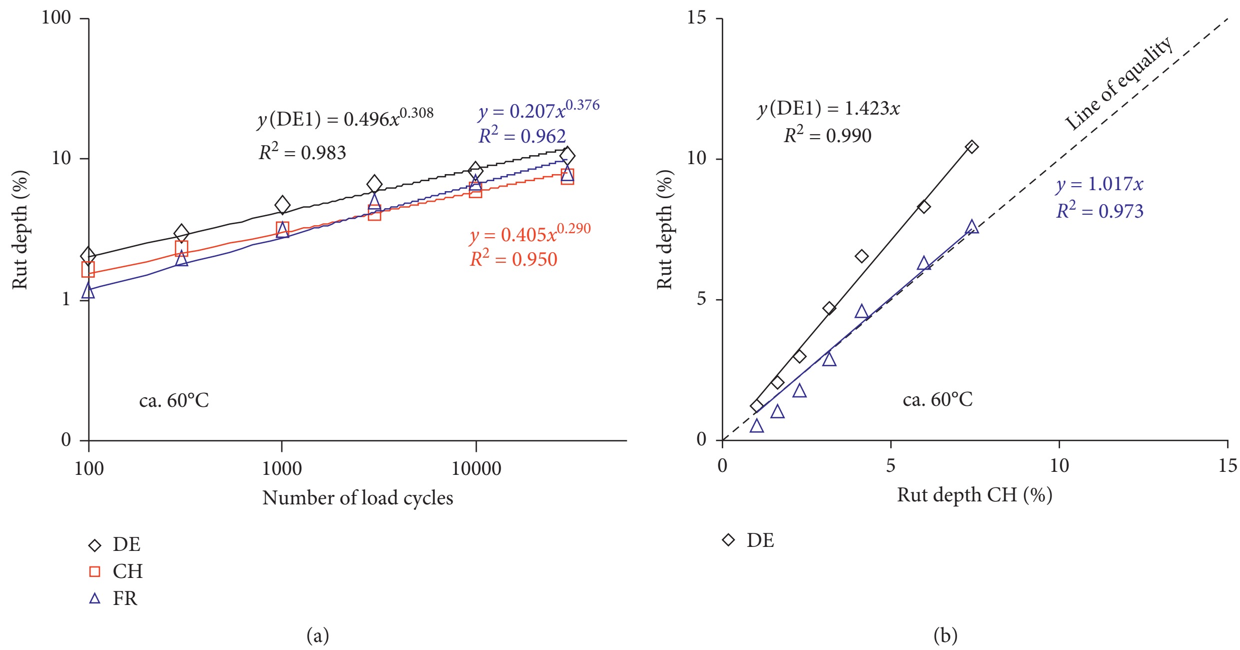


Figure 8: Comparison of rutting test results. (a) Rut depth versus load cycles. (b) Rut depth with respect to CH mixture behaviour, ignoring DE2 results.

In this case, the difference is less significant for all the mixtures. However, the slope of the overall power function for the FR mixtures is clearly higher than that for the CH and DE1 mixtures. FR has a higher rutting speed in particular at the beginning. The slope of the DE1 mixture is comparable with CH, but DE1 has a clearly low rutting resistance at the beginning. Overall, the DE1 mixture is still less rutting resistant but produces a reasonable rutting speed.

As compared to the requirements for AC of Swiss standard [15], one can observe that only the CH mixture fulfils the requirements for mixture type S for heavy traffic (≤10% after 10,000 load cycles) and very heavy traffic H (≤7.5% after 30,000 load cycles), whereas the FR mixture fulfils only the requirement for type S. When comparing the rut depth of the DE1 and FR mixtures in relation to the CH mixture (Figure 8(b)), one can see that the FR mixture is roughly 1.7% higher than the CH mixture. The comparison with the CH mixture shows a reasonable linear behaviour of DE1. However, the DE1 mixture shows about 42% higher rutting and would still not meet the requirements according to the Swiss standard.

4.2. Rutting Test with Laboratory-Scaled Mobile Traffic Simulator. Figure 9 summarizes the MMLS3 results of all individual mixtures. Table 3 shows the functions of the power law regression curves and the R^2 values. The power law regression curves are calculated in each case considering all single values of the three profiles measured. This is the reason why the R^2 values are so low. The points show the mean values of the three profiles for each mixture.

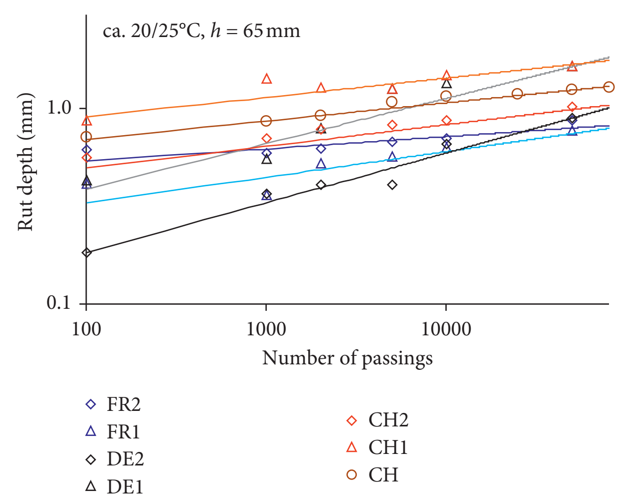


Figure 9: Individual MMLS3 rutting curves at ca 20/25°C. Points are mean values of 3 profiles; regressions are calculated from all individual profile points.

Table 3: Function of power law regression curves and R^2 values.

RAP source	Function of power law regression curve	R^2
CH	$y = 0.453x^{0.093}$	0.467
CH1	$y = 0.571x^{0.099}$	0.464
CH2	$y = 0.297x^{0.111}$	0.227
FR1	$y = 0.179x^{0.131}$	0418
FR2	$y = 0.401x^{0.063}$	0.235
DE1	$y = 0.133x^{0.232}$	0.557
DE2	$y = 0.057x^{0.054}$	0.557

One can clearly see that all RAP mixtures CH, DE, and FE show considerable scatter. For CH, not only are CH1 and CH2 plotted (which have been tested at ca 20°C), but also the data of an earlier test at ca 25° up to 80,000 passings is shown. It is interesting to see that these results blend nicely with CH1 and CH2 in spite of the fact that the temperature was about 5°C higher. This means that the material scatter was overshadowing the influence of temperature in case of this RAP mixture. Therefore, in principle, these early test results can be blended with the CH1 and CH2 data for calculating the mean value of the rutting behaviour of the CH mixtures.

One can also see that the CH mixtures showed larger rutting at 60°C with MMLS3 than the FE mixtures but similar rutting speed. Rutting of the DE mixtures was clearly lower at the beginning but, due to clearly higher rutting speed, they produced ruts in the same order of magnitude than the other two mixtures at the end of testing.

The remarks made above are confirmed and shown more clearly when comparing the overall mean values for each mixture (see Figure 10). The CH and FR mixtures have similar rutting speeds, but CH shows higher initial rut depth. The DE mixture produces clearly higher rutting speed starting from the lowest initial rutting as mentioned before. The influence of including the earlier CH mixture at 25°C is marginal (Figure 10(b)). R^2 values are extremely low due to the large scatter when calculating the power law regression from all individual profile points. As visible from Figure 10(c), R^2 reduces significantly, when the power law regression is calculated only from the overall mean values.

When comparing the MMLS3 rut depth of the DE and FR mixtures at 20°C in relation to the CH mixture at 20/25°C (Figure 11(a)), one can see that the FR mixture is generally about 40% lower. The DE mixture for low rut depths is clearly different but gets much closer to the CH mixtures for high rut depths. This tendency of high rut resistance at the beginning and equally high rutting with an increasing number of passings leads to a nonlinear relationship. As compared to the large wheel rutting results at 60°C Figure 11(b), the ranking is different. Both the DE and FR mixtures display higher rutting resistance in the MMLS3 test at 20°C but lower and almost equal rutting resistance in the large wheel rutting test at 60°C. Here, the DE rut depths from the large wheel rutting test are calculated as mean from both DE1 and DE2 specimens. It appears that the DE mixture is much more temperature-dependent than the CH mixture. One would also conclude that from the three mixtures the FR mixture was the least rutting susceptible mixture of all mixtures.

This temperature dependency may be due to the RAP binder properties but also due to the type of RAP grading curve and the size of RAP clusters. It may well be that large RAP clusters may be stable in the form of aggregate chunks during MMLS3 testing at 20°C but fall apart easily at higher temperatures such as 60°C during the large wheel rutting test. DE2 could be one example of that. In practice, this would mean that the thermal stability of the RAP clusters is crucial for this type of mixture, in terms of compaction and workability during construction as well as after-compaction from traffic. Very large chunks of RAP are certainly negative in that respect and careful mechanical pretreatment of the RAP in the plant appears crucial for this 100% RAP approach. Further investigations in that direction may help to understand these mechanisms.

In that context, it may make sense to consider also investigations with the Compaction Flow Test (CFT), as recently developed at the Royal Institute of Technology (KTH) [16]. This test was found to provide an indication about the workability and flow of aggregates during static loading of loose mixtures in a compaction-like laboratory situation based on material lift-up as shown in the X-ray CT images in Figure 12. A combination of CFT with X-ray CT may help to understand the mechanism of decay of RAP chunks under loading. However, such an investigation was out of the scope of this study but may be kept in mind for future studies.

In order to visualize differences in the deformation behaviour, the mean values of the transversal rutting profiles of the different mixtures in the MMLS3 tests at 20°C after 1000 and 50,000 channelized wheel passings are plotted in Figure 13. Obviously, these deformations are quite low, demonstrating that the mixtures were generally of high rutting resistance. However, it is very clear that the CH mixtures suffered most of the rutting already during the first loading cycles with a practically negligible increase during the rest of trafficking (as already mentioned above), whereas rutting of the DE and FR mixtures showed a remarkable increase. The lateral bulging of CH after 1000 passings suggests that a local material flow took place as simulated in the CFT (see Figure 12). For DE and FR, no bulging was observed.

In Figure 14, a comparison of the MMLS3 results with two asphalt concrete (AC) pavements with hot mix asphalt surface layers HMA1 and HMA2 for low-traffic AC 8 L recently compacted and tested with MMLS3 in the field in another context at ca. 32°C and ca. 27°C, shows that the rutting deformations of the cold mixtures CH, DE, and FR with 100% RAP can be considered as small. HMA1 was 28 cm thick containing no RAP and HMA2 was 40 mm thick and contained 80% RAP. The temperatures of the field pavements in 6 cm depth, in particular, of HMA1 were higher than those of the CH, DE, and FR pavements in the lab and had not a homogeneous temperature distribution over the whole cross section (gradient). The different temperature gradients between the field and lab tests as well as the different compaction methods and types of mixtures have certainly influenced the rutting rate of the field tests as compared to the CH, DE, and FR mixtures. One should also not forget that both HMA1 and 2 had a smaller maximum aggregate size of 8 mm as compared to 16 mm of the CH, DE, and FR mixtures. The higher temperature of HMA1 as compared to HMA2 may have created a higher rut depth in that case.

5. Construction of In Situ Test Section

The in situ test section constructed between the Swiss villages of Wahlen and Büsserach is a low-traffic volume road with an average daily traffic ADT of 200 vpd. The length of the

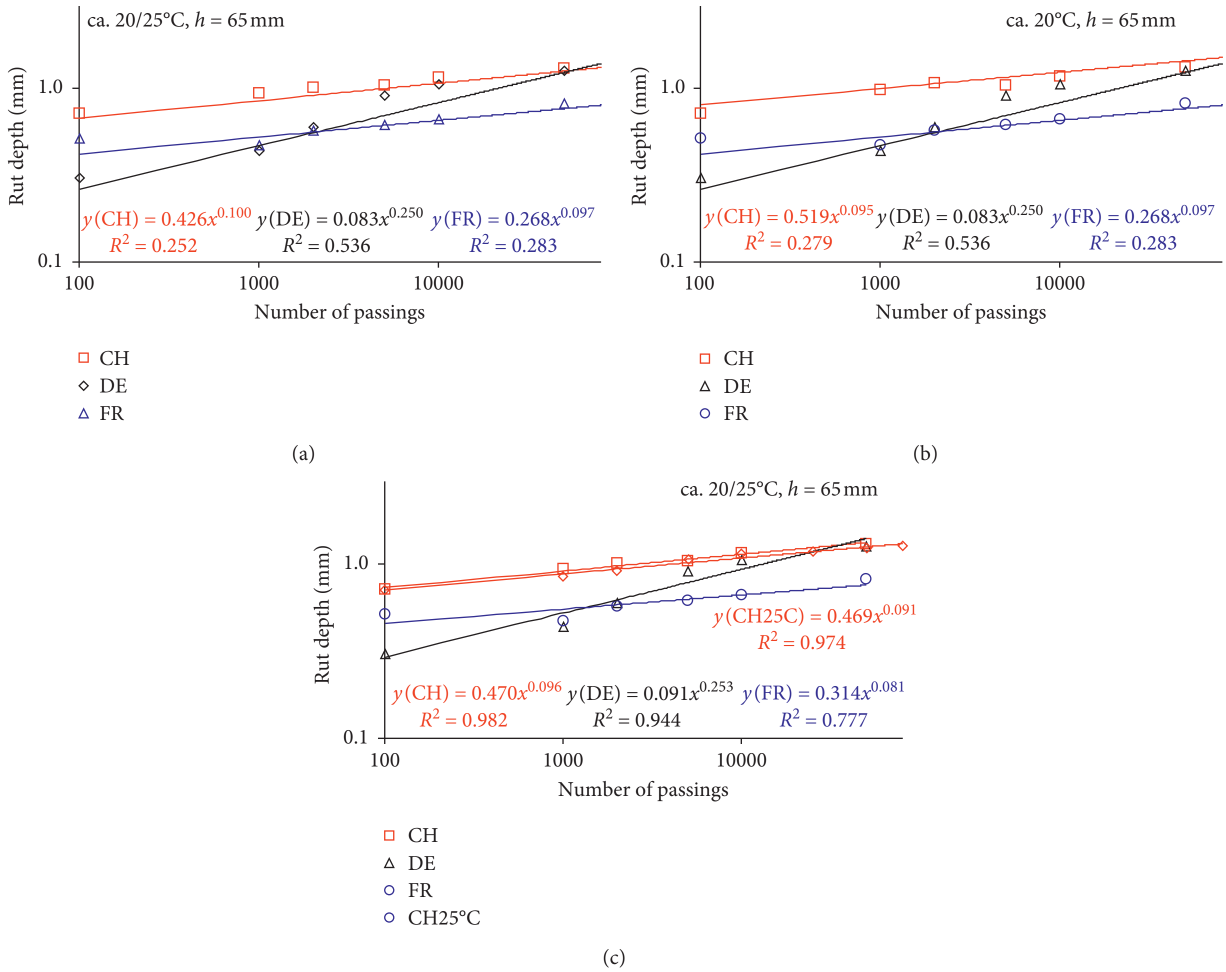


Figure 10: Mean values of MMLS3 rutting curves at ca 20/25°C. Points are mean values of all profiles for each mixture. (a) Including and (b) excluding the earlier mixture CH at 25°C, calculating regressions from all individual profile points, and (c) regression only from mean values. CH at 25°C is shown separately.

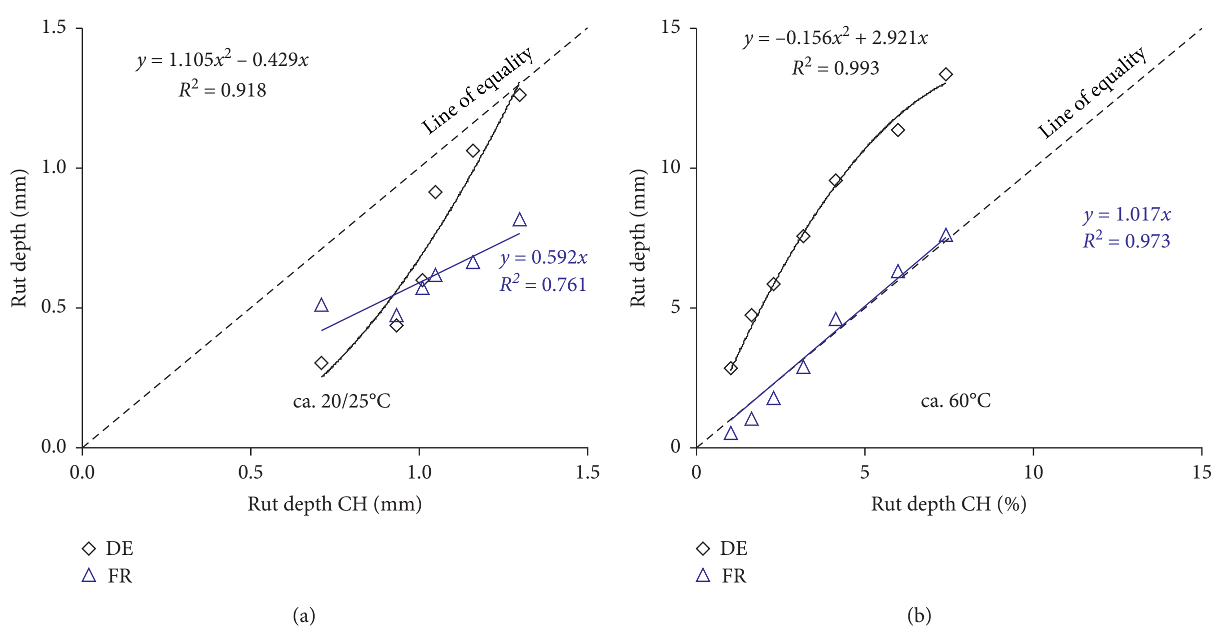
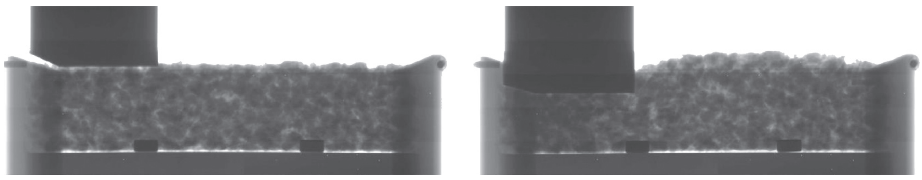


Figure 11: Rut depth with respect to CH mixture behaviour, demonstrating clearly the abnormal results of DE in both cases. (a) MMLS3 at 20/25°C. (b) Large wheel rutting test at 20°C.



(a) (b)

Figure 12: Example of X-ray CT images from flow measurements on coarse (0–16 mm) cold mixture specimens. (a) Before and (b) after the CFT [16].

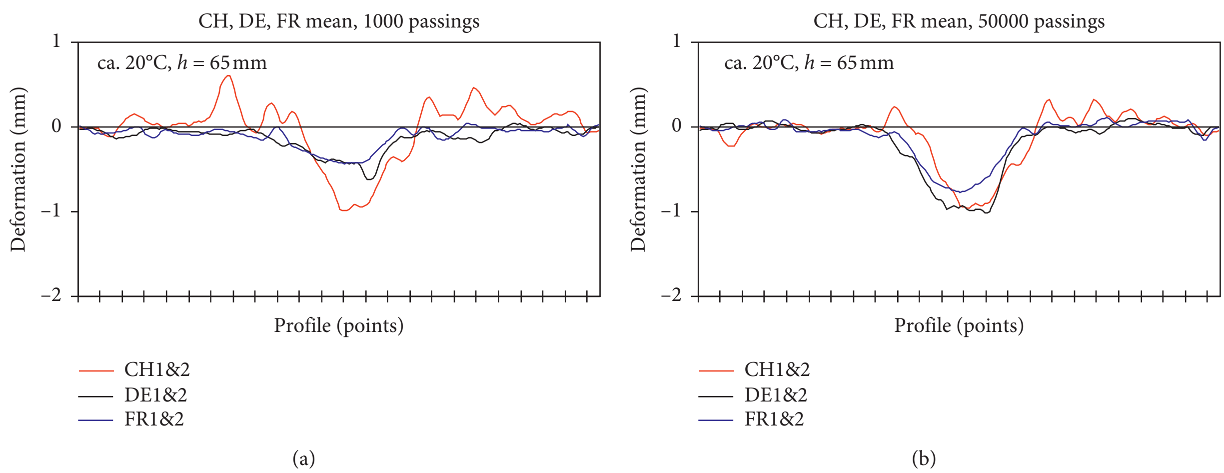


Figure 13: Comparison of MMLS3 profiles at 20°C. (a) After 1000 passings. (b) After 50000 passings.

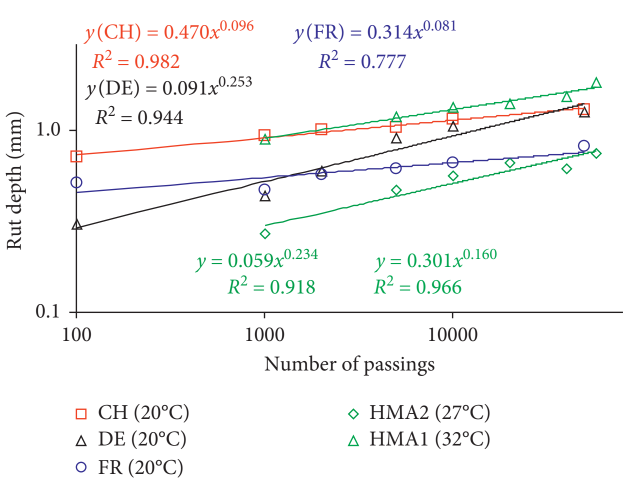


Figure 14: Comparison of MMLS3 rutting curves at 20°C for CH, DE, and FE in the lab with the MMLS3 in the field on two AC asphalt pavements HMA1 and HMA2.

ORRAP test section was 380m. The average width of the road is 5.5 m, with a shoulder width of 1.5 m. For the construction, the existing asphalt layer with a thickness of 10 cm was milled between 3 and 5 cm and the ORRAP material RAP 0/22 with a thickness of 10 cm was placed on top of a tack coat (cationic bitumen emulsion). The day after, the 4 cm thick surface course was constructed consisting of a hot mix asphalt concrete AC 11 N for normal traffic with 11 mm maximum aggregate size and a conventional penetration grade binder 70/100 according to the Swiss standard (Swiss Standard Annex SN 640431). Since the paved RAP material had no side support, the shoulders were considered as weak points and were therefore constructed 20 cm wider than the surface layer at each side. After the construction of the surface course, the 20 cm was backfilled with soil.

Figure 15 shows the profile of the test section.

The construction took place on a very hot dry summer day with a maximum temperature of 36°C in the afternoon and the sun radiation on the construction was very high.

The material was transported by trucks from the storage place which was about 35 km away from the construction side.

The water content of the RAP 0/22 mm had been determined between 4.2 and 4.6%. However, for better workability and compaction under this hot climate and in order to avoid fast surface drying, water was sprayed onto the material in the paver augers as well as after the paver screed.

Compaction was done using 3 different compactors:

(i) Steel roller with a weight of 2.5 t for precompaction and levelling partly in vibration mode

(ii) Pneumatic tire roller with a weight of 4.5 t and

(iii) Pneumatic tire roller with a weight of 24 t

Compaction with a heavy steel roller compactor (12.5 t) in vibration mode led to transversal cracking as visible in Figure 16(a) and was therefore stopped. Transversal cracking was partly attributed to the fact that the 100% RAP material was paved on the comparatively stiff rest old asphalt pavement after milling.

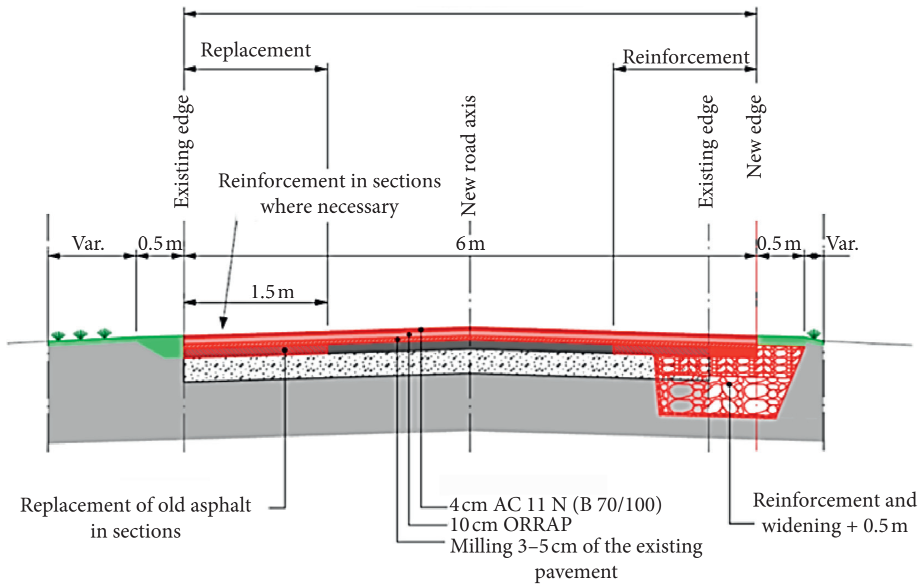


Figure 15: Profile of the in situ test section in Switzerland.

(a) (b)

Figure 16: Cracking during compaction. (a) Transversal cracks caused by heavy steel roller compactor in vibration mode. (b) Shoulder instability.

Regarding the anticipated shoulder instability, it was found that this was a real problem with the breaking of edges as shown in Figure 16(b).

Apart from the abovementioned, further problems and noteworthy observations became obvious during construction, especially considering the RAP material in comparison to hot mix asphalt:

(i) The number of rounded aggregates was found to be considerably high whereas the bitumen coating was considerably low

(ii) The compaction effort was considerably high, about twice compared to HMA constructions

(iii) Large aggregates (up to 12 cm) and chunks of material were found in the RAP and had to be taken out of the compacted surface by workers with shovels and the cavities had to be refilled in quite a cumbersome process

(iv) Besides, of causing cumbersome work, large chunks of RAP material were sometimes blocking the paver screed and the construction had to be stopped for more than half an hour

(v) In addition to these interruptions in construction, further delays occurred when hauling trucks were delayed by traffic jams and the water supply had to be refilled

Figure 17: Test section with RAP material at the end of compaction.

Despite all difficulties, at the end of the day, the RAP material was well compacted, stable, and even, as depicted in Figure 17, providing a good base course for the hot mix surface course. The pavement will be observed during at least one year, and different material and pavement characteristics such as rutting and evenness will be determined at different time intervals.

6. Conclusions

In the present study, a laboratory compaction evaluation and performance characterization of 100% recycled reclaimed asphalt pavement (RAP) were carried out, using different methods and specimen sizes. Particular focus was laid on the rutting behaviour and performance under accelerated traffic loading with a model laboratory traffic simulator. The laboratory study clearly showed the potential of using a high percentage of RAP at low compaction temperatures and was, therefore, very promising for a successful in situ installation of these materials on a test section in Switzerland. From the study which was part of an international project ORRAP, the following conclusions can be drawn:

(i) Although laboratory compaction at an ambient temperature of 20°C turned out to be insufficient, it was found that increasing the temperature only a little (60°C) changed compaction behaviour drastically allowing the construction of stable and rutting resistant asphalt specimens.

(ii) Investigation of rutting resistance with the large wheel rutting tester at 60°C as well as the laboratory scaled mobile traffic simulator MMLS3 at ambient temperature, both under laterally confinement of the specimens, generally produced low rut depths with all three RAP materials from the different sources in Switzerland, Germany, and France. However, significant differences were found, revealing different temperature dependencies and rutting susceptibilities. Although only planed for low-traffic volume applications, some specimens investigated with the large wheel rutting device even fulfilled the requirements for heavily trafficked roads according to Swiss standards.

(iii) Material scatter was comparatively high and overshadowing the influence of temperature during rutting tests. In some cases, it was assumed that RAP clusters may have formed aggregate chunks that remained stable at 20°C but were destroyed due to kneading during rutting tests at 60°C.

(iv) RAP chunks were also found during field construction blocking the paver screed causing working interruptions. This means that for this RAP application careful mechanical pretreatment of the material in the plant and before compaction is necessary in order to avoid those RAP chunks.

(v) From the investigation and findings, it seems feasible to construct low-traffic volume roads with 100% of RAP at low compaction temperature as it was the goal of the ORRAP project. Compared to the construction of hot mix asphalt pavements, the compaction effort has to be increased.

Further studies on the test section will show if enough information is available as a basis for producing a technical guideline for application and construction. In any case, selected additional studies, such as studying the effect of oversized RAP clusters on compaction and mechanical behaviour, must be undertaken in order to develop this promising technology into an environmentally friendly affordable standard application for low-traffic volume roads.

Data Availability

The data used to support the findings of this study have not been made available because the ORRAP "Optimal Recycling of Reclaimed Asphalts for low-traffic Pavements" project is still ongoing and ends on June 30, 2020.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] M. Hugener and M. Seeberger, "Optimum RAP content in hot mix asphalt recycling," in *Proceedings of the 4th ISAP APE Symposium*, p. 11, Tokyo, Japan, November 2015.

[2] Q. Aurangzeb, I. L. Al-Qadi, I. M. Abuawad, W. J. Pine, and J. S. Trepanier, "Achieving desired volumetrics and performance for mixtures with high percentage of reclaimed asphalt pavement," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2294, no. 1, pp. 34–42, Washington, USA, 2012.

[3] M. Zaumanis, R. Mallick, and R. Frank, "Evaluation of rejuvenator's effectiveness with conventional mix testing for 100% reclaimed asphalt pavement mixtures," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2370, no. 1, pp. 14–25, 2013.

[4] A. Cannone Falchetto, L. Porot, C. Riccardi, M. Hugener, G. Tebaldi, and E. Dave, "Effects of rejuvenator on reclaimed asphalt binder: an exploratory study of the RILEM TC 264-RAP Task Group 3," in *Rilem Bookseries: Vol. 20, RILEM 252-CMB Symposium, Chemo-Mechanical Characterization of Bituminous Materials*, L. D. Poulikakos, A. Cannone Falchetto, M. P. Wistuba, B. Hofko, L. Porot, and H. Di Benedetto, Eds., Springer, Berlin, Germany, pp. 195–200, 2019.

[5] ORRAP (2016–2020), http://www.interreg-oberrhein.eu/projet/orrap-optimales-recycling-von-ausbauasphalt-auf-verkehrsschwachen-strasen.

[6] ORRAP (2016–2020), https://www.orrap.org/.
[7] T. Jacobson, "Reclaimed crushed asphalt—experiences from field studies examples from Jönkönping, Västeras, Goteborg municipal roads (asfaltgranulat som obundet bär- och förstärkningslager. Återvinning av krossad asfalt som bäroch förstärkningslager. del 2—erfarenheter från fältstudier) VTI notat 32," 2002.
[8] European Union, *European Project: FP 7th Project DIRECT-MAT Dismantling and RECyling Techniques for Road MA-Terials (2007–2011)*, European Union, Brussels, Belgium, 2012.
[9] L. Gaillard, C. Chazallon, P. Hornych, J. C. Quezada, and C. Raab, "Thermo-hydro-mechanical behaviour of cold reclaimed asphalt aggregates without binder addition," *Road Materials and Pavement Design*, vol. 20, no. 1, pp. S49–S63, 2019.
[10] C. Raab, N. M. Partl, and C. Bensa, "100% recycling of low-temp asphalt for minor roads—lab compaction and traffic simulation," in *Proceedings of the 5th International Symposium on Asphalt Pavements & Environment (APE) in Padova*, pp. 235–245, Springer Book Series, Padua, Italy, September 2020.
[11] European Standard EN 932-1, *Tests for General Properties of Aggregates—Part 1: Methods for Sampling*, CEN, Brussels, Belgium, 1996.
[12] C. Raab, M. Arraigada, M. N. Partl, and F. Schiffmann, "Cracking and interlayer bonding performance of reinforced asphalt pavements," *European Journal of Environmental and Civil Engineering*, vol. 21, no. 1, pp. 14–26, 2017.
[13] European Standard EN 12697-22, *Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 22: Wheel Tracking*, CEN, Brussels, Belgium, 2003.
[14] F. Hugo and A. Epps, *Significant Findings from Accelerated Pavement Testing*, NCHRP Synthesis 325, TRB 2004, Washington, DC, USA, 2004.
[15] Swiss Standard Annex SN 640431 to European Standard EN 13108-1, *Mischgutanforderungen—Teil 1: Asphaltbeton*, Swiss Standard SN 640431-1b-NA, Switzerland, 2014.
[16] E. Ghafoori Roozbahany, M. N. Partl, and A. Guarin, "Introducing a new method for studying the field compaction," *Road Materials and Pavement Design*, vol. 18, no. 2, pp. 26–38, 2017.