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Results of surface hot-in place recycling (remix) of modified and alternative asphalt mixtures in Finland. Part I: mixture scale

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ABSTRACT

Surface hot-in place recycling of asphalt mixtures has been conducted on Finnish roads for several years. The procedure is performed either in full-lane ('remix') or shorter widths ('rut-remix'). In a 2020–2021 project, different mixture types were subjected to both kinds of recycling; reference mixtures, and mixtures modified with aramid fibres, FEP elastomer pellets, polymer, Storelastic rubber additive, recycled asphalt shingles, steel slag, and soft bitumen. This paper (Part I) presents the results of an extensive laboratory test plan at the mixture scale. Asphalt mixture cores were recovered from four roads. Various tests were performed on the mixtures in original state (aged, before recycling) and after recycling (remix or rut-remix), including strength (ITSR), stiffness, Prall abrasion, creep permanent deformation, as well as bulk, air voids, and thickness measurements. The effect of remix/rut-remix is assessed using scores calculated from mixture-scale test results. The results show that remix and rut-remix are highly heterogeneous processes, affecting every material differently and sometimes erratically. Adequate air void contents and evenness in compaction are critical for good performance. The results provide a reference performance database for an extended group of materials. Data appendices are accessible from the link at the bottom of the page.

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1. Introduction

Hot mix asphalt is a material of great importance for the construction and rehabilitation of road infrastructure worldwide. It is already common practice to add modifiers to the asphalt mixture (Romeo *et al.* 2010, Eskandarsefat *et al.* 2020). Such additions aim to improve the material's performance, which is exposed to various elements and solicitations that accelerate its deterioration during service life, mainly weather and traffic. At the same time, sustainability-related considerations enable the addition of industrial waste materials to the mixture, as well as the utilisation of previously in-place bitumen or asphalt shingles. These 'alternative' materials may enter the mixture either as additives to the binder, or to replace a fraction of neat binder, fine or coarse aggregates. Such additions can potentially impact the material's performance and are thus the object of research. However, from a life-cycle point of view, the addition of industrial by-products and the reuse of asphalt is usually desirable as it can positively impact sustainability, energy demand, and global warming potential (Al-Qadi *et al.* 2015, Vega *et al.* 2020). Moreover, transport agencies are increasingly interested in implementing recycling processes as part of their maintenance and rehabilitation strategies. Mainly, such techniques partially or entirely reuse the asphalt mixture already in place to build base or surface layers. Recycling thus provides economic and environmental benefits, as it reduces the need for raw materials and lowers the energy demand during construction.

In Finland, the most popular technique of hot-in-place recycling of surface asphalt layers of roads is called remix (REM). During remix, the road's surface is heated until it reaches a temperature between 180 and 220°C. The material is then milled, combined with new asphalt mixture (~30 kg/m², including 150–250 g/m² of soft bitumen 650/900), and compacted (Pellinen and Makowska 2018). Remix is commonly used to counter rutting due to studded tires. The operating width of the remix process is one entire lane and even larger depending on the equipment. Nevertheless, this procedure can also be performed over a shorter width to correct a section of the lane locally, i.e. only the most deteriorated 'rut' (~1 or 1.25 m width). This smaller-scale type of remix is called rut-remix (RUT-REM). An example of the results of rut-remix is presented in Figure 1. Although relatively minor worldwide, remix is a major application in Finland. This process is considered a low-disruption, cost-efficient maintenance approach (Pellinen and Makowska 2018); it reduces the hauling of materials, which is a critical advantage given that Finland has centralised asphalt plants with long distances in between. At the same time, remix reduces asphalt demand. In Finland specifically, there have been documented recycling patterns using remix since 1990 (Apilo and Eskola 1999, Makowska *et al.* 2017).

The objective of this study was to measure the effect of remix and rut-remix on a set of modified and alternative asphalt concrete composites. For this, we received specimens of modified or alternative asphalt mixtures from four roads in Finland:

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Figure 1. Example of typical results of rut-remix (RUT-REM) treatment (Väylä, 2019).

Note: This road is not part of the project.

Ylöjärvi, Kilvakkala, Riihimäki, and Oulu. Of these four sites, Ylöjärvi and Oulu received full-lane width remix treatment, while Kilvakkala and Riihimäki received rut-remix treatment. Together, the four roads included seven materials between modified and alternative mixtures. These materials were aramid fibres (ARA), elastomer pellets (FEP), polymer-modified asphalt (KB), soft asphalt (PAB), Storelastic tire rubber powder (STO), recycled asphalt shingles (RAS), and slag aggregates with two target gradations (OKTO SMA and OKTO AC). Additionally, reference material (REF) was obtained from Ylöjärvi, Kilvakkala, and Riihimäki. We received several cores of all these materials, before and after remix/rut-remix. The project took place in 2020–2021 at Aalto University with the support of the Finnish Transportation Infrastructure Agency (Väylä). The preparation and testing of specimens were performed in the asphalt laboratories at Aalto University.

This paper describes the results at the scale of the asphalt mixture (specimens). Results at the bitumen scale are presented in Part II of this study. This paper includes information on the roads and materials, the laboratory test plan proposed for the project, the preparation and characterisation of specimens in the laboratory, and the results of the laboratory tests at the mixture scale. We aim to shed light on how the treatments affect the properties of the modified and alternative asphalt mixtures, and ultimately find out if these materials are recyclable through remix or rut-remix. To establish this, the performance of the materials was evaluated from the perspective of air void contents, moisture susceptibility (indirect tensile strength ratio), abrasion, and permanent deformation requirements, before and after REM/RUT. As it will be presented later, the different techniques may have an important influence on the performance of the materials, particularly related to the compaction quality at the edges of the ruts after RUT-REM.

2. Road sites and materials

2.1. Roads, materials, and conventions

Figure 2 shows the location in Finland of the four test road sites of the project. Three sites are located in the south-western

part of the country: Ylöjärvi (MT2773) and Kilvakkala (KT261) in the vicinity of the city of Tampere, and Riihimäki (MT2879) some 60 km north of the capital city Helsinki. The roads near Oulu (VT4 and MT847) are located to the north of the country.

A large number of field cores were received as part of the project. Therefore, a system of conventions was established to facilitate the identification and management of cores and specimens, labelling, processing of data, and the presentation of the laboratory test results of the project. The roads are herein identified with a short name or label and an accompanying symbol, as presented in Table 1. Roads and materials after REM/RUT are marked with a star.

In total, there were seven non-reference materials coming from the roads. These included modified and alternative mixtures, as well as mixtures with bitumen or aggregate replacement (industrial waste). Additionally, samples of reference



Figure 2. Location of the roads in Finland. The road codes are presented as well. Notice that every road is identified with a unique marker (symbol). Source (map): Google Maps.

Table 1. Roads, codes, and conventions of the project.

Site	Road code	Convention		Symbol
		Short label	After RUT-REM	
Ylöjärvi	MT 2773	Ylö	Ylö*	● – Circle
Kilvakkala	KT 261	Kil	Kil*	▲ – Triangle
Riihimäki	MT 2879	Riihi	Riihi*	■ – Square
Oulu	VT 4 and MT 847	Oulu	Oulu*	◆ – Diamond

Note: Roads and materials after remix/rut-remix are marked with a star (*).

material (REF) were received from Ylöjärvi, Kilvakkala, and Riihimäki. The materials were identified with a short label and a unique colour convention. They are as follows:

- (1) **ARA** is a blend of aramid and polyolefin fibres used for the reinforcement of asphalt mixtures. The use of fibres intends to improve performance against cracking and rutting.
- (2) **FEP** is 80% rubber elastomer pellet and 20% Arbocel (cellulose) fibre.
- (3) **KB** is polymer-modified bitumen. A previous denomination for polymer-modified bitumens with rubber-like properties named this material ‘rubber bitumen’ (*kumibitumi* in Finnish) (PANK 2017). Bitumen products of this kind are currently marked PMB, i.e. polymer-modified bitumen.
- (4) **PAB** is soft asphalt concrete (*pehmeä asfalttibetoni* in Finnish) used for weather resistance. It contains bitumen of low viscosity, commonly associated with high penetrations in the range 250–900 dmm.
- (5) **STO** is ‘Storelastic’, truck tire rubber powder granular additive, treated with oil to improve mixing.
- (6) **RAS** is recycled asphalt shingles, i.e. roofing bitumen.
- (7) **OKTO** is ferrochromium slag aggregate, an industrial waste product.

A summary of the materials and their roads of origin is presented in Table 2. Three of the materials (**ARA**, **FEP**, **KB**) were present in two of the roads: Ylöjärvi and Kilvakkala. Ideally, this would mean that redundant results were available for comparison and verification of consistency among roads. However, it is essential to remark that in Ylöjärvi the materials underwent remix, whereas in Kilvakkala they received rut-remix treatment. The two procedures were found to affect the properties of the materials differently, particularly due to differences in compaction evenness. Pictures of some of the additives or materials from the project are presented in

Table 2. Roads and materials of the project.

Ylöjärvi (MT 2773)	Kilvakkala (KT 261)	Riihimäki (MT 2879)	Oulu
REM	RUT-REM	RUT-REM	REM
●	▲	■	◆
REF	REF	REF	OKTO SMA (VT 4)
ARA	ARA	RAS	OKTO AC (MT 847)
FEP	FEP		
KB	KB		
PAB	STO		

Note: The colour and symbol conventions are consistent throughout the document.

Figure 3. Additional information on the materials, including bitumen types, road-specific additive proportions, and more details on the incorporation of additives to the mixtures can be found in Part II.

The four roads contain several sections, each several hundred metres long. Each section was originally constructed to test the performance of one additive. The cores were thus obtained from each section to sample all modified/alternative materials separately. Detailed information on the sections’ addresses can be found elsewhere (Rossi 2016, Heinonen 2017, Valkonen 2020).

2.2. Core procurement and comments

A sizable number of field cores were received as part of the project. Overall, 10–25 cores were obtained per material per road, before and after REM/RUT, for a total of more than 500 cores for preparation, sawing, characterisation, and testing. A summary of the cores is as follows:

- **Ylöjärvi** (●), 5 materials. 50 cores before REM (100-mm diameter), 95 cores after REM (100-mm diameter), 30 cores after REM (150-mm diameter). Total: 175 cores.
- **Kilvakkala** (▲), 5 materials. 50 cores before RUT-REM (100-mm diameter), 95 cores after RUT-REM (100-mm diameter), 30 cores after RUT-REM (150-mm diameter). Total: 175 cores.
- **Riihimäki** (■), 2 materials. 26 cores before RUT-REM (100-mm diameter), 38 cores after RUT-REM (100-mm diameter), 12 cores after RUT-REM (150-mm diameter). Total: 76 cores.
- **Oulu** (◆), 2 materials. 27 cores before REM (100-mm diameter), 44 cores after REM (100-mm diameter), 13 cores after REM (150-mm diameter). Total: 84 cores.

Figure 4 illustrates the approximate locations of the field cores obtained from the roads before and after REM/RUT. As it can be observed, different coring patterns were used. Some cores were obtained from a unique location in the road, around the centre of the lane (i.e. Riihimäki before RUT-REM, Oulu before and after REM). For the other cases, the cores were extracted from two locations in the lane: approximately towards the middle of the lane between the driving tracks (marked AV, *ajourien välistä* in Finnish), and next to the edge road markings (marked RV, *reunaviivan vierestä* in Finnish). For all materials, the cores were collected from the same location before and after REM/RUT, aiming to work (in the recycled stage) with material as similar as possible to the original (aged). The coring addresses coincided within ~10 m for all roads.

The distinction between AV and RV cores was kept as much as possible during the laboratory testing to identify potential differences between the material properties obtained at the two locations. Nevertheless, it is important to note that when RUT-REM took place, an AV or RV label does not necessarily represent a similar location within the road. In Kilvakkala and Riihimäki after RUT-REM, AV and RV are better understood as locations towards the edges of the treatment. At the same time, in Ylöjärvi after REM (and in Oulu REM) AV is expected to represent a location away from the edges of the



Figure 3. Examples of some materials used in the project. (a) **ARA**, (b) **FEP**, (c) **STO**, (d) **OKTO**. Notice the air bubbles inside the **OKTO** aggregates. Credits: Valkonen (2020), Michalina Makowska, www.veritalo.de.

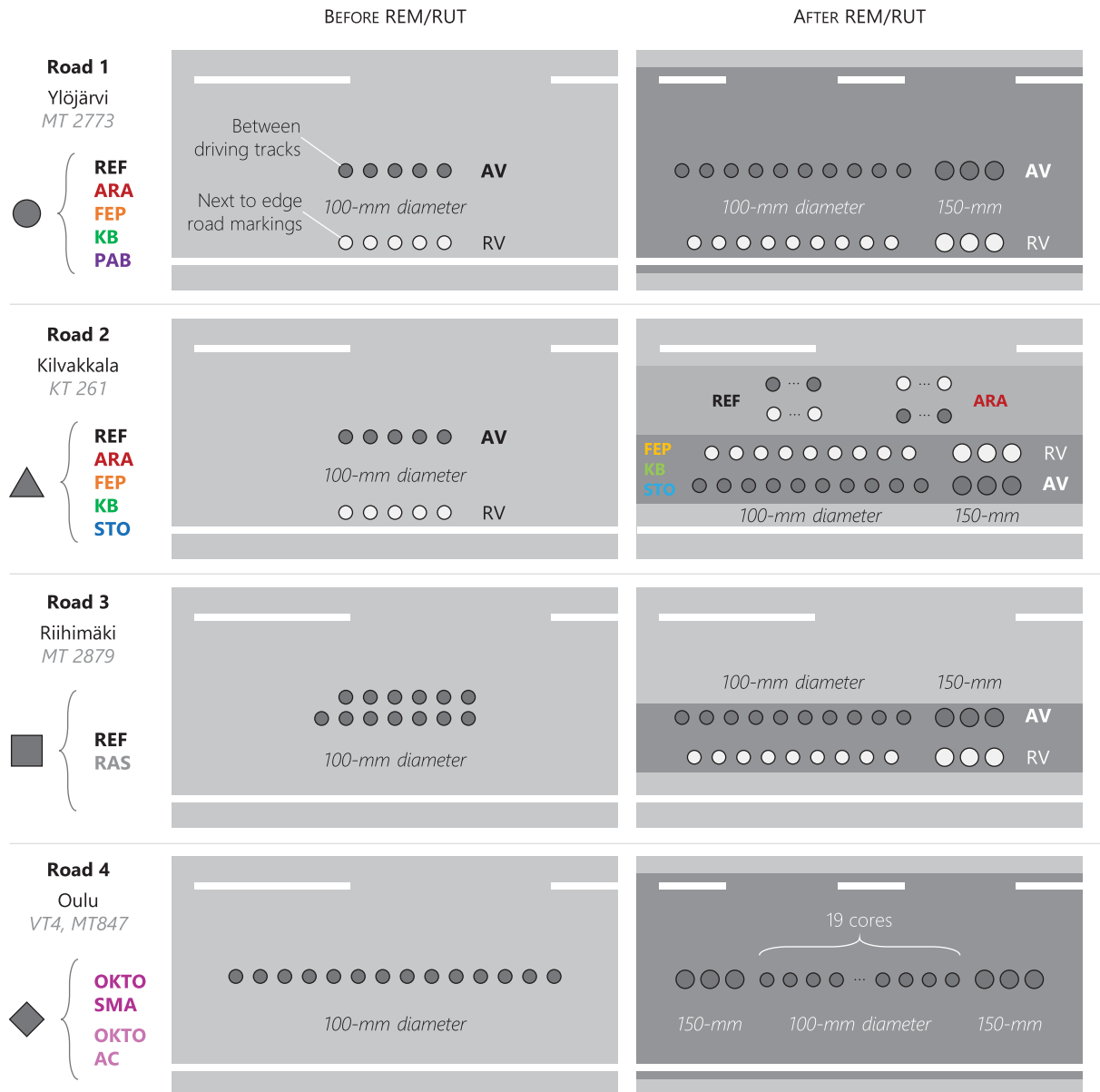


Figure 4. Approximate locations of the field cores obtained per material, before and after remix/rut-remix

Notes: Notice the different coring patterns. Some roads have only one location: between driving tracks (AV, *ajourien välistä*) and next to the edge or markings (RV, *reunaviivan vierestä*). Notice the changes to the AV/RV convention for Kivakkala RUT-REM. **KB** location in Kivakkala RUT-REM is approximate.

treatment, towards the centre of the lane. Some images taken during the coring process are presented in Figure 5, showing some of the different coring patterns and conventions of the project. The cores from Oulu, REM (OKTO SMA*, OKTO AC*) were taken 0.5 metres apart along the rut line and labelled consecutively. Therefore, these are the only cores in the project where the numbering of the specimens (and the test data) corresponds directly with the geometric location of the cores in the road. This will be noted in later figures when appropriate.

3. Test plan

A test plan was proposed to evaluate the performance of the materials. The test plan covers the mixture and bitumen scales, and it is slightly different for the specimens before and after REM/RUT. Overall, tests at the mixture scale include strength in indirect tensile mode (dry and wet) (SFS-EN-12697-23 2017), stiffness (SFS-EN-12697-26 2018), Prall abrasion (SFS-EN-12697-16 2016a), and creep permanent deformation (SFS-EN-12697-25 2016b). These tests are intended to produce enough data to assess the quality requirements for the finished pavement as per the Finnish asphalt standard (PANK 2017). Additionally, the results can be used to evaluate the susceptibility of the asphalt mixtures and the recovered bitumen materials to moisture damage, rutting (tested at both scales, bitumen and mixture), low temperature cracking, and the effect of modification on the bitumen. The test plan is presented in Figure 6.

4. Specimen preparation and preliminary measurements

4.1. Processing of cores and specimens

The cores were received in the laboratory and processed as follows:

- (1) The cores were first organised and classified. The exterior of the cores was washed to remove dirt, and they were allowed to dry for a few days. Only the cores from Oulu were not washed on arrival, as they were already remarkably clean.
- (2) Every core in the project was then identified with a unique label. The label included the project number, road of origin, location, material type, and a unique core number. The label facilitated the handling of the cores during the laboratory testing and the data processing. These labels are used in the Database (<https://doi.org/10.5281/zenodo.6908195>).
- (3) A preliminary measurement was taken of the thickness of the upper and lower layers of the cores. The upper layer is the remixed layer, which is the focus of this project. Meanwhile, depending on the height of the core, up to three additional lower layers could be identified. These thicknesses were measured and registered as well. This preliminary assessment was performed to set up the finer cutting plan for the specimens, depending on the tests to be performed.

- (4) Two pictures were taken per core: a side view and a top view. Images of selected cores are presented in the Appendix (<https://doi.org/10.5281/zenodo.6908195>).
- (5) The cores were then ready for sawing. The specimens were prepared by sawing the upper layer of the core at a given thickness. This target thickness depended on (1) the available upper layer thickness, and (2) the test planned for the specimen. For strength, stiffness and Prall abrasion tests, the specimens were prepared such that the original road surface was left exposed on top of the specimen. This procedure is allowed by the standards for specimens cored on site. For creep permanent deformation tests, the specimens were cut twice to obtain two flat, parallel surfaces, to mount two specimens per test.

Although the present study focuses on the surface layer of the pavement structures, the thickness of the lower layers of the cores was measured when available. A summary of the layer thickness measured for all the cores of the project is presented in Figure 7. Several cores exhibited up to three additional layers below the surface, particularly the cores from Oulu (before and after REM) and the 150-mm diameter cores from Ylöjärvi REM and Kilvakkala RUT-REM.

4.2. Cutting plan and thickness restrictions

Regarding the laboratory tests and the AV/RV distinction, the specimens were selected as follows. From every group of ten cores per material before REM/RUT (100-mm diameter), six cores were selected for strength (3 AV, 3 RV) and four cores are selected for stiffness (2 AV, 2 RV). After REM/RUT, there are 19 cores of 100-mm diameter, and 6 larger cores of diameter ~150 mm per material. From each group of 25 cores per material after REM/RUT, ten cores were selected for strength (6 AV, 4 RV), five cores were selected for stiffness (2 AV, 3 RV), four cores were selected for Prall abrasion (2 AV, 2 RV), and six cores were selected for creep (3 AV, 3 RV). Three of the AV cores were tested for strength after wet conditioning. One creep test involves two specimens.

Thickness restrictions were observed when selecting the appropriate height for cutting the specimens. Some of the materials had very thin upper layers, particularly before REM/RUT. For example, in Ylöjärvi (KB, PAB) and Kilvakkala (ARA/AV) some materials had layer thicknesses below 4 cm. Many other materials in all sites had thicknesses around 4 cm on average (i.e. RAS). Apart from these limiting cases, the thicknesses of the layers were comparatively larger. With the objective of guaranteeing comparable results among testing sites, low thicknesses were proposed overall for the testing. A target thickness of 35 mm was selected for the strength, and a target thickness of 32 mm for the stiffness. Both Prall and creep have a target thickness of 30 mm. These target values were maintained for consistency and comparability among materials. The values were within limits allowed by the standards.

Additional restrictions were observed for the PAB material (Ylöjärvi). This material is exceptionally soft, and it had the lowest thickness overall before REM. A different set of target specimen thickness was thus proposed. Stiffness and Strength (before REM) had a target thickness of 30 mm (PAB only). To increase the strength values for this material



Figure 5. Selected images of the cores after extraction from the roads. (a) Ylöjärvi REM, (b) Kilvakkala RUT-REM, (c) Riihimäki, (d) Oulu.

after REM to levels more comparable to the other materials, the target thickness for the Strength after REM was 45 mm (PAB only).

Due to thickness restrictions, the nominal maximum aggregate size (16 mm, all mixtures) could represent up to 50% of the thickness for the thinnest specimens. Size effects have

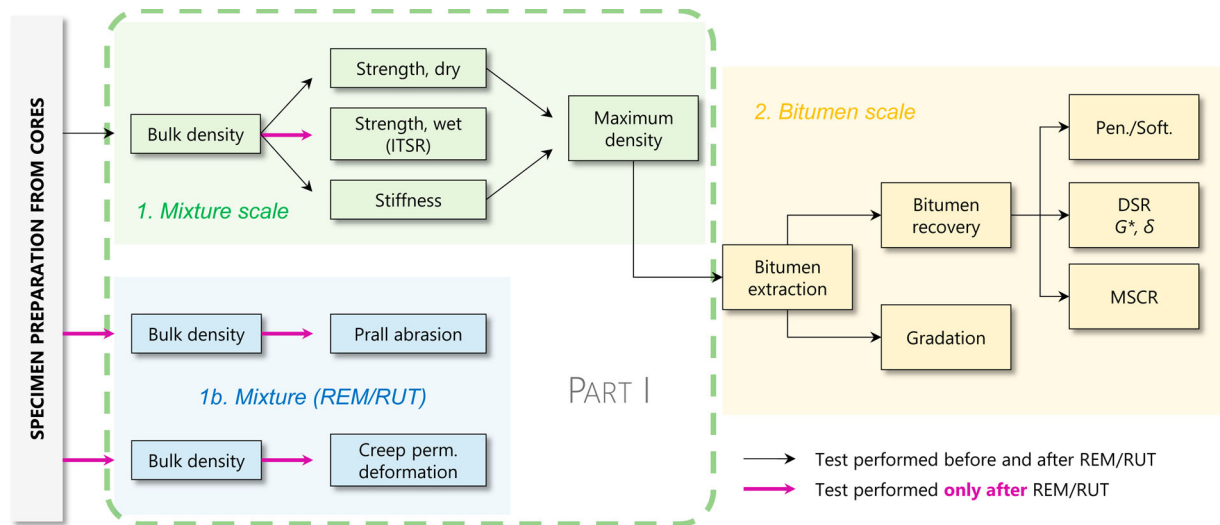


Figure 6. Flowchart of the test plan. Notice that some tests are performed only *after* REM/RUT at the mixture scale (1b). The results at the bitumen scale are presented in Part II.

been studied especially for fracture tests and different specimen sizes and thicknesses, and low temperatures (Stewart *et al.* 2018, Xiongzhou *et al.* 2021); generally, a thickness of ~30 mm was in the lower end of acceptable performance ranges. However, it should be acknowledged that potential localised specimen size effects may be in effect, and perhaps responsible for part of the variability in performance. At the same time, specimen sizes were traditional and according to standards.

The decisions limiting the target specimen thickness were taken at the beginning of the project when only the cores from Ylöjärvi and Kilvakkala before REM/RUT had arrived at the laboratory. Ultimately, no other materials before or after REM/RUT presented limiting conditions of even lower thicknesses.

5. Laboratory test results

5.1. Characterisation of the specimens

The dimensions of the specimens were measured accurately after sawing and drying. These include four measurements of thickness (distributed evenly around the perimeter of the specimen) and six measurements of diameter (surface, mid-height, and bottom, across two perpendicular diameters of the specimen). Some comments are presented next regarding the thickness of the specimens after sawing. The thickness tolerance provided in the standards is ± 2 mm. The variability of the specimens was relatively high but within limits.

- *Thickness of strength specimens:* Only the AV specimens were tested after REM/RUT, half of them in wet conditions. A target thickness of 35 mm (except for **PAB**) was selected because of thickness limitations in the first cores that were received. The value of 35 mm is the minimum by the standard. **PAB** thickness was set at 30 mm before and 45 mm after REM/RUT, aiming for an expected

strength closer to the order of magnitude of the other materials.

- *Thickness of stiffness specimens.* The selected target thickness was 32 mm (except for **PAB**) due to thickness limitations. The target for **PAB** was 30 mm before and after REM/RUT.
- *Thickness of Prall specimens:* This test was performed only after REM/RUT. The target thickness was 30 mm.
- *Thickness of creep specimens:* This test was performed only after REM/RUT. The specimens were combined in pairs, and each pair was mounted as one test of permanent deformation. The target thickness per specimen was 30 mm. The specimens from Ylöjärvi REM were about 4 mm below the target of 30 mm.

Diameters: Two nominal core diameters were received for the project: 100 mm ('small') and ~150 mm ('large'). On average, the small cores had a lower actual diameter ranging from 98.5–99.7 mm. The dispersion in diameter increased for all materials after REM/RUT. It was largest in Ylöjärvi REM (**PAB*** AV), Kilvakkala RUT-REM (**FEP*** and **KB*** – this dispersion was affected by the presence of large amounts of bitumen on the sides of the cores), and Oulu REM (**OKTO AC*** and especially **OKTO SMA***), with coefficient of variation (CV, ratio of standard deviation to the average) larger than 0.25%. On the other hand, the 'large' cores had an average diameter of 143.5 mm, except for the Oulu cores, which had a diameter of 149.5 mm. The dispersion in this set was relatively lower than for the small cores, and it was highest for Ylöjärvi REM **REF*** and **OKTO SMA*** (CV above 0.20%). The increase in uncertainty of the diameter after REM/RUT suggests that the materials may be softer and more malleable after this process.

5.2. Change in upper layer thickness during remix/rut-remix

Before sawing the specimens, an examination was conducted to measure the 'available' upper layer thickness for every

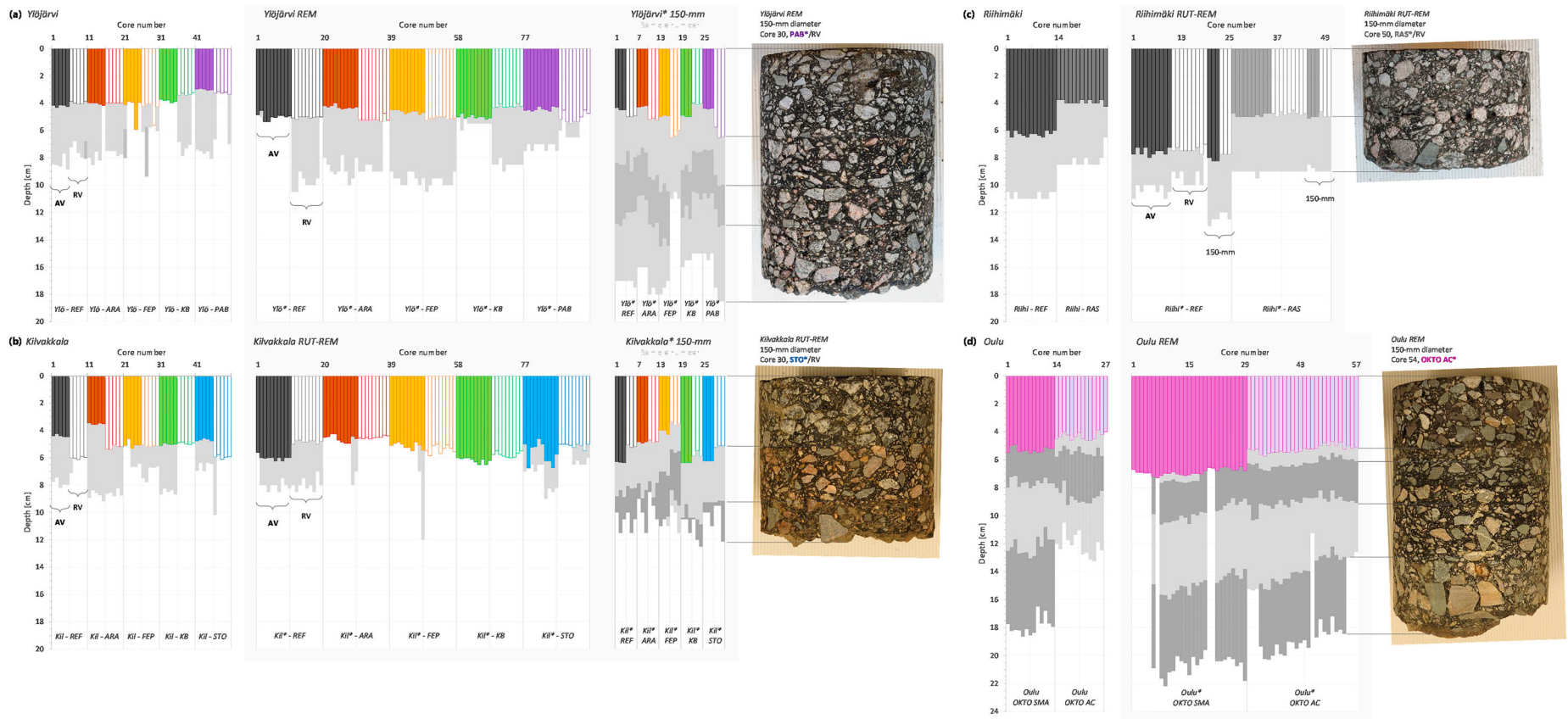


Figure 7. Layer thickness of all cores from the project, before and after remix/rut-remix. Up to four layers were identified. (a) Ylöjärvi, (b) Kivakkala, (c) Riihimäki, (d) Oulu.

Notes: Notice the AV/RV distinction when applicable. Vertical axes are shown to scale. 100-mm and 150-mm diameter cores are presented together in Riihimäki RUT-REM and Oulu REM. Notice the spatial correlation in Oulu REM.

core. It was found that **FEP** had the largest variability in thickness (particularly **Ylö-FEP** and **Kil-FEP***), with CV above 10% in several cases, when the average for most other materials was around 5%. Based on these measurements it was possible to establish an average change in thickness due to the treatments. **Figure 8** summarises the change in thickness of the upper layer after remix/rut-remix for all materials.

In most cases, REM/RUT increased the thickness of the upper layer of the road. Considering that on average, about 25 kg/m² of new mixture are added during remix, an average increase of 1 cm may be expected. In fact, values around and above 1 cm were measured for most materials under REM (except **Ylö-ARA/RV**, **FEP/AV**), and also for RUT-REM in Riihimäki. On the other hand, RUT-REM in Kilvakkala produced remarkably uneven results between the edges of the rut for **Kil-REF**, **ARA**, and **STO**, and almost no change for **Kil-FEP**. Interestingly, the *average* change under RUT-REM in Kilvakkala was close to 0 between the edges of the rut (except **Kil-KB**). This result is consistent with the concept of rut-remix, as this treatment aims to keep the existing thickness of the road even around the ruts. As it will be presented later, large differences in air voids exist between the AV and RV locations in Kilvakkala. **PAB** and **OKTO SMA** increased their thickness the most, suggesting high amounts of added mixture during REM.

These results provide an overview of the differences that may exist in the construction procedures used by the contractors, as well as the amount of mixture added during REM/RUT. These results can be later revisited in conjunction with the bulk and air void content data from the roads of the project.

5.3. Test results. Mixture scale

This section summarises the data measured in the laboratory at the mixture scale. This includes bulk (dry and SSD) and maximum density, air void content, strength (wet and dry), stiffness, Prall abrasion, and creep permanent deformation. The Finnish asphalt standard establishes criteria and quality requirements for roads (PANK 2017). Part of the data will be compared to the limits provided in the standard, with the objective of establishing a frame of reference. When possible, the results before REM/RUT are compared with data reported after the last reconstruction of the road.

5.3.1. Bulk density

The bulk density was measured for all the specimens from the project, following procedure A of the standard (SFS-EN-12697-6 2012). Considerable amounts of data were gathered during the project; data summaries for all cores, while comprehensive, may be overwhelming. Complete, individual bulk results for all specimens are presented in the Appendix (<https://doi.org/10.5281/zenodo.6908195>). To reduce the complexity and to facilitate the comparison among materials and the analysis of results, the average and CV were calculated per material, distinguishing AV/RV when it was the case. The summary of bulk density averages and CV is presented in **Figure 9** for all materials. Standard deviation data is included as well on the plots, plus and minus one standard

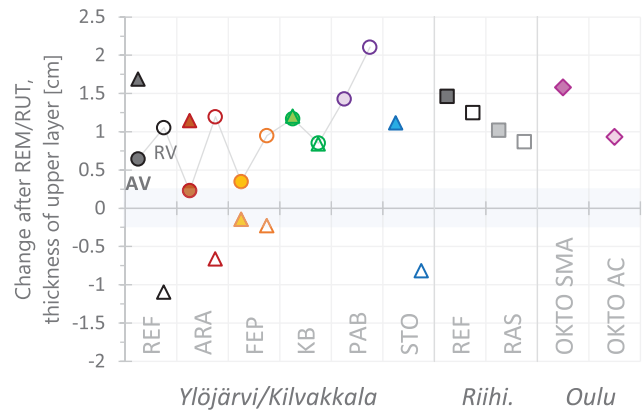


Figure 8. Average change in thickness of the upper layer after remix/rut-remix, all materials.

Notes: Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line. AV and RV are locations on the lane.

deviation from the average. In the figures that follow, the values from the *Ylöjärvi* road (●) are linked with a line to increase clarity. Both the standard deviation error bars and the CV are presented, to provide a sense of scale to the variability of each material in context, to facilitate the identification of materials with high variability, and to appreciate changes in variability after recycling.

The bulk of the materials ranged between 2.300 Mg/m³ (the lowest densities, **Riihi-REF***, **RAS***), up to 2.600 (the highest densities, **OKTO SMA**). This range represents about 11% of the maximum average bulk that was measured. The CV of bulk was at most 1% (**Ylö-REF*/RV**, **STO*/RV**, **Riihi-REF*/RV**, **RAS*/RV**); that is, the largest variabilities were always found *after* REM/RUT. These high CV correspond to standard deviations of the order of 30×10^{-3} Mg/m³; this value is close to the upper limit of repeatability presented in the standard, $8-28 \times 10^{-3}$ Mg/m³ (SFS-EN-12697-6 2012). All other values are below this limit.

5.3.1.1. AV/RV differences in bulk density. For some materials, the average bulk differed importantly between AV and RV locations. In some materials the absolute difference in AV/RV average surpassed 1% (**Ylö-REF**, **ARA***; **Kil-ARA**, **REF***, **FEP***, **KB***, **STO***, **Riihi-RAS***). In Kilvakkala (RUT-REM) the density of all materials changed 1–3.5% between AV and RV. These changes are quite drastic in comparison with the results from Ylöjärvi (REM), which were quite even. Recall that Kilvakkala received rut-remix, so AV and RV here represent the edges of the rut. The difference is also clear in Riihimäki (RUT-REM), where there was a 1–1.5% change between AV and RV for both materials. It is apparent that these differences are heightened in the roads that were treated with rut-remix (Kilvakkala and Riihimäki). The introduction of a marked difference in the density across the rut, with ensuing effects on performance, seems to be characteristic of the RUT-REM treatment.

5.3.1.2. Overall change in bulk density caused by remix/rut-remix. It is of interest to observe the *change* in material properties caused by REM/RUT. One way to evaluate it is to

compute the percentage change in average properties before and after REM/RUT; i.e. for bulk density, the values from Figure 9(a). The percentage change in average bulk due to REM/RUT is presented in Figure 10.

Depending on the material and location, the bulk density after REM/RUT increased as much as 5% or it reduced as much as 7%. REM seems more likely to maintain or increase bulk density. In contrast, RUT-REM affects the edge locations of the rut differently: the AV and RV values may alternatively increase, remain constant, or decrease with respect to the original density. Usually, one of the edges of the rut changed only little; however, this was not the case in Riihimäki. The bulk density of the materials was affected differently by REM/RUT:

- In Ylöjärvi, where the bulk was originally lowest, the density of **ARA** increased the most, followed by **REF/AV** and **FEP**. The bulk of **REF/RV**, **KB** and **PAV** changed or reduced slightly.
- In Kilvakkala, where the bulk was originally intermediate, rut-remix caused the density of most materials to increase at one edge of the rut (AV location; **ARA**, **FEP**, **KB**), but to reduce at the other edge (RV location; **REF**, **ARA**, **KB**, **STO**). **FEP** density increased at both edges of the rut, although unevenly. Previously it was seen that the thickness of **FEP** also increased along the rut, and that the thickness of this material was highly variable.
- In Riihimäki, the density of **REF** and **RAS** was greatly reduced by rut-remix (more than 4%). This was later related to poor compaction.
- In Oulu, the density of **OKTO SMA** reduced 2% after REM, while the density of **OKTO AC** remained approximately constant.

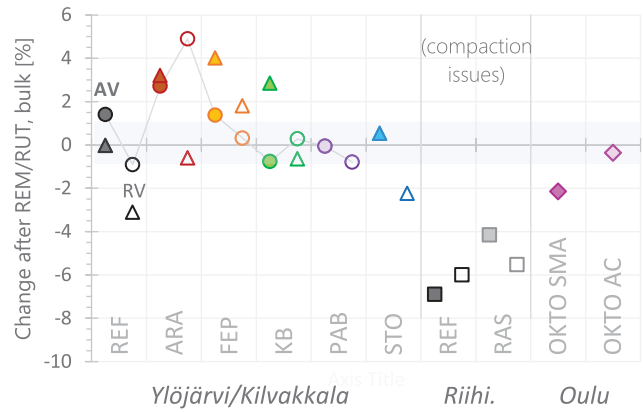


Figure 10. Percentage change in average bulk (dry) density after remix/rut-remix. Notes: Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

In the sites where the average bulk density decreased after REM/RUT, the change may be explained by the addition of a considerably less dense material. This was confirmed to be the case for **OKTO SMA***, where the cores were numbered according to their location. Here it was observed that one end of the line of cores kept high bulk values (similar to before REM), and the bulk reduced progressively along the line. Therefore, in this case cores to the middle and the end of the line would be more representative of the remixed material. This change also caused the variability of **OKTO SMA*** to appear high.

It is also possible to observe the effect of REM through the changes in the variability of the properties (CV, Figure 9b). In Ylöjärvi and Oulu, the treatment contributed to an increase in the variability of the properties for most materials; the

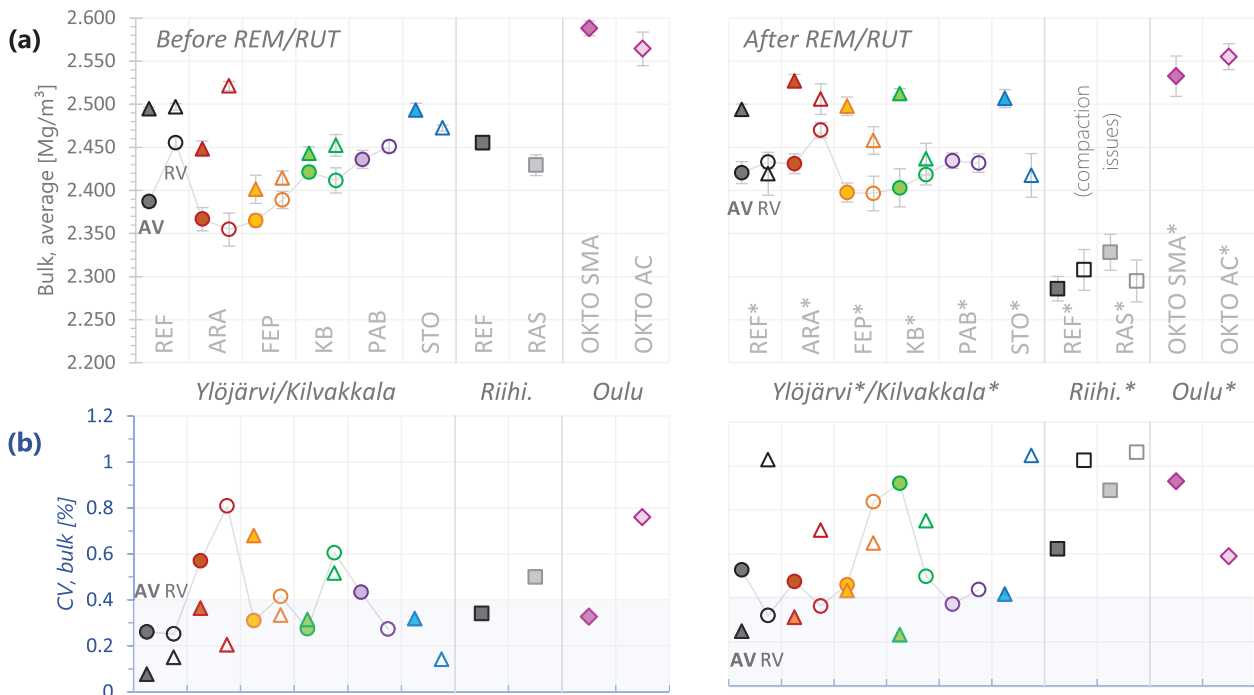


Figure 9. (a) Averages ± 1 standard deviation, and (b) CV of the bulk density of all materials, before and after remix/rut-remix.

Notes: Ylöjärvi (●), Kilvakkala (▲). To facilitate the distinction among the data series, the values from Ylöjärvi are linked with a line.

exceptions were Ylö-ARA, Ylö-KB/RV, PAB/AV, and OKTO AC. On the other hand, RUT-REM had a strongly differentiating effect: in Kilvakkala, it increased the variability of RV specimens of all materials considerably, while it mostly maintained or even reduced the variability of AV specimens. In Riihimäki, RUT-REM increased the variability of the AV and RV locations.

5.3.1.3. Overall change in maximum density caused by remix/rut-remix. Remix and rut-remix also affected the maximum density of the materials, slightly and in an erratic way, depending on the properties of the mixture added during the treatment. The maximum density before and after treatment is summarised in Figure 11. The percentage change in maximum density after REM/RUT for all materials is presented in Figure 12.

In most cases, REM/RUT caused the maximum density to decrease or increase within $\pm 1\%$; however, OKTO SMA was the exception (it reduced almost 5%). The materials in Ylöjärvi were the least affected by REM; the change in maximum density was mostly within $\pm 0.5\%$ except for Ylö-ARA/RV and FEP/RV. RUT-REM had a comparatively larger effect on the maximum density in Kilvakkala and Riihimäki, inducing changes above $\pm 0.2\%$ for all materials and locations except for Kil-REF/AV. The changes in maximum density happened over a smaller scale than the bulk; therefore, they are also within the repeatability limits presented in the standard.

As mentioned previously, a decreasing maximum density may result from adding material with a lower density than the original material during REM/RUT. This was evidenced in the bulk data measured from Oulu OKTO SMA*, where it seemed apparent that the additional mixture used for REM did not include the OKTO slag material. Consequently, the added mixture had a considerably lower density (measured value: 2.435 Mg/m^3) and as a result, the maximum and dry bulk of OKTO SMA* reduced greatly after REM. It was also found that the maximum density of the OKTO SMA* specimens was equal to their bulk and SSD densities (bulk SSD was measured for the Prall abrasion specimens). As a result, the air void content for this material was mostly estimated to be 0%, as will be presented later. This may be a result of excessive compaction. Additionally, the fact that the bitumen

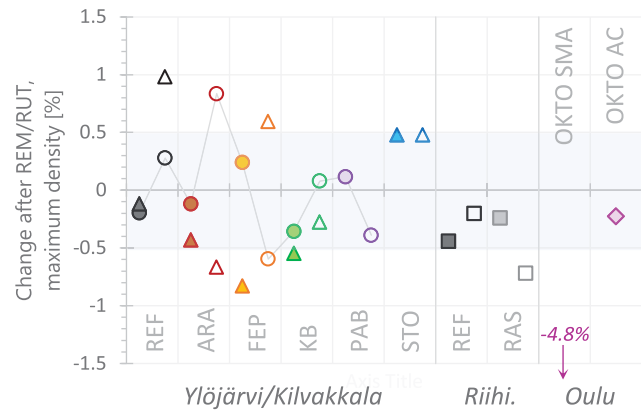


Figure 12. Percentage change in maximum density after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

content of this material was quite high (above 6%, see Part II) was consistent with a higher susceptibility to permanent deformations evidenced later. The average maximum density measured for this material is representative of most of the cores, except for the first 150-mm specimens whose density appears to be higher than the others, and closer to the value before REM.

Nevertheless, for most materials (except OKTO SMA) the changes measured in maximum density were relatively small, and the changes in bulk are likely due to compaction after REM/RUT. This may be better observed after the air void contents in the next section. For example, it is also clear from Figure 12 that the drastic reduction of dry bulk that was observed previously in Riihimäki (Riihi-REF, RAS) was not due to the added mixture.

5.3.2. Air void contents

The air void content of the specimens was estimated from the bulk density (measured individually for all specimens) and the maximum density most applicable to the specimen, i.e. the average maximum density of the corresponding AV or RV material. This was done because of the large number of specimens tested in the project. Nevertheless, the bulk dry and SSD were measured for several specimens of all materials after REM/RUT (Prall abrasion specimens), and for most materials the results were comparable. In some cases where differences

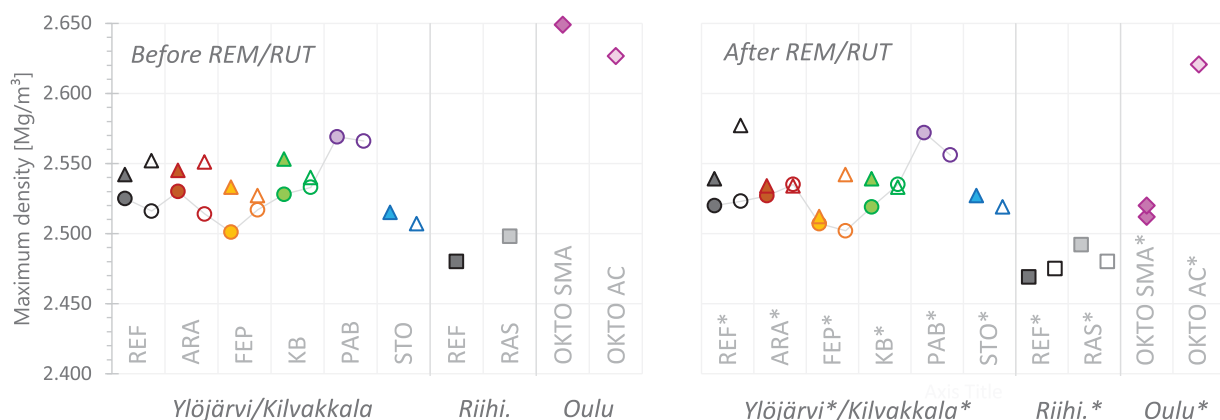


Figure 11. Maximum density, all materials. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

were observed, the bulk SSD seemed lower than the dry bulk for some specimens in Kil-REF*/RV, KB*/RV, and Riihi-REF*. These materials have in common that their air void contents are high (Kil-REF* and Riihi-REF* were considerably above standard limits), signalling issues with compaction. Therefore, the already high air void content may be slightly higher for some specimens of these materials.

5.3.2.1. Average and variability of air void contents. The average and variability (CV) of the air void contents for all materials are summarised in Figure 13, along with the upper and lower limits presented in the Finnish asphalt standard for dense and SMA asphalt concrete (PANK 2017). The air void contents for all specimens are presented in the Appendix (<https://doi.org/10.5281/zenodo.6908195>).

Air void contents varied considerably among the roads, ranging from as low as 0-1% to 6-8%. Before REM/RUT, some materials were above the limit provided by the standard. Ylö-ARA had 6.5% air voids, the highest of the materials before REM/RUT, and about 1.5% above the suggested limit. Other materials were quite close to the limit, i.e. FEP in both roads (Ylöjärvi and Kilvakkala), and PAB. High air voids were also measured at the middle of the REF lane in Ylöjärvi (5.5%), but this was not the case at the edge of the lane.

For most materials in Ylöjärvi there was good agreement between AV and RV air void contents, before and after REM (the exceptions were Ylö-REF, and ARA*). However, in Kilvakkala there were large internal differences after RUT-REM between the values measured at the edges of the ruts, above 250% for all materials. These large variations are consistent with the uneven thickness and densities at the edges of the rut presented before. The AV/RV differences were not too pronounced in Riihimäki after RUT-REM.

In Kilvakkala after RUT-REM, one side of the rut in Kil-REF* was above the limit, but this was not the case for the other end of the rut. At the same time, part of the rut for some materials in Kilvakkala had air voids that may be considered too low (below 1%) after RUT-REM, i.e. Kil-ARA*/AV and FEP*/AV. However, air voids in the opposite side of the rut were higher and within limits, which may indicate that the average air void content at the centre of the rut is acceptable. Particularly for Kil-ARA* the average air void content after RUT-REM was very low (below 1%). The air void contents of the materials in Ylöjärvi were mostly within limits after REM. PAB kept close and slightly above the upper limit (~0.5% over), before and after REM.

The air void content of the materials in Riihimäki (Riihi-REF* and RAS*) was considerably above the upper limit after RUT-REM. The thickness of the upper layer in this site increased 1 cm evenly after RUT-REM (see Figure 8). The resulting high air voids may indicate the addition of too little new mixture to fill the rut during rut-remix, and/or insufficient compaction.

OKTO SMA* had a very low air void content below the lower limit for SMA. This material may have been over compacted during REM. Together with a high bitumen content, this creates a risk of bleeding (evidenced in the cores). The penetration of the binder after REM was later found to be 60 dmm (see Part II), among the highest in the project. Taken together, these characteristics may indicate an inadequate binder for the mixture, or excessive softening during REM. On the other hand, contrary to what was expected, the gradation of OKTO AC was later found to be consistent with an SMA mixture (see Part II). The air voids of this material were within the SMA limits as well.

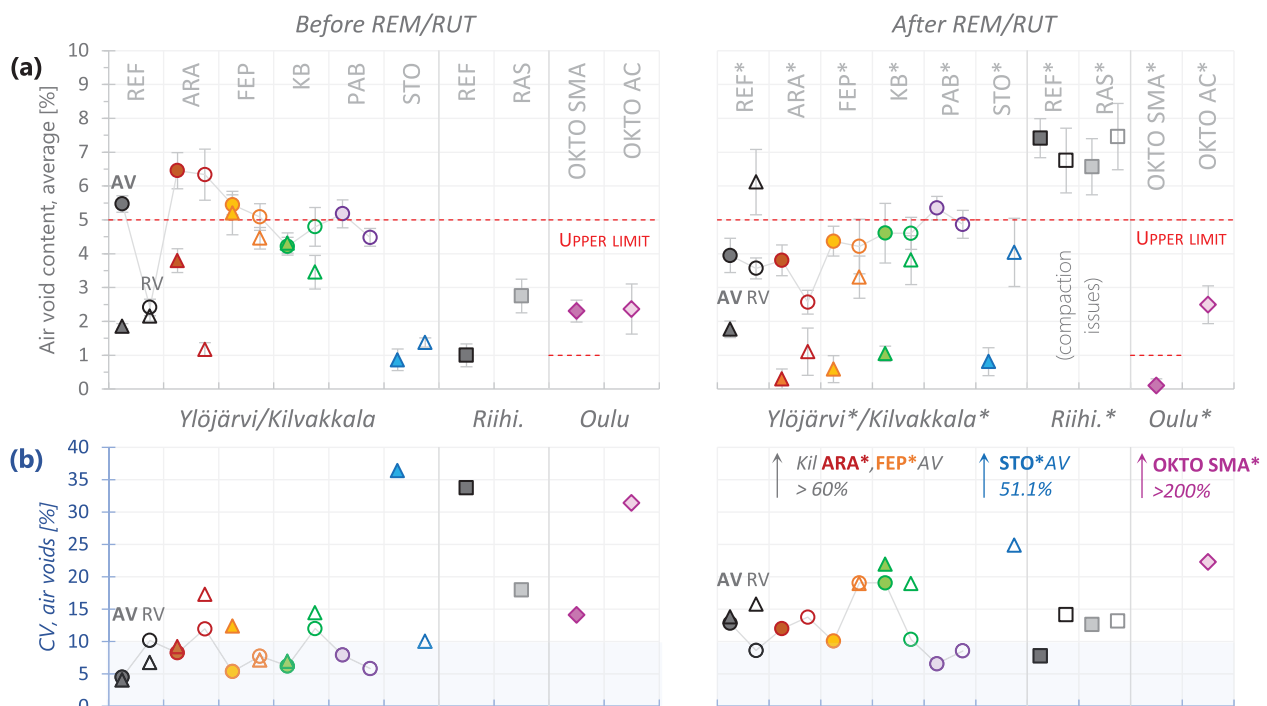


Figure 13. (a) Averages ± 1 standard deviation, and (b) CV of the air voids content for all materials before and after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

For most materials, the variability of air void content increased after REM/RUT (Figure 13b). When this was not the case, the reduction was mostly because of a large increase in average; i.e. the CV of air voids in Riihimäki reduced after rut-remix, but its average increased five-fold. Notice also that an exceptionally high CV in air voids for some materials was caused by a low average (below 1%, i.e. Kil-ARA*/AV, FEP*/AV, STO*/AV, OKTO SMA*). PAB was the material that saw its variability less affected during REM. The largest standard deviations in air void content, of the order of 1%, were measured for Kil-STO*/RV and Kil-REF*/RV (both after REM/RUT). This value is still below the 2.8% limit suggested by the Finnish asphalt standard (PANK 2017).

5.3.2.2. Change in air void content during REM/RUT. The change in average air void content after REM/RUT is illustrated in Figure 14 for all materials. In most cases, a material with similar density to the original material was added during REM/RUT. This suggests that the changes observed in air voids are mostly due to differences in compaction.

After REM, the air voids mostly reduced or changed slightly for Ylö-FEP, KB, PAB, and OKTO AC (within -20 – 10%). At the same time, Ylö-REF and ARA were affected more importantly by REM. ARA reduced its air void content around 50% after REM. Ylö-REF was ‘homogenized’; before REM, its AV and RV values were quite different (5.5% and 2.5%) but after REM they were both close to 4%. OKTO SMA appears to have been over compacted during REM.

RUT-REM induced a highly heterogeneous result. After this treatment, air voids were mostly maintained to one side of the rut (either AV or RV) while the other side experienced a large change in air void content; this was true for all materials in Kilvakkala. The change in air voids is likely gradual across the rut. Meanwhile, both materials in Riihimäki (Riihi-REF and RAS) increased their air voids uniformly along the rut after RUT-REM, suggesting a lack of compaction or too little additional mixture. In particular, Riihi-REF experienced a major increase, from 1 to 7% air voids (more than 500% increase).

The situation after the previous reconstruction of the roads was also assessed (i.e. before the current REM/RUT) using

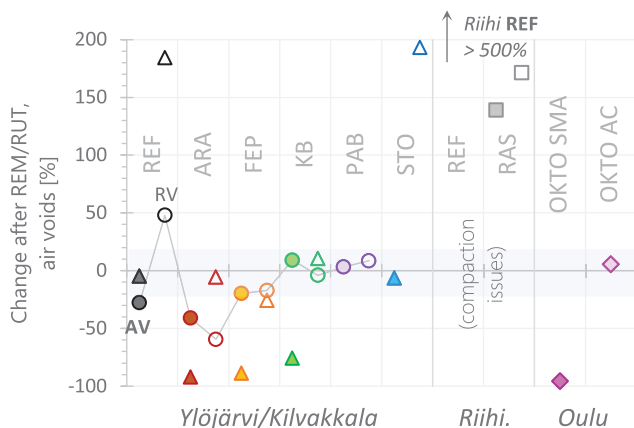


Figure 14. Percentage change in average air void content after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

available data from the first three roads (Rossi 2016, Heinonen 2017, Valkonen 2020):

- In Ylöjärvi, the air void content changed for most of the materials in the five years since the reconstruction (2015): **ARA**, **FEP** and **KB** increased 2–3% in average, while **PAB** decreased 2%. **REF** kept the original air void content (RV location), while the centre of the lane increased almost 3% (AV location).
- In Kilvakkala (2017 reconstruction), **ARA**, **FEP** and **KB** experienced less drastic changes or remained relatively constant before rut-remix. Only **REF** and **STO** decreased their air void contents by 2%.
- The materials in Riihimäki (2015 reconstruction, **REF** and **RAS**) kept a relatively constant air void content during the life of the road, with a slight increase in the case of **RAS**.

5.3.3. Strength at 10°C

The specimens were tested for dry and wet strength in the indirect tensile strength configuration (SFS-EN-12697-23 2017). While all the specimens before REM/RUT were tested, only the AV specimens after REM/RUT were tested due to time constraints and the number of available specimens. The averages (dry strength) and CV of the strength tests per material are summarised in Figure 15. The complete, individual strength results are presented in the Appendix (<https://doi.org/10.5281/zenodo.6908195>).

5.3.3.1. Dry strength. Before REM/RUT, there was remarkable consistency among the average values for AV and RV locations in Ylöjärvi and Kilvakkala. These values differed by relatively little (the difference was highest for Kil-ARA, 9%). An important change was noted after REM/RUT: while the materials in Ylöjärvi and Oulu seemed to maintain similar strengths after REM, the strength after RUT-REM increased considerably in Kilvakkala and reduced almost as much in Riihimäki. This is better observed as a percentage change in strength (dry), summarised in Figure 16.

The results suggest that REM affected the materials’ strength moderately. The strength remained constant (Ylö-REF, KB, OKTO SMA) or increased by at most 20% (Ylö-ARA, FEP, OKTO AC). The 50% increase for PAB can be attributed to the increase in thickness of the specimens, which were 1.5 times thicker than the other materials. Notice that even so, the average strength of PAB* after REM was still below the average of all other materials in Ylöjärvi and Oulu; therefore a more realistic increase for PAB* is likely around or below 20%.

The effect of RUT-REM was considerable but different in Kilvakkala and Riihimäki. The strength of all the materials in Kilvakkala increased by about 50%. The large increase in strength was likely caused by the low values of air voids created by the rut-remix towards one edge of the rut (AV location). In this location of the rut, the air void contents were greatly reduced by RUT-REM to values below 2% (see Figure 13a, average after RUT-REM). To the opposite side of the rut, air voids were 1–4% higher, and the air void content is likely intermediate at the centre of the rut. In fact, a strong correlation existed between air voids and dry strength after REM/RUT

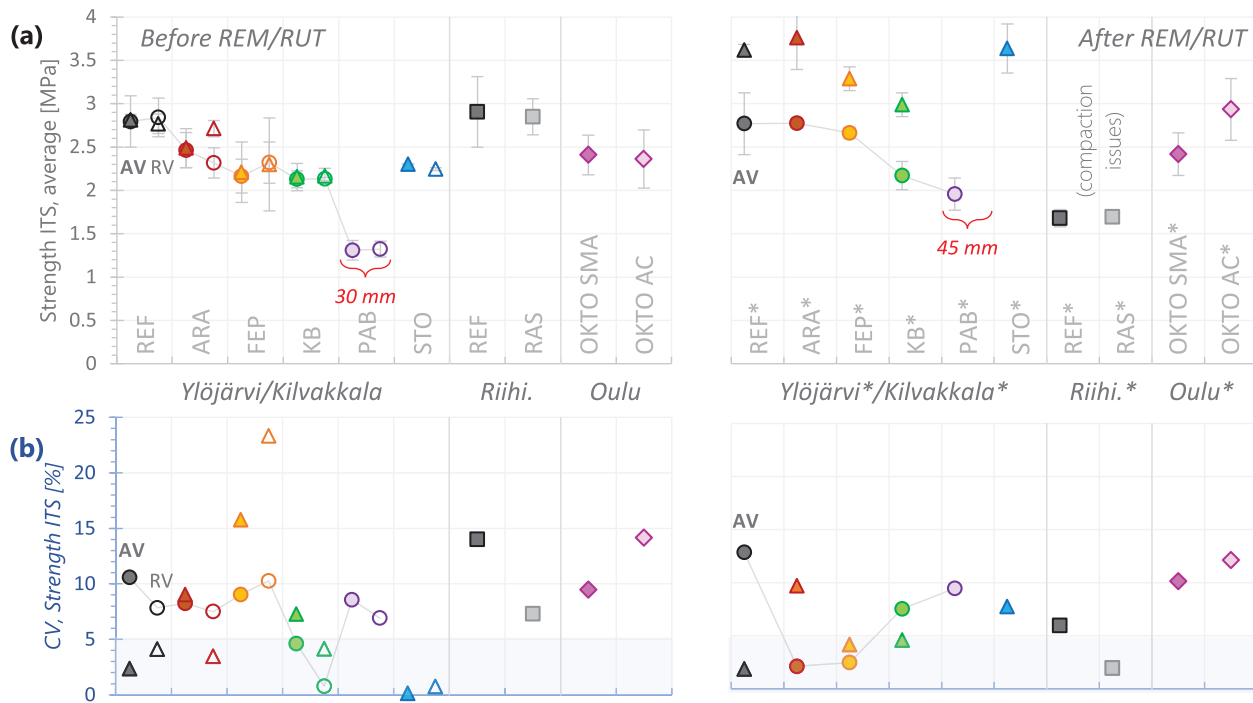


Figure 15. (a) Averages ± 1 standard deviation, and (b) CV of the dry strength, for all materials before and after remix/rut/remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.
 Notes: Only AV specimens were tested after REM/RUT (3 specimens per material). Specimen thickness was 35 mm; note the different thicknesses of the PAB specimens (30 mm before and 45 mm after REM). The CV after REM/RUT is calculated based on only 3 values per material.

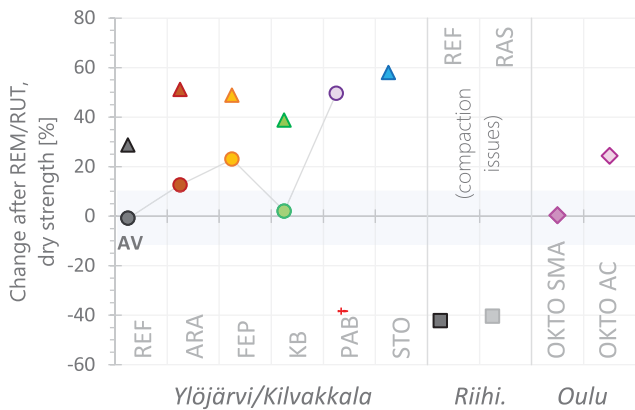


Figure 16. Percentage change in average (dry) strength after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.
 Notes: (†) PAB specimens had a different thickness (30 mm before and 45 mm after REM); all other specimens were 35 mm thick. Only AV specimens were tested after REM/RUT.

for most materials, as shown to the right of Figure 17. These results suggest that the strength at the centre of the rut in Kilvakkala may be around 0.5 MPa lower than measured. This reduced strength would be more representative for the materials after RUT-REM, with still a ~20% increase after RUT-REM. The correlation between strength and air voids was not apparent before REM/RUT.

The correlation between air voids and strength has been explored before by means of the fracture energy. This energy is obtained from the area below the load vs. displacement curve of a strength test. High fracture energies of the order of 6–8 kJ/m² were measured for specimens with air voids below 1%; the energy of fracture reduces as air void content

increases, in a similar trend to that of Figure 17 (right-hand). This was found consistently among a set of materials before and after remix (Pellinen and Makowska 2018).

The strength of Riihi-REF* and RAS* reduced by 40% after RUT-REM. Once again, the low strengths may be attributed to issues with the compaction processes that lead to very high air void contents after rut-remix. The data also indicates that larger strengths may be expected for OKTO SMA after REM, if the compaction process is more appropriate and allows for larger air void contents.

The variability of the results was below 10% for most materials (Figure 15b); this value was exceeded only by Kil-FEP, Riihi-REF, Ylö-REF*, and Oulu-OKTO AC (before and after REM). The variability of STO was remarkably low. Contrary to what was observed for bulk density and air voids, the variability in (dry) strength actually decreased after REM/RUT for Ylö-ARA, FEP, OKTO AC, Kil-FEP, Riihi-REF, and RAS, and it remained around the same level for several materials.

5.3.3.2. ITSR. Six AV specimens per material were tested for strength after remix/rut-remix. Of these, three were conditioned wet to establish the ITSR ratio of strength under wet to dry conditions. This index can be used as a measurement of the susceptibility to moisture damage of the remixed materials. The ITSR measured for the materials after REM/RUT is presented in Figure 18. The ITSR values were established only after REM/RUT.

It is apparent that the type of treatment has an important effect on the resulting moisture sensitivity of the materials. After REM, most of the materials in Ylöjärvi and Oulu had

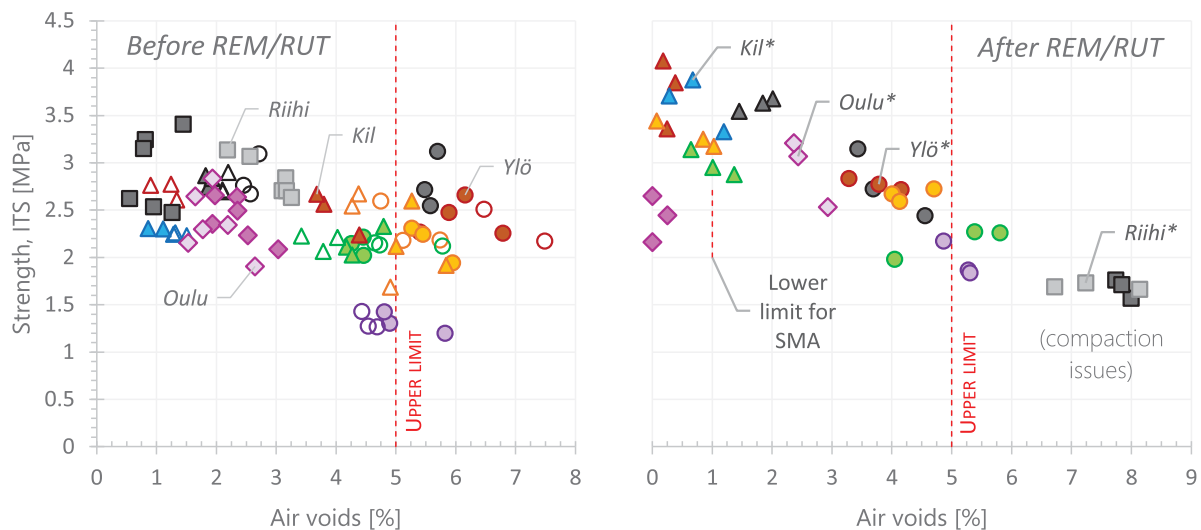


Figure 17. Dry strength versus air void content for all materials, before and after remix/rut-remix.

Notes: PAB specimens had a different thickness than the target of 35 mm; it was 30 mm before and 45 mm after REM. Notice only the AV specimens were tested after REM/RUT.

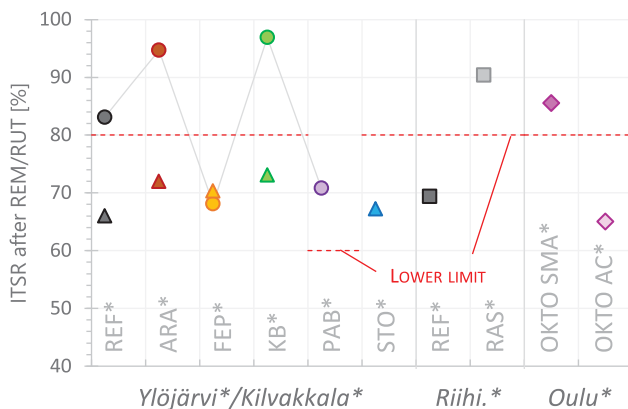


Figure 18. ITSR for all materials after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line. The lower limit is provided by the Finnish Asphalt Standard (PANK, 2017).

ITSR larger than 80%, that is, relatively good resistance to moisture damage. **ARA*** and **KB*** seemed to resist moisture effects better than **REF*** and **OKTO SMA***, but these materials were still above the limit. **PAB*** had ITSR 70%, above its limit. However, **Ylö-FEP*** and **OKTO AC*** had ITSR close to 70%, below the lower limit proposed by the standard. On the other hand, RUT-REM induced a greater susceptibility to moisture damage in the reference and most of the modified/alternative materials. **RAS*** was the only material to comply with ITSR requirements after RUT-REM. RUT-REM caused all the materials in Kilvakkala and Riihimäki (except **RAS***) to have an ITSR near or below 70%, which is below the limit. No correlation was found between the ITSR after REM/RUT and the air void content of the specimens.

Regarding the situation after the previous reconstruction of the roads, all materials experienced an increase of 0.5–1.5 MPa in dry strength during the life of the roads (Rossi 2016, Heino 2017, Valkonen 2020), which was 5 years for Ylöjärvi and Riihimäki, and 3 years for Kilvakkala. This behaviour is consistent with aging of the bitumen. On the other hand, at the

time of last reconstruction the ITSR requirements were well met by all the materials. The current results indicate that REM and particularly RUT-REM may negatively affect the susceptibility to moisture of some materials. Specifically, **Ylö-FEP*** and **PAB*** originally had ITSR above 90%, but saw their susceptibility greatly affected by REM (ITSR reduced 20–30%). The same was true under RUT-REM for **Kil-REF***, **ARA***, **FEP***, **KB***, **STO***, and **Riihi-REF***. ITSR of **RAS*** reduced 10%. The presence of aged asphalt, which increases the susceptibility to moisture damage, also contributes to increasing moisture susceptibility.

5.3.4. Stiffness at 10 °C

The stiffness was tested using cylindrical specimens in the indirect tensile configuration (SFS-EN-12697-26 2018). In the test, a stiffness is first calculated along an arbitrary diameter of the specimen. Then, the specimen is rotated 90 degrees, and a second value of stiffness is obtained. According to the standard, a change within –20% to +10% between the two tests is considered acceptable. In this study, however, all the values obtained from the tests were maintained for averaging. This decision was based on the following reasons:

- As mentioned before, the specimens from some roads (Ylöjärvi and Kilvakkala before REM/RUT) were thin because of the original low thickness of the layers. For this reason, the target thickness for sawing was quite low (32 mm) for all materials. It seems from the results that the low thickness was causing a large variability in the response, as several tests surpassed the range of acceptability proposed by the standard. Additionally, we have observed that the materials after RE/RUT are more heterogeneous; from this, it follows that greater variability than usual is expected in the results.
- At the same time, there were many materials in the project, each with relatively few stiffness tests; due to the AV/RV division, some materials had as little as only 2 tests to characterise their stiffness, and sometimes both of the

tests failed the criterion (i.e. Ylö-PAB/RV, REF*; Kil-ARA/RV, Riihi-REF/RV, REF*/RV).

- Ultimately, the interest of the project is to assess the effect of REM/RUT on the materials. All the data points obtained in the laboratory provide a real and representative characterisation of the response that can be expected from the materials before and after REM/RUT.

The average and CV values of the stiffness tests are summarised in Figure 19. The stiffness results for all specimens are presented in the Appendix (<https://doi.org/10.5281/zenodo.6908195>). The stiffness of the materials varies greatly, ranging from ~3000 MPa (lowest stiffness, PAB) to stiffnesses surpassing 10000 MPa (Ylö-REF/RV, and especially after REM/RUT Ylö-REF*, ARA*, Kil-ARA*, FEP*/RV). PAB presented a characteristically low stiffness before and after REM/RUT, and comparatively low values were measured as well for Riihi-REF, REF*, and RAS*. In contrast to the strength results presented before, the differences in AV/RV noticed in previous measurements (such as bulk and air voids) can indeed be observed in the stiffness results. While mostly there is consistency in the stiffness for similar materials among sites, there are some differences in the AV/RV average stiffness of materials. After REM/RUT, differences are above 10% for all materials except STO* and Riihi-REF*.

A considerable number of tests presented a large interval between the stiffnesses in the two perpendicular directions. The materials seemed slightly more prone to fail this criterion after REM/RUT, once again hinting to an increase in uncertainty because of the process. The variability was relatively high, in the 10–20% range for several materials, and even surpassing it. The variability was high even before REM/RUT, on a similar level for all the roads. For most materials, the internal variability in stiffness seems to keep constant or increase

slightly. In future, a larger specimen thickness is suggested whenever possible to guarantee higher consistency for stiffness tests.

The percentage change after REM/RUT per material is presented in Figure 20. It was observed that some materials increased their average stiffness (ARA, KB, PAB, STO, OKTO AC) about 20% or more in average, while others changed relatively little or kept their average (Ylö-Kil-REF, FEP, OKTO SMA). Only Riihi-REF and RAS reduced consistently for AV and RV; similarly to the strength, the stiffness of the materials from Riihimäki (particularly RAS) was affected negatively after rut-remix. It was observed before that these materials have very high air void contents, and it will be seen later that their bitumens are also relatively soft when compared to the other materials of the project (see Part II). There was no apparent correlation between air voids and stiffness.

It would be possible to establish a preliminary analysis on the change of stiffness and strength, as proposed by Pellinen (2004). In this work, the author proposes a four-quadrant methodology where increases in strength and stiffness are associated with lower susceptibility to rutting. In this project, most materials either maintained or increased strength and stiffness after REM/RUT, indicating that overall, these treatments may be reducing the susceptibility of the materials to rutting. However, at the bitumen scale the opposite trend was found (see Part II).

Based on the available data (Rossi 2016, Heinonen 2017, Valkonen 2020), the stiffness of all materials increased during the life of the roads after last reconstruction (Ylöjärvi and Riihimäki, 5 years; Kilvakkala, 3 years). The increase was between 2000–6000 MPa depending on the material. This increase is likely due to aging of the asphalt mixture. Only Riihi-REF

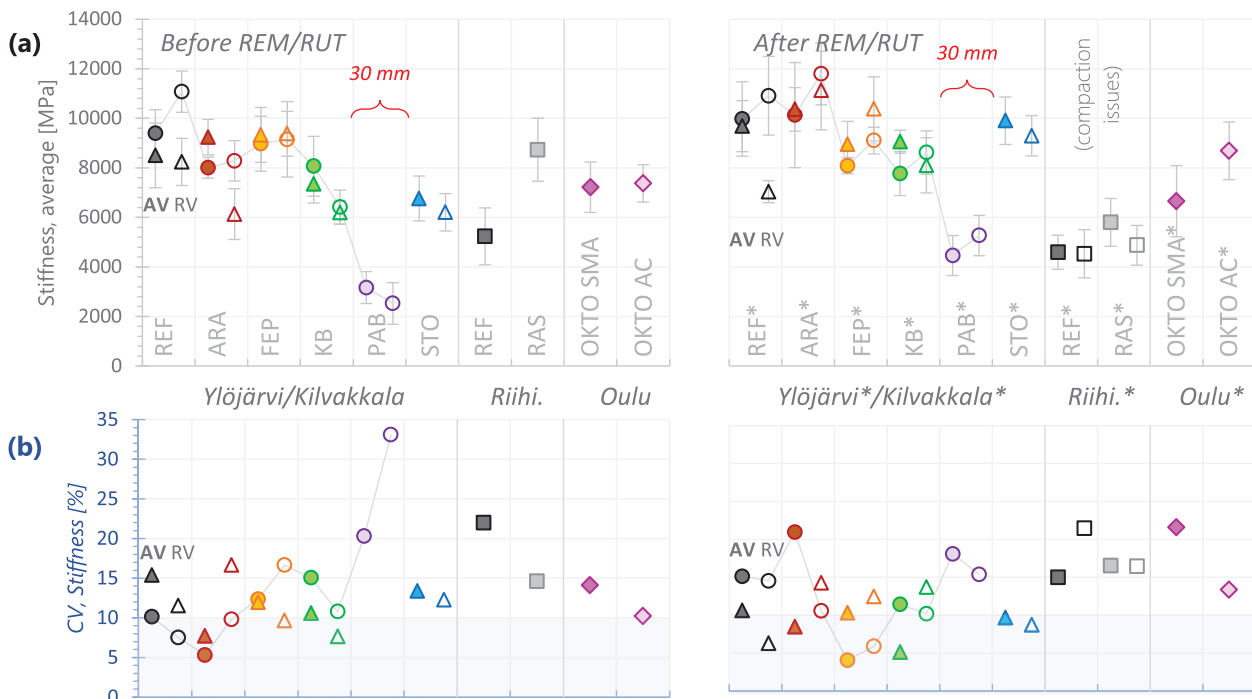


Figure 19. (a) Averages ± 1 standard deviation, and (b) CV of the stiffness, for all materials before and after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line. Note that the PAB specimens had a slightly lower thickness (30 mm); all other specimens were 32 mm thick.

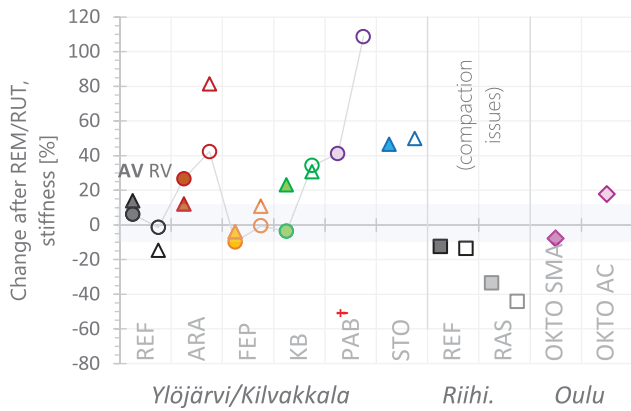


Figure 20. Percentage change in average stiffness after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

Notes: (†) **PAB** specimens had a lower thickness (30 mm) than the other specimens (32 mm).

reported a stiffness in level with the original values after last maintenance.

5.3.5. Prall abrasion after REM/RUT

The Prall abrasion test was conducted on the specimens after REM/RUT to assess their relative susceptibility to damage due to studded tires, following Method A of the standard (SFS-EN-12697-16 2016a). This type of damage is of interest in Finland, and it is characteristic of countries with cold weather. Four specimens were prepared and tested per material. The average and CV are summarised in Figure 21 (individual specimen results in the Appendix [https://doi.org/10.5281/zenodo.6908195]). During some of the tests, the hose was blocked or partially blocked. These tests are marked

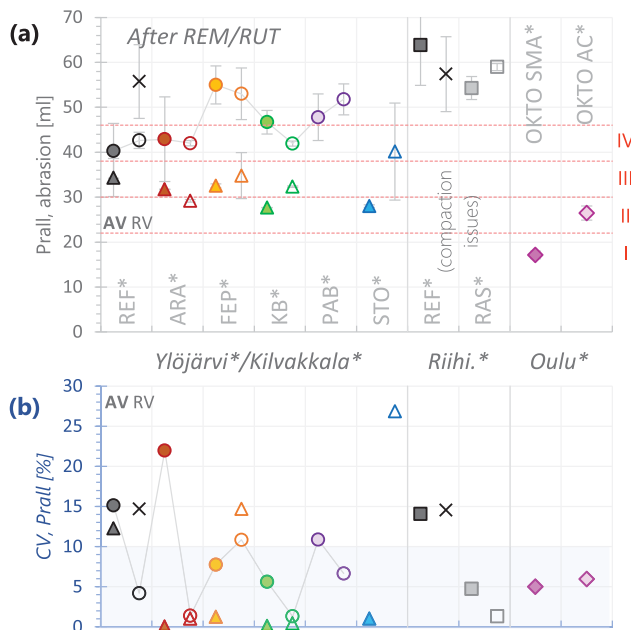


Figure 21. (a) Averages ±1 standard deviation, and (b) CV of the Prall/abrasion, for all materials after REM/RUT. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

Notes: CV of all materials (except **OKTO SMA*** and **OKTO AC***) was calculated only from two values. The abrasion classes (I to IV) shown to the right are defined in the Finnish Asphalt standard (PANK, 2017).

with an X. Notice that only two test results were available for most materials to obtain the CV, except for **OKTO SMA*** and **OKTO AC***, with four test specimens each.

After REM, Ylö-FEP* and PAB* were the most susceptible to abrasion, falling mostly outside class IV as defined by the Asphalt standard (PANK 2017). They were followed in classes III-IV by Ylö-KB*, ARA* and REF*. The results suggest that REM in Ylöjärvi may have been detrimental to the resistance to abrasion of the materials. In contrast, **OKTO SMA*** (class I) and **OKTO AC*** (class II) seemed to hold very good abrasion resistance after remix, likely due to their slag aggregates. On the other hand, after RUT-REM the materials in Kilvakkala mostly presented good resistance to studded tires. The majority of the tests fell in classes II and III (except Kil-REF*/RV-blocked hose, and one test of STO* RV). In this road, rut-remix seemed to produce results that are favourable under studded tyres. Additionally, in Kilvakkala the consistency among the tests was high, which was reflected in very low CV values for most materials. However, it is important to note that most of the CV values presented in the figure were obtained from only two tests.

The materials in Riihimäki (Riihi-REF* and RAS*) were highly susceptible to abrasion after RUT-REM. In the case of Riihi-REF*/RV, both tests were blocked, making it difficult to assess the resistance of this material to abrasion. Nevertheless, the same material at the opposite side of the rut presented the highest average abrasion of all the materials. Overall, the abrasion results from Riihimäki are in line with what was observed before (strength and stiffness); the high air void content of these materials has negatively affected the performance. In fact, the Prall abrasion of the specimens appears to be strongly correlated to the air void content, regardless of the material. This is apparent from the summary of Prall abrasion values vs. air void content, as presented in Figure 22. This relationship has been observed and reported before (Makowska and Pellinen 2016, Pellinen and Makowska 2018)

From this figure, it can be concluded that the ‘recyclability’ of a material may not necessarily be connected with the

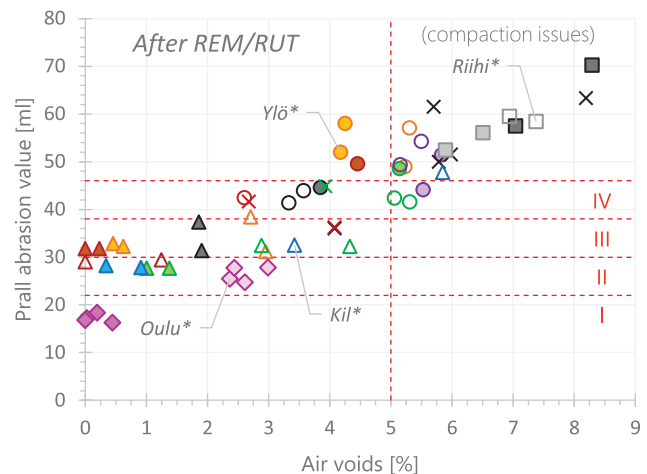


Figure 22. Prall abrasion versus air void content for all materials, after remix/rut-remix. The abrasion classes (I to IV) shown to the right are defined in the Finnish Asphalt standard (PANK, 2017).

material itself, but with its capability to be reheated and recompact. Field and construction qualities are essential for the good performance of the materials after REM/RUT; particularly, appropriate compaction has proven to be critical, and the introduction of high contents of air voids should be avoided.

After the last reconstruction (Rossi 2016, Heinonen 2017), some materials were around the upper limit of class IV and kept a similar Prall abrasion value (Ylö-REF, ARA; Riihi-REF, RAS). Other materials had a two-class increase (detrimental) in Prall abrasion (Ylö-FEP and Ylö-KB). Such changes may be due to air voids, but they can also mean that the aggregates that were added during REM/RUT had a different abrasion class than the original aggregates.

5.3.6. Creep permanent deformation at 40°C after REM/RUT

The creep/permanent deformation test was conducted for the materials after REM/RUT (SFS-EN-12697-25 2016b) to assess their relative susceptibility to rutting at high temperatures. The averages and CV values of the creep tests are presented in Figure 23 (individual specimen results in the appendix [https://doi.org/10.5281/zenodo.6908195]).

Most materials fell within Class I (least deformation) as defined by the Finnish Asphalt standard (PANK 2017). After REM, ARA*, FEP*, and KB* presented the lowest permanent deformations on average, around and below 1%. Ylö-REF* and OKTO AC* deformed slightly more, within 1–1.5% in average, but still within Class I. After RUT-REM, STO* and KB* presented the lowest permanent deformations (around and below 1%), followed by Kil-ARA*, FEP*, REF* and RAS* within Class I.

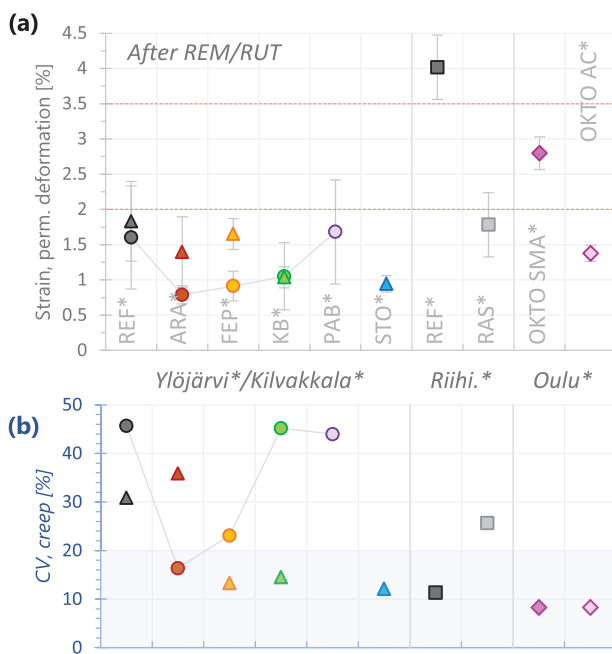


Figure 23. (a) Averages ± 1 standard deviation, and (b) CV of the creep permanent deformation, for all materials after remix/rut-remix. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line. The permanent deformation classes (I and II) as specified by the Finnish asphalt standard (PANK, 2017) are shown to the right.

There was a high dispersion in the creep test data, and some test results differ widely for the same material. The highest consistencies in Class I were presented by OKTO AC* (REM), STO* (RUT-REM), FEP* (RUT-REM), KB* (RUT-REM) and ARA* (REM). Relatively few data points were available, as only three tests were performed per material. Even so, it can be noted that the permanent deformation of the three REF materials was in average the highest of their respective roads. This indicates that REM/RUT of modified materials may effectively reduce permanent deformations with respect to the reference.

Remix and rut-remix may have a different effect on the susceptibility to permanent deformations of the materials. For example, REM may favour ARA and FEP more than RUT-REM to sustain lower permanent deformations. RUT-REM may have a similar effect on STO and KB. The REF materials from Ylöjärvi and Kilvakkala, as well as KB, seemed to be equally or similarly affected by remix and rut-remix. ARA performed slightly better than FEP in both sites. From the results, there does not seem to be an increased risk for permanent deformation from the remix of polymer-based additives.

The deformation of Riihi-REF* was the highest (outside Class II), above the level of all the other materials. Riihi-REF* presented breaking of the surface of the specimen around the rim of the piston, and bonding loss of the aggregates after the creep test. Like before, performance issues in this material after RUT-REM may originate from its above-average air void content. Additionally, the bonding loss may also be linked to the high susceptibility to moisture found for this material (ITSR 69.4%, see Figure 18). In this case however, the permanent deformation of RAS* was acceptable (Class I) despite its high air void content.

With the exception of OKTO SMA*, only a few isolated tests fell into Class II (Ylö-PAB*, Kil-REF*, Riihi-RAS*). Therefore, it is noticeable that OKTO SMA* presented such high deformations consistently, with values twice as large as OKTO AC*. This behaviour is not desirable nor expected, as the SMA material should have good resistance to permanent deformation (also, it was the best performer under abrasion thanks to its aggregates). The results may therefore be related to excessively low air voids in OKTO SMA* due to over compaction. Also, they may be related to the bitumen; OKTO SMA* had the largest bitumen content among all materials in the project, and it was comparatively soft (see Part II).

No correlation was immediately apparent between creep permanent strain and air voids for the materials tested in the project. Most materials fall within Class I and below 5% air voids. OKTO SMA* has extremely low air voids (below the SMA range, 1–5%), therefore its deformation was high (Class II). Riihi-REF* had very high air voids (above the 5% limit), contributing to a larger permanent deformation. These two extreme situations exemplify compaction conditions that should be avoided. Additionally, there was no apparent correlation between bitumen content and permanent deformation at the mixture scale (see Part II).

The original values measured for creep after the previous reconstruction were obtained for Ylöjärvi and Riihimäki

(Rossi 2016, Heinonen 2017). Overall, Ylö-REF*, ARA*, FEP*, KB* and RAS* had presented similar or slightly higher permanent deformations within Class I as during the current round of testing. Additionally, in 2015 Riihi-REF was complying with requirements, which was not the case this time because of issues with the compaction. The two PAB samples tested in 2015 registered very high deformations and broke; after aging and REM the deformations of this material are now in Class I. However, for these (relatively low-volume) roads other distresses such as flexibility and resistance to thermal cracking are of more concern.

6. Assessment of the effect of remix and rut-remix: perspective of mixture

At this point we can propose an overall assessment of the test results, to provide an overview of the performance of the materials of the project to different distresses and conditions at the mixture scale. To facilitate this assessment, we can interpret the relative quality of a material through a *score*, calculated before and/or after remix/rut-remix.

6.1. Scores

A *score* is a weighted mean of an average index and a variability index, calculated for one property of a given material. The average and variability indices are distributed linearly between the most favourable and most unfavourable values of the property. For example, a material with low Prall abrasion in average (*favourable*, high average index) and low variability (*favourable*, high variability index) would have a high Prall abrasion score. Since the definition of favourable depends on the material, proper adjustments were made on a case-by-case basis. For PAB, the stiffness criterion was reversed (lower stiffness is favourable) as the objective of this material is to provide a soft mixture.

The score was established in the range 0–100. A weight of 85% was assigned to the average index, and 15% to the

variability index. There were few Prall and Creep tests available per material, therefore the weight of the variability index was reduced to 10% in these cases. A score was calculated per property for each material. The scores are relative to the other materials in the project.

Because some properties were obtained both before and after REM/RUT (air voids, strength, stiffness) it was possible to calculate a *change* in score after REM/RUT. A reduction in score can be caused by the average of a property moving towards the unfavourable side, and/or an increase in variability after REM/RUT. On the other hand, a change close to zero indicates little variation in average and CV after REM/RUT. Thus, this change is indicative of the effect of REM/RUT on the materials.

It can be observed that the scores consider only the average and variability of each property as basic components to characterise the performance of the materials. By this, we mean to offer a ‘bulk’ analysis that considers all the test results available per material (all tested in equivalent conditions for all materials), to evaluate each material against the other materials of the group. This is in contrast with the complexity of variables that are affecting the results, such as construction conditions (original and during recycling), sources of the components, different aging levels of the bitumens, and even the existing correlations among some of the properties (as presented before).

Figure 24 presents a summary of the criteria for the assessment at the mixture scale. The following criteria were used to assess the effect of remix and/or rut-remix on each material:

- Change in air voids score after REM/RUT
- Change in strength score after REM/RUT
- Change in stiffness score after REM/RUT
- ITSR after REM/RUT
- Prall/abrasion score after REM/RUT
- Creep/permanent deformation score after REM/RUT

The change in air voids was computed based on the compliance of the air void contents before and after REM/RUT with

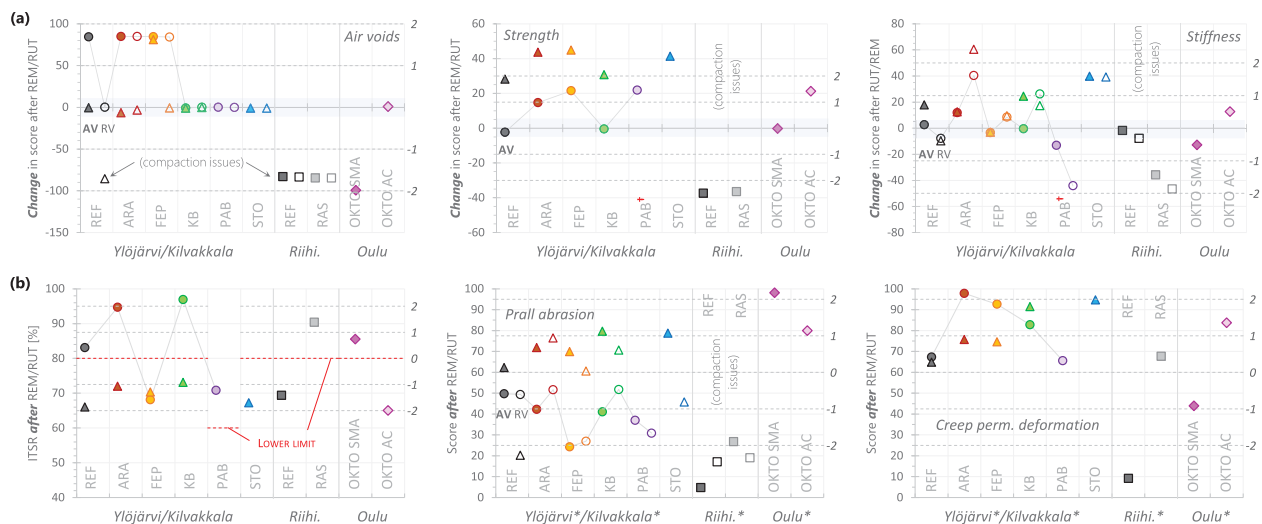


Figure 24. Criteria for the assessment at the mixture level. (a) Change in score after remix/rut-remix for Air voids, Strength, and Stiffness. (b) ITSR and score after remix/rut-remix of Prall abrasion and creep permanent deformation. Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line.

Notes: (†) Strength specimen thickness was 35 mm except for PAB (30 mm before, 45 mm after REM). Stiffness specimen thickness was 32 mm except for PAB (30 mm).

the ranges provided by the Finnish standards. This change is mostly indicative of the quality of compaction after the treatment; in the cases where this quality was lacking, the air voids had a low score after REM/RUT and the change was markedly negative. This change is also useful to signal, for example, if an air void content which was originally above standards may have been brought within limits after the treatment (as it was the case for Ylö-ARA). In other cases, an ‘even’ situation may have been altered by the rut-remix (as in Kil-REF), causing a detrimental change in the air void score for this material.

6.2. Effect of remix and rut-remix – matrix value assessment

The assessment of the materials was performed using a matrix based on the criteria presented before. In this matrix, an approximately round value was assigned to represent the relative effect of remix and rut-remix on the properties that were tested per material. A value of 2 represents the most favourable influence, 0 means unaffected, and -2 indicates the most negative effect. These values were assigned for all properties to have a comparable, relatively coarse, and intuitive unit, instead of ‘score’, ‘change in score’, or ITSR percentage. The assessment is done separately for remix and rut-remix. The ranges for 2, 1, 0, -1 and -2 can be observed in Figure 24; for each criterion, the impact ranges from 2 to -2 were laid based on the maximum and minimum test results from the current group of materials. The matrix is presented in Table 3. By selecting a material from the matrix, it is possible to identify the critical properties that were more negatively affected after REM and RUT-REM. Some comments are provided as follows:

- When AV/RV values are available, average values are used.
- To balance the overestimation of score in the strength from Kilvakkala (RUT-REM), the assessment value of this road was reduced by 1 point to account for the effect of reduced air voids.
- The ITSR criteria was adjusted for PAB (0.5) as it had a different lower limit than the other materials.
- To balance the change in strength score of PAB due to change in thickness, a moderately positive effect (0.5) was assigned in the matrix.

Once the assessment matrix was completed, the values were used to establish a *weighted* value per material. The weights are presented in Table 3, and the resulting weighted values are plotted in Figure 25. It is important to note that this assessment is only from the point of view of the *mixture*, and it can be complemented after the bitumen data (see Part II). A precedent for a similar type of assessment can be found in Rochlani *et al.* (2019), where the authors used a performance diagram to contrast six criteria that characterised their set of materials.

6.3. Result from the assessment

A material with full marks (2 in all criteria) would have a weighted value of 2. Therefore, according to the test results, all the materials lost at least some performance quality at the mixture scale during REM/RUT. The materials with a weighted value close to 0 saw their properties changing less on average during REM/RUT. The weighted value for Ylö-REF* was close to 0 under REM, which provides a good frame of reference for comparison with the other materials of the project.

The air voids are a good indicator of quality of the performance. In this project, four materials revealed issues in compaction (Kil-REF*, Riihi-REF*, RAS*, OKTO SMA*), which in turn affected the test results and the weighted value of the materials. Nevertheless, the weighted values of these materials are likely to improve under adequate compaction conditions, and RAS performed well at the bitumen scale (see Part II).

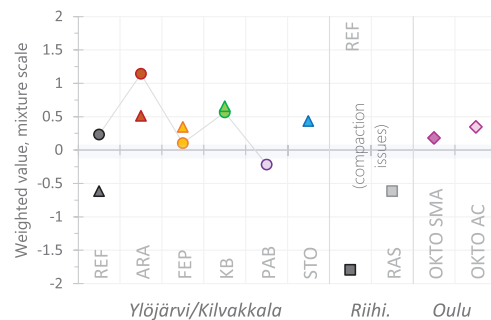


Figure 25. Weighted value at the mixture scale, see Table 3. Notes: Ylöjärvi (●), Kilvakkala (▲). The values from Ylöjärvi are linked with a line. REM (Ylöjärvi and Oulu) and RUT-REM (Kilvakkala and Riihimäki).

Table 3. Matrix of weighted criteria for all materials under remix and rut-remix, mixture scale.

	Effect of REM						Weight	Effect of RUT-REM						Weighted value	
	Change in property			Property after remix				Change in property			Property after rut-remix			Remix	Rut-remix
	Air voids	Strength	Stiff	ITSR	Prall	Creep		Air voids	Strength	Stiff	ITSR	Prall	Creep		
	0.5	0.4	0.2	0.8	1	1	0.5	0.4	0.2	0.8	1	1			
ARA	2	1	1	2	-0.75	2	0	2	1.25	-1	0.75	1	1.14	0.51	
KB	0	0	0.5	2	-0.75	1.25	0	1	-1	0.75	2	0.56	0.65		
STO							0	2	1.5	-1.75	0	2		0.44	
OKTO AC	0	1.5	0.5	-2	1	1.25							0.35		
FEP	2	1.5	0	-1.5	-2	2	1	2	0	-1.5	0.25	1	0.10	0.35	
Ylö-REF	1	0	0	0.5	-0.5	0.5							0.23		
OKTO SMA	-2	0	-0.5	1	2	-1							0.18		
PAB †	0	0.5	-1	0.5	-1.5	0.25							-0.22		
RAS														-0.62	
Kil-REF														-0.62	
Riihi-REF														-1.79	

Note: 2 = Most favourable influence, 0 = Unaffected, -2 = Most negatively affected. (+) For PAB, the stiffness criterion was reversed (lower stiffness is favourable).

From the perspective of the mixture, the results suggest that most materials may potentially be subject to remix or rut-remix with moderate to good response. Some comments and limitations of the materials are as follows:

- **ARA** and **KB** were the materials that best responded simultaneously to remix and rut-remix. **ARA** responded better to REM than to RUT-REM, while **KB** responded similarly to both treatments. Recall that not all materials were tested under both types of treatment.
- **ARA** and **KB** had a relatively poor performance to *abrasion* after REM. However, the response may be improved by reducing the air void content of the materials. Like most materials, **ARA** and **KB** were susceptible to *moisture damage* after RUT-REM. Otherwise, both materials had a good response to permanent deformations (REM and RUT-REM), to moisture damage (REM), and their strength and stiffness were little to positively affected by both treatments.
- **STO** was susceptible to *moisture damage* after RUT-REM. However, it had a relatively good abrasion resistance, good creep resistance, and its strength and stiffness changed positively.
- **OKTO AC** was susceptible to *moisture damage* after REM. Otherwise, it had good abrasion and creep resistance, and its strength and stiffness increased.
- **FEP** had a poor performance to *abrasion* after REM, and it was susceptible to *moisture damage* both after REM and RUT-REM. **FEP** had a slightly better response to RUT-REM than to REM. It had a relatively good creep response, and its strength varied favourably.
- **PAB** may be susceptible to *abrasion* after REM, although its behaviour may improve for lower air void contents. The stiffness of **PAB** increased during REM (likely due to aging during the treatment), which may be considered unfavourable given that this is a soft material. The material had a good response to moisture damage and creep, and its strength varied favourably.

The mixture scale response of some materials was affected by compaction issues:

- **OKTO SMA** had compaction issues (very low air voids), which may have induced a high susceptibility to permanent deformations after REM. However, it had good resistance to moisture damage and very good resistance to abrasion.
- **RAS** had compaction issues (very high air voids), which likely led to poor abrasion performance as well as critical reductions in strength and stiffness after RUT-REM. However, it kept a good resistance to permanent deformations, and it was the only material passing ITSR criteria after RUT-REM. It is still important to note that, after the previous construction, the stiffness of **RAS** was on level with typical Finnish asphalt mixtures, and there were no major differences between the **RAS** and **REF** in Riihimäki (Heinonen 2017). As well, the performance at the bitumen scale was satisfactory (see Part II).

Regarding the reference materials:

- **REF** in Ylöjärvi had its properties on average slightly affected by REM (some susceptibility to abrasion).

- **REF** in Kilvakkala had compaction issues (very high air voids) that affected its performance to abrasion after RUT-REM. The material also had high moisture susceptibility after RUT-REM. Strength and stiffness varied favourably.
- **REF** in Riihimäki had compaction issues (very high air voids) affecting its performance to abrasion after RUT-REM. Riihi-REF had issues with moisture, permanent deformation, and strength as well.

It is important to recall that the scores presented in this study are *relative* indices, intended to rank the materials among themselves.

7. Concluding remarks

7.1. Summary of comments

The objective of this project was to study the effect of remix and rut-remix on modified and alternative asphalt concrete composites. We have observed that all the materials were affected differently by remix or rut-remix. A good quality in the construction process is essential for the good performance of the materials after REM/RUT. In particular, a proper and even compaction leading to air void contents within standards has proven to be critical, regardless of the material type. High air void contents should be avoided. A matrix was presented where it is possible to identify critical properties that were more negatively affected by REM and RUT-REM per material. A summary of the most important observations at the mixture scale is provided in Table 4. As reported in the literature and experienced by the practitioner and research community, recycled asphalt materials exhibit significant levels of variability (Montañez *et al.* 2020). Herein we have confirmed that REM and particularly RUT-REM increase the uncertainty in performance associated with the recycled material.

7.2. Relative ranking of materials depending on their performance after remix/rut-remix: perspective of mixture

We may define the ‘recyclability’ of a material based on its performance and compliance with standard requirements after REM/RUT. Based on the results at the mixture scale, a score was calculated per property tested, for each material, before and after REM/RUT when possible. From the perspective of the mixture scale, it was found that all the materials lose at least some quality in performance during REM/RUT. More details are presented in the body of the document (see section *Assessment: Perspective of mixture*).

- The following ranking was estimated for REM: **ARA** (good); **KB**, **OKTO AC** (positive or moderately positive); **OKTO SMA**, **FEP**, **PAB** (neutral). *Considerations:* After REM, some materials were susceptible to moisture damage (**OKTO AC**, **FEP**), abrasion (**FEP**, **PAB**, **ARA**, **KB**), and permanent deformations (**OKTO SMA**).
- The following ranking was estimated for RUT-REM: **KB**, **ARA**, **STO**, **FEP** (moderately positive). *Considerations:*

Table 4. Summary of comments on performance.

Property	Mixture scale Comments
Core dimensions	The dispersion in the diameter of the cores increased after REM/RUT for all materials. This was an early indication of the softening of the materials and the increase in variability after REM/RUT.
Thickness of remixed layer	<ul style="list-style-type: none"> • REM may increase the thickness of the surface layer. For most materials the increase was ~1 cm. • For most materials RUT-REM induced markedly different changes across the rut, i.e. increasing to one side but decreasing towards the other, evening the result.
Bulk density	<ul style="list-style-type: none"> • Differences in the composition and density of added materials during recycling are reflected in bulk values. Depending on the material, REM/RUT usually maintained or increased the density. Depending on material and location, the bulk density after REM/RUT increased as much as 5% or reduced as much as 7%. • RUT-REM produces quite uneven results across the rut, between the edges of the treatment. Rut-remix increased the heterogeneity of the remixed material. For example, AV/RV bulk differed by more than 1% for several materials after rut-remix (this difference could be as high as 3.5%). Rut-remix also affects differently the AV and RV locations, i.e. AV may increase while RV may decrease and vice versa. Usually, one edge of the rut keeps its density relatively unchanged after rut-remix. • REM/RUT caused changes in maximum density mostly within $\pm 1\%$, depending on the material (OKTO SMA was an exception). Rut-remix had a comparatively larger effect than remix. • The maximum density of OKTO SMA* reduced almost 5% because the bulk of the added mixture was considerably lower than the original material. However, this does not seem to be the case for the large bulk reductions in Riihimäki. • Remix and especially rut-remix are likely to increase the variability of the bulk density. REM contributed to a slight increase in the variability of bulk of most materials (except Ylö-ARA, Ylö-KB/RV, PAB/AV, and OKTO AC). Rut-remix increased considerably the variability of specimens of all materials, particularly towards one side of the rut.
Air voids	<ul style="list-style-type: none"> • REM affected the air void content of the materials less drastically than RUT-REM. • The change on the air void content after REM/RUT seems to be erratic. Mostly, air void contents reduced within 50% or changed only slightly, but depending on the material and technique, air voids increased or decreased, sometimes dramatically. • OKTO SMA appears to have been over compacted during REM; air voids are too low, close to 0%. Conversely, Riihi-REF and RAS may have been under-compacted, with air voids well above 7%. • RUT-REM can considerably decrease or increase the air voids, differently to either side of the rut. Rut-remix in Kilvakkala produced an especially highly heterogeneous result within the relatively thin width of the rut; differences in air voids from side to side of the rut were above 250% for all materials. • Some materials also presented very low air void values after rut-remix (below 1%). • In general, the results indicate repeatedly that REM/RUT increases the variability of air voids, and rut-remix particularly tends to produce highly heterogeneous results.
Strength	<ul style="list-style-type: none"> • REM affected the materials' strength moderately. The strength remained constant for Ylö-REF, KB, and OKTO SMA, and it increased by at most 20% for Ylö-ARA, FEP, and OKTO AC. It is estimated that REM may have increased the strength of PAB by less or as much as 20%. REM had a detrimental effect on the moisture sensitivity of FEP and OKTO AC. PAB reduced its ITSr but it remained within acceptable limits. • RUT-REM may have increased the strength of most materials by about 20%. However, it negatively affected their moisture susceptibility. RUT-REM may induce a greater susceptibility to moisture damage in most materials. RAS* was the only material to comply with ITSr requirements after RUT-REM. • The detriments in moisture resistance (as evidenced by ITSr) may also be due to the presence of aged asphalt, which increases moisture damage susceptibility. • A correlation between air voids and dry strength seems to be induced by REM/RUT (i.e. low air voids, high strengths). There was no correlation between the air void content of the specimens and the resulting ITSr. • Variability in dry strength after REM/RUT decreased for several materials.
Stiffness	<ul style="list-style-type: none"> • There was consistency among the materials. However, there were some differences in the average AV/RV stiffness. • Some materials increased their average stiffness after REM/RUT (ARA, KB, PAB, STO, OKTO AC). Other materials changed little (Ylö-Kil-REF, FEP, OKTO SMA). Once again, the effect of increase or decrease by REM/RUT was slightly erratic for the AV/RV locations. The increase of stiffness of PAB may be considered detrimental. • The stiffness of Riihi-REF and particularly RAS was negatively affected after rut-remix, due to high air void contents and soft bitumen. • After REM/RUT the materials seemed more likely to have a large difference between the two stiffness tests per specimen. For most materials, the levels of internal variability in stiffness kept constant or increased slightly after REM/RUT. The variability of the stiffness test was larger than that of the strength. • Combined stiffness and strength variations indicate that REM/RUT may overall reduce the susceptibility to rutting at the mixture scale. However, at bitumen scale the effect may be opposite (see Part II).
Prall abrasion (After REM/RUT)	<ul style="list-style-type: none"> • OKTO SMA* and OKTO AC* had good abrasion resistance after REM.** • REM may have been detrimental to the resistance to abrasion of the materials in Ylöjärvi, particularly FEP* and PAB*. • RUT-REM, on the contrary, may be favourable to reduce this type of degradation. The materials shared with Ylöjärvi (ARA*, FEP*, KB*) presented better resistance to studded tires after RUT-REM in Kilvakkala, as well as higher consistency. The variability after rut-remix was generally lower than for the remixed materials. • The materials from Riihimäki (Riihi REF* and RAS*) were highly susceptible to abrasion after rut-remix, due to their high air void contents. • Prall abrasion correlated well with air void content. As the materials had more air voids, they became more susceptible to abrasion.
Creep (After REM/RUT)	<ul style="list-style-type: none"> • The permanent deformation of the three REF materials was the highest of their respective roads (Ylöjärvi, Kilvakkala, Riihimäki). Thus, REM/RUT of modified/alternative materials may result in reduced or at least similar permanent deformations with respect to a remixed reference material. • Most materials classified within Class I after REM/RUT, meaning that they seem to respond favourably to REM/RUT. REM may favour ARA*, FEP*, and KB* to sustain lower permanent deformations. RUT-REM may have a similar effect on STO* and KB*. Ylö-Kil-REF* and KB* seemed to be similarly affected by remix and rut-remix.

(Continued)

Table 4. Continued.

Property	Mixture scale Comments
	<ul style="list-style-type: none"> • OKTO SMA* accumulated considerably high permanent deformations (Class II). This result may be due to low air voids (close to 0%) and high bitumen content. • Riihi-REF* had the highest permanent deformation of all the materials, probably due to a combination of high air voids, high moisture susceptibility, and soft bitumen. RAS* presented acceptable permanent deformations (Class I). • There does not seem to be an increased risk of permanent deformation from the remix of polymer-based additives. • There was no clear relationship between air void content and the permanent deformation of the materials. There was also no apparent correlation between bitumen content and permanent deformation at the mixture scale. • There was high dispersion in the test data.

Note: Mixture scale.

After RUT-REM, all the materials except **RAS** were susceptible to moisture damage, although **RAS** was susceptible to abrasion.

RAS was negatively affected by rut-remix at the mixture scale. However, this was likely due to issues during compaction (very high air voids), and the material performed well at the bitumen scale (see Part II). Overall, four materials presented issues in compaction (**Kil-REF***, **Riihi-REF***, **RAS***, **OKTO SMA***). A proper assessment of these materials at the mixture scale may be obtained after a more appropriate compaction.

7.3. Limitations of the study, recommendations, and future work

The present document is a case study. The data and results presented represent the current practice, and they correspond specifically to a subgroup of modified and alternative asphalt concrete composites, as well as the construction processes associated to the roads of the project. Similarly, the mix design of the asphalt mixtures can have important effects on the performance, and different mix designs may produce different results. Such comprehensive analysis implies that variations in construction quality already exist in the data; this was made clear in the figures (i.e. compaction issues with some of the materials). In a way, a study that entails several materials from different roads, constructed at different times by different crews, also in itself becomes a test of consistency in current construction practices. We also hope we have emphasised the importance of good-quality compaction for the performance of the mixtures, regardless of the material.

When defining the ‘recyclability’ of a material, it is important to stress that it may not only depend on the material itself or the REM/RUT process, but also on its ability to be reheated and recompacted. For example, rut-remix induced differential compaction, producing important differences in performance for the same material in locations across the rut. Additionally, the roads in Kilvakkala and Riihimäki were cold-milled to introduce artificial ‘ruts’ before RUT-REM. Some of the materials located in these two sites experienced issues in compaction as well.

While this testing plan hopefully provided a performance characterisation for a wide range of properties and materials, concentrating on fewer materials would allow for better specific characterisation. For future plans, it is recommended

to focus on one or two materials of particular interest. This would allow for a larger number of specimens of the same material to be tested, as well as more representative results on variability. Ideally, the spectra of results of the present project may still provide a good overall idea of the response of the materials under REM/RUT. Additional comments to be considered in future research are as follows.

- Remix and rut-remix increase the heterogeneity of the materials. It is thus recommended that compaction is performed with care to obtain the most even results possible. This is especially true for rut-remix, where the materials can display large differences from side to side of the rut.
- More tests are suggested under *remix* for **STO**.
- For rut-remix, it is suggested that at least some cores be extracted from the centre of the treated rut. Currently, they are extracted only from the edges of the treatment.
- Obtaining the laboratory samples from the roads implies that there is a possibility of receiving very thin layers in the cores. Because of this, some thickness restrictions were needed, and relative thin specimens were tested. A larger thickness is suggested for the specimens (especially stiffness) to guarantee higher in-test consistency. Avoiding thin specimens may reduce variability and make the results less prone to size effects.
- The consecutive numbering of the cores in Oulu REM was highly beneficial. For example, it was used in the selection of the cores for testing, based on their location (closer cores were tested for the same properties). This fact also provides highly useful information on the spatial correlation of properties during after construction, giving additional value to the data. It is therefore recommended that this individual labelling is provided from all sites where a series of cores is extracted.

It could be possible to propose a comparison with remix-like conditions to be replicated in the laboratory. This would provide a comparison to the conditions in the field, for example, to evaluate sources of variability. It is also planned to implement semi-circular bending tests and the flexibility index to characterise resistance to fracture at low temperatures (Ozer and Al-Qadi 2018). Additional work is in progress regarding the study of multiple cycles of recycling from a laboratory perspective, as well as on thermal properties of asphalt mixtures with steel slags...

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References

- Al-Qadi, I. L., *et al.*, 2015. Scenarios developed for improved sustainability of Illinois tollway: life-cycle assessment approach. *Transportation Research Record (Journal of the Transportation Research Board)*, 2523, 11–18.
- Apilo, L., and Eskola, K. 1999. Recycled asphalt pavement studies [In Finnish, Uusiopäällystetutkimukset]. In: VTT Technical Research Centre of Finland, ed. Helsinki, Finland: Tiehallinto.
- Eskandarsefat, S., Hofko, B., and Sangiorgi, C., 2020. A comparison study on low-temperature properties of stone mastic asphalts modified with PmBs or modified fibres. *International Journal of Pavement Engineering*, 21, 1541–1549.
- Heinonen, A., 2017. *Development of the requirements for market validity of recycled asphalt – asphalt pavement containing asphalt shingles (roofing felt) as a case study (in Finnish)*. M.Sc. Thesis, Aalto University.
- Makowska, M., Aromaa, K., and Pellinen, T., 2017. The rheological transformation of bitumen during the recycling of repetitively aged asphalt pavement. *Road Materials and Pavement Design*, 18 (sup2), 50–65.
- Makowska, M., and Pellinen, T. 2016. Development of specifications and guidelines for hot in-place recycling in Finland—outline and framework. In: F. Canestrari and M. Partl, eds. *8th RILEM international symposium on testing and characterization of sustainable and innovative bituminous materials*. RILEM Bookseries. Dordrecht: Springer, 851–862.
- Montañez, J., *et al.*, 2020. Variability of the mechanical properties of reclaimed asphalt pavement (RAP) obtained from different sources. *Construction and Building Materials*, 230, 116968.
- Ozer, H., and Al-Qadi, I. L., 2018. Development and implementation of the Illinois flexibility index test: A protocol to evaluate the cracking resistance of asphalt mixtures. *Transportation Research Circular E-C237*.
- Pank, 2017. *Asphalt standards (in Finnish)*. Helsinki, Finland: Finnish Asphalt Pavement Association.
- Pellinen, T. K., 2004. Conceptual performance criteria for asphalt mixtures. *Journal of the Association of Asphalt Paving Technologists*, 73.
- Pellinen, T., and Makowska, M., 2018. *Research on the hot-in-place recycling of asphalt pavements by the REMIX technique [In Finnish]*. Aalto University: Helsinki.
- Rochlani, M., *et al.*, 2019. Influence of filler properties on the rheological, cryogenic, fatigue and rutting performance of mastics. *Construction and Building Materials*, 227, 116974.
- Romeo, E., *et al.*, 2010. The effect of polymer modification on hot mix asphalt fracture at tensile loading conditions. *International Journal of Pavement Engineering*, 11, 403–413.
- Rossi, J., 2016. *Suitability of modified bitumen pavements for low-traffic volume roads (in Finnish)*. M.Sc. Thesis, Tampere University of Technology.
- SFS-EN-12697-16, 2016a. Bituminous mixtures. Test methods. Part 16: Abrasion by studded tyres. Finnish Standards Association.
- SFS-EN-12697-23, 2017. Bituminous mixtures - Test methods - Part 23: Determination of the indirect tensile strength of bituminous specimens. Finnish Standards Association.
- SFS-EN-12697-25, 2016b. Bituminous mixtures - Test methods - Part 25: Cyclic compression test. Finnish Standards Association.
- SFS-EN-12697-26, 2018. Bituminous mixtures - Test methods - Part 26: Stiffness. Finnish Standards Association.
- SFS-EN-12697-6, 2012. Bituminous mixtures - Test methods for hot mix asphalt - Part 6: Determination of bulk density of bituminous specimens. Finnish Standards Association.
- Stewart, C. M., Oputa, C. W., and Garcia, E., 2018. Effect of specimen thickness on the fracture resistance of hot mix asphalt in the disk-shaped compact tension (DCT) configuration. *Construction and Building Materials*, 160, 487–496.
- Valkonen, A., 2020. *Monitoring of test construction sites of asphalt additives and glass fibre grids, 2015–2019 (in Finnish)*. Helsinki: Finnish Transport Infrastructure Agency.
- Vega, D. L., Santos, J., and Martinez-Arguelles, G., 2020. Life cycle assessment of hot mix asphalt with recycled concrete aggregates for road pavements construction. *International Journal of Pavement Engineering*, doi:10.1080/10298436.2020.1778694.
- Väjälä, 2019. *Patching of pavements (In Finnish: Päällysteiden paikkaus)*. Helsinki, Finland: Finnish Transport Agency.
- Xiongzhou, Y., *et al.*, 2021. K1c and KIIc measurement and theoretical study using the semicircular bend specimen with different thicknesses. *Fatigue & Fracture of Engineering Materials & Structures*, 44, 832–846.