Construction and Building Materials 364 (2023) 129939

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluating raveling susceptibility of asphalt by Pull-off tests

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ARTICLE INFO

Keywords:
Low noise pavement
Raveling
Pull-off test

ABSTRACT

Porous low noise wearing courses are popular in Switzerland. However, after 4 to 5 years in service distresses appear mostly due to raveling. Measuring the susceptibility to loss of aggregates is therefore considered a desirable step of quality control. The research project was able to demonstrate the problematic nature of the scuffing test according to EN 12697–50. Instead, it has been shown that a simple pull-off test has many advantages. The handheld device is easy to operate and applicable on site. The method discriminates between types of mix-designs, degrees of compaction and is performing satisfactory with respect to accuracy. It was found that pull-off results correlated reasonably well with visual raveling field inspection.

1. Introduction

Raveling is one of the most common surface distresses in asphalt wearing courses, especially in case of environmentally friendly mixtures with high porosity for noise reduction. This traffic and weather induced loss of mineral aggregates may increase braking distances and cause windshield damage from flying loose gravel which is inacceptable for safety reasons. It has not only negative effects on durability of the surface layer but also annihilates noise reduction properties which, by the way, cannot easily be recovered by simple rehabilitation measures. Raveling may be caused by loss of adhesion between binder and aggregates or by loss of cohesion within the aggregates or within the binder due to binder degradation. This study focuses primarily on the adhesive raveling effects.

During recent years, both porous asphalt PA and the so-called semi dense asphalt SDA, with smaller maximum aggregate size and a slightly higher content of fines, have become more and more popular surface layers in Switzerland due to their ability to significantly reduce noise from the tire/road interaction of passenger cars and trucks at speeds above 35 km/h and 60 km/h respectively [1]. However, the skepticism with respect to raveling and durability was growing and even led to a ban of porous asphalt on motorways by the Swiss Road Administration. Although semi dense pavements seemed initially to be more resistant against such failures, after several years, aggregate loss frequently was observed due to combined environmentally-driven bituminous binder deterioration and trafficking.

Due to the complexity of the mechanisms that cause raveling, no general consensus regarding a suitable test method exists, so far. On the one hand it is difficult to simulate in the lab the repeated combined environmental and traffic effects in the field, including the influence of water, ice, air, UV, temperature and time on the adhesion properties between mineral aggregates and the binder film; on the other hand it is challenging to induce simultaneously a realistic repeated mechanical loading on the surface exposed aggregates, not only in the vertical and horizontal translational directions but also in a rotational way by mechanical momentums that may cause peeling between aggregate and binder as shown schematically in Fig. 1a). So far, all those effects are not well understood leading to numerous practical test methods that focus on one or the other of these mechanisms in a more or less intuitively pragmatic way and that provide at least some indicators for simple evaluation of the raveling potential, for example, by investigating the scuffing behavior as described in EN 12697–50 [2] or abrasion by studded tires as in EN 12697-16 [3].In Europe, four different scuffing devices and procedures for predicting the ravelling potential of asphalt mixtures have been developed and integrated into the technical specification CEN/TS 12697–50 *Resistance to Scuffing* [2]. Unfortunately, no data were reported on validation of each individual test method by a suitable round robin test, such that reproducibility and repeatability errors could be estimated. It is good scientific practice and should be clear that without those fundamental data, a test method is not ready to be integrated in a standard or technical specification and not considered as applicable in practice.Following the first publication of the CEN/TS in

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https://doi.org/10.1016/j.conbuildmat.2022.129939
Received 28 July 2022; Received in revised form 22 November 2022; Accepted 29 November 2022

2016, a European interlaboratory testing program was undertaken. The main goal of this program was to develop one harmonised test method out of the existing four. The outcome was published by Nicholls et al [4]. The testing program included three types of asphalt mixtures: a Dutch PA, a French BBTM (béton bitumineux très mince, engl. very thin asphalt concrete) and a German SMA (stone mastic asphalt). For each type, the mix design was slightly modified to obtain standard specimens and poor-quality specimens. It was found that none of the devices was able to discriminate between both poor-quality and the standard specimens. Further, none of the devices provided the same results in comparison to the other three and all 4 devices showed large standard deviations (often more than 30 %).At the time of the actual research project, these findings from the European interlaboratory testing had not been published yet, but it was considered unfortunate that all 4 methods described in the CEN/TS 12697–50 [2] required rather specific costly test devices and were applicable in the laboratory only. It was also noted that scuffing tests are probably not accounting for the most relevant mechanism, since the combined translational and rotational mechanical loading described earlier is the result of the vertical tire load and therefore not considering the most critical loading of the aggregates in pure tension or peeling mode.

Since some preliminary tests at the beginning of this research project with waterjet or scraper-brushes were not satisfactory (see [5]), and due to the limited validity of the scuffing tests as alternative, finally, the pull-off test was chosen for evaluating the raveling susceptibility of asphalt surface courses, based on the following three reasons: (1) it is a practical test method for the laboratory without needing expensive equipment and machinery; (2) it is applicable for on-site testing as it is already available and practiced in the field, e.g. for waterproofing membranes on bridge decks [6]; (3) it is a test method that focusses on the critical tension and adhesion properties of aggregates on the surface. As depicted in Fig. 2, showing a pull-off fracture area of a specimen (SDA 4-16, see below), tension and adhesion properties of the aggregates were predominant.The pull-off test has also some drawbacks. One is the fact that gluing requires skilled personnel and may lead to locally larger glued areas than intended, since the glue may also adhere to the zones in between the aggregates as shown in Fig. 1b). However, this influence may be assumed minor in cases where the glued pavement area primarily consists of well packed aggregate surfaces. Another drawback may be the number of tests for obtaining significant result. However, it was found that this number can be minimized by an appropriate choice of test geometry. An extensive discussion about different pull-off test methods is provided in [14].Although, not designed for the probably more critical but hard to simulate rotational peel-off action of aggregates during raveling, it was hypothesized that the pull-off test assesses the behavior more on the “safe” side as compared to scuffing tests, since it is not affected by vertical tire load and due to its clear tension loading more accounting for adhesion properties of the aggregates and therefore for raveling.In spite of the fact that the pull-off test is not included in the European standard for raveling testing, variations of the method appear in different other European standards such as EN 1542 *Measurement of Bond Strength by Pull-off* [7], EN 12697–48 *Interlayer Bonding* [8] or EN 12697–51 *Surface Shear Strength Test* [9]. They all have in common that a metal plate is glued to a surface and tensile or torsional loading is applied to the plate. The method presented here uses a tensile force.

2. Research approach

Four surface pavement materials and one reference mixture were investigated in the laboratory, focusing on the influence of different parameters on the pull-off results of laboratory produced specimens, in particular: the relevance of presence or absence of a steel collar ring as counter-frame, the effect of pull-off speed, the role of changing plate diameters as well as the influence of specimen compaction. Moreover, a comparison with the so-called Darmstadt Scuffing Device (DSD) [2] was performed on selected laboratory specimens at two different institutions in Germany.For the laboratory testing, a commercial handheld device marketed throughout Europe as well as a test set-up built into a universal testing machine were used.In addition, two on-site test campaigns were conducted: the first one with six materials on the same two years old road section and the second one on six different road sections paved with the same mixture type but showing different degrees of raveling after four to six years of operation.

3. Materials

3.1. Laboratory materials

The asphalt mixtures chosen for the laboratory tests were a porous asphalt PA 8 as well as several semi-dense asphalts SDA 4–20, SDA 4–16, SDA 8–16 according to Swiss Standard [10] and designated according to nominal maximum aggregate size and nominal air voids. For comparison purposes, a low noise but dense mixture, a so-called macrorugueux AC MR 8 according to Swiss Standard [11], was added. All mixtures were produced at the same mixing-plant to ensure that the origin of the aggregates and polymer modified bitumen, a PmB 45/80–65 according to SN EN [12], were identical.

The mixtures were compacted in a double size mold 390 × 590 × 40 mm^3 using the compactor of the large wheel rutting tester modified with a steel roller instead of a pneumatic tire [5]. Material characteristics are provided in Table 1.

3.2. Materials on Test-sites

Within the framework of research, two on-site test campaigns were carried out on rural roads (whose materials are different from those mentioned in 3.1). The first site included numerous test sections laid during the same week in 2018. These sections consisted of a great variety of pavements with semi dense SDA mixtures, including standardized mixtures such as SDA 4–20 and SDA 8–16 and non-standardized

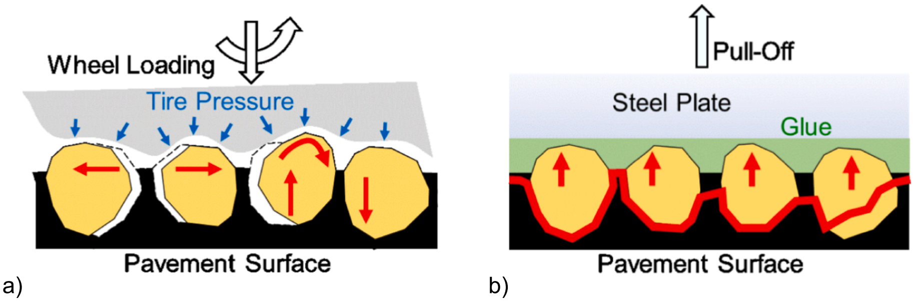

Fig. 1. A) adhesive raveling mechanism under vehicle loads caused by interaction between rubber tire and the surface aggregates due to horizontal tension and peeling through rotation and tension. b) fracture mechanism in case of well glued pull-off test: adhesion failure between binder and aggregates, between binder and glue as well as cohesion failure within the binder and aggregates.

Fig. 2. Pull-off fracture area of a specimen with a diameter 100 mm (SDA 4–16, see below).

Table 1
Main characteristics of the slabs.

Mixture	PA 8	SDA 4–20	SDA 4–16	SDA 8–16	AC MR 8
Binder content [mass-%]	5.7	5.9	6.2	5.6	5.9
Compaction [%]	99.1	95.9	100.6	98.5	100.4
Air voids [vol-%]	18.7	19.2	12.5	13.6	3.9

mixtures such as SDA 2–10, SDA 4–5, SDA 4–15 and SDA 6–20 with different air voids contents. With exception of SDA 2–10, no SDA surface layer showed extended raveling at the time of testing in 2020 as shown in Table 2.

The second on-site campaign took place on several SDA 4 sections constructed between 2015 and 2016, which in 2021 showed different levels of raveling. A brief description with some characteristics potentially affecting the raveling behavior is given in Table 3.

4. Pull-Off testing

4.1. *Laboratory devices*

As mentioned earlier, two different kinds of tensile testing devices were used for laboratory testing:

Table 2
Overview of series 1 test sections selected for this study.

Section	Material	Air Void Content	Raveling
1	SDA 2–10	19.9	heavy
2	SDA 4–5	8.8	none
3	SDA 4–15	20.1	slight
4	SDA 4–20	20.1	slight
5	SDA 6–20	17.4	none
6	SDA 8–16	18.2	none

Table 3
Overview of SDA 4 test sections from series 2; all surface courses were tested in 2021; Mean Texture Depth (MTD) measured according to EN 13036-1 [13].

Section	Build in year	Daily truck traffic	Slope [%]	Raveling	MTD [mm]
7	2015	520	1.5	slight	0.7
8	2016	460	2.5	heavy	1.4
9	2015	220	2.9	slight	0.6
10	2015	250	5.6	heavy	1.0
11	2017	830	1.1	none	0.8
12	2015	490	7.0	heavy	0.9

- A universal testing machine (200kN) with load control and a collar-ring as counter-frame to ensure that the specimens with diameter 100 mm were firmly fixed and held down during the load application as shown in Fig. 3 (left)
- A handheld pull-off device with a maximum load of 16kN and without using a counter-frame to prevent deformation of the slab as shown in Fig. 3 (right).

All devices come with steel plates with diameters of 50 mm or 100 mm and thicknesses of 20 mm and 40 mm respectively, which incorporate a fitting enabling them to be coupled to the pull-off axis.Unless otherwise specified, pull-off tests were conducted by default at a standard loading rate of 20 N/s and at a temperature of 20 °C. Grinding was used to remove the bitumen film and/or smoothen the surface irregularities. The adhesives used for gluing the steel plate to the asphalt were fast curing 2-component methylmetacrylates with a setting time of 30 min. The way of applying the glue is crucial for the quality of the test results. In order to avoid glue penetrating into the cavities, the glue was applied homogeneously to the steel plate with a comb.After preliminary trials [5], pull-off tests were decided to be performed without drilling in order to avoid damaging the aggregates at the edge of the pull-off steel plate and to keep practical application as simple as possible. Moreover, drilling was considered negative regarding artefacts from drilling (water, temperature).

Fig. 3. Left: test set-up in the universal testing machine with counter-frame; right: handheld pull-off device without counter-frame, here shown during on-site testing.

4.2. In situ devices

In situ testing (Fig. 3, right) was conducted directly on the road surface with two different handheld pull-off devices (16kN and 20kN maximum load). The road surface was cleaned and prepared the same way as in the laboratory (grinding, gluing), while the temperature during the tests varied between 15 °C and 24 °C. Each test consisted of three measurements.More details concerning the testing parameters can be found in the research report [5].

5. Results and discussion

In order to evaluate a suitable pull-off test for determining the susceptibility to raveling, various variables were analyzed. In the following, the parameters whose influence on the test results seemed most significant are shown and discussed.

5.1. Influence of Counter-frame

In case of tests performed on laboratory slabs, the pull-off strength was strongly influenced by the presence or absence of a counter-frame to hold the specimen plate down, so as to avoid an uplift around the area being tested. The measured strength was 30 to 50 % higher when the experimental set-up prevented the vertical deformation of the peripheral area. The influence of this effect on the pull-off result is shown in Fig. 4. It may be explained by the fact that the testing machine with counter-frame was a much stiffer experimental setup and allowed a better-defined vertical loading than the handheld device without counter-frame. Moreover, it has been observed that the uplift occurs irregularly, i.e. not in radial symmetry. The differences between the setups has to be accounted for when comparing absolute values. However, the ranking of the different mixtures was very similar, indicating that relative comparisons between mixtures are possible regardless of using or not a counter-frame. It should be noted that laboratory tests with a handheld device can also be carried out with a counter-frame. The use of a counter-frame is not limited to the testing machine.Counter-frames proved necessary in case of laboratory tests on specimens. However, on-site, where the surface course is firmly bound to the substrate, the above-mentioned up-lift does not occur or is small enough to be neglected.

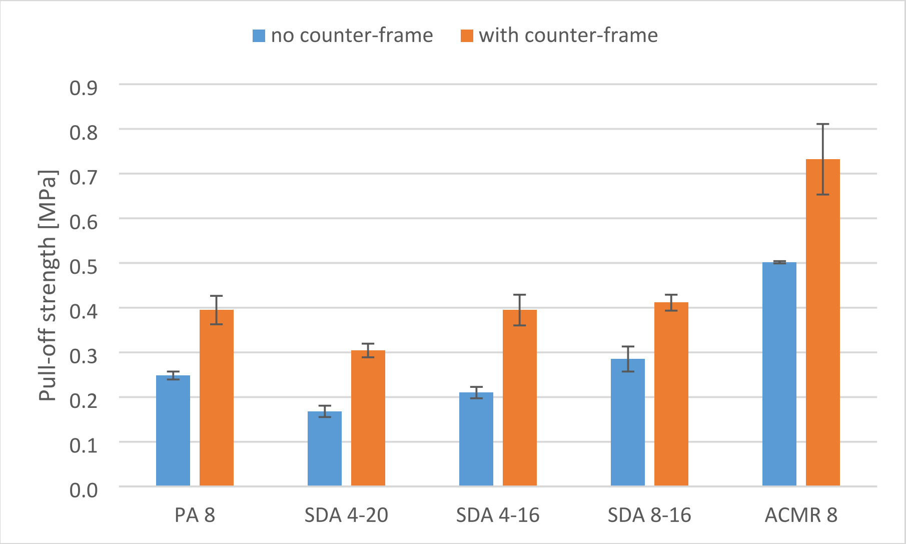

Fig. 4. Effect of counter-frame on pull-off strength at 20 °C (mean values of 12 measurements with and 3 without counter-frame); plate diameter 100 mm.

5.2. Pull-off speed

Since asphalt is a viscoelastic material, strain rate dependency of strength is a crucial testing parameter, and it is no surprise that the pull-off speed strongly determines the pull-off strength. With respect to this behavior, it must be stressed that many commercially available handheld pull-off devices may not be able to control the loading rate as precisely as it is common for universal testing machines. The control is particularly critical for pull-off speeds above 50 N/s. For example, in case of 100 N/s up to 35 % lower speed than the target was found. Hence, the capacity of the devices must be carefully verified before performing tests with handheld pull-off devices.

Knowledge of the strength-speed relation is of importance when it comes to interpret measurements or compare results from different devices. In Fig. 5, the speed dependency of pull-off strength for SDA 4–16, SDA 8–16 and the reference AC MR 8 during handheld tests at 18 °C are presented as mean values of three measurements. It can be seen that the speed dependency is not significantly different from one mixture to another, which may indicate that the strength-speed relation mainly reflects the use of the same binder in all laboratory mixtures.

5.3. Plate diameter

On-site tests showed that the plate diameter has an influence on the pull-off strength. Fig. 6a refers to measurements of plates with a diameter of 50 mm or 100 mm, while all the other parameters and conditions were constant. The use of the larger plate (100 mm) led to pull-off strengths that were about 30 % less compared to the results obtained with the smaller plate (50 mm). As shown schematically in Fig. 6b, one possible reason is that aggregates along the perimeter of the plate are bound to adjacent aggregates outside the nominal loading area, thus creating a circular influence zone of width w and an effective pull-off area, which increases the pull-off forces. This influence zone also depends on how carefully the glue was applied. It is obvious that the effect of the circular influence zone is higher in case of smaller than larger plate diameters. In case of about 30 % difference in pull-off strengths between 50 mm and 100 mm plates, the width of the maximal influence zone can be estimated to be in the order of 1.5 to 2 maximum aggregate sizes. However, not all differences can be explained by this effect, since in some cases it was observed that the 100 mm plate tilted slightly during pull-off, which resulted in inhomogeneous tearing and therefore to lower maximum loads.

5.4. Influence of compaction

It was already described by the authors of the interlaboratory test mentioned before [4], that the pull-off strength and with that the susceptibility to raveling should be connected to the asphalt quality. As reported in [5], the pull-off strength was compared for 3 mixtures with sufficient and poor degree of compaction. Fig. 7 confirms that pull-off strength of poorly compacted specimens is significantly reduced. In case of SDA, a reduction of compaction by 1 % results in a reduction of pull-off strength by about 3 % whereas in case of AC MR 8 a reduction of about 6 % was found. Poorly compacted specimens are the values 85.7 %, 85.1 % and 92.3 %.

5.5. In situ testing aspects

5.5.1. Repeatability and reproducibility

As described earlier, two different handheld devices were used for on-site evaluation. In order to analyze the variability of the method, tests were carried out by two operators, each handling his own device. Testing took place under the same conditions (grinding, gluing and surface temperature). However as visible in Table 4, the surface temperatures on the different sections varied in the range of 19 ± 5 °C The results show that the repeatability (standard deviation) of each device was quite good. Furthermore, it shows good reproducibility since the average deviation between the devices was only 2 %, with a maximum of 4.1 %, though. This deviation can be considered as small taking into account that the tests were done directly on the road and not on carefully prepared laboratory specimens. For practice, this means that different handheld devices are suited to produce acceptable ranking of raveling properties in the field if properly validated.

5.5.2. Temperature correction for field measurements

In order to be able to compare results, the influence of temperature must be taken into account for interpretation. For example, laboratory measurements at 10 °C and 20 °C have shown a reduction of pull-off strength of around 50 % (Fig. 8).

Relationships between mechanical properties and temperature of viscoelastic materials are generally nonlinear, typically following hyperbolic trends. Especially in the field, a temperature correction must be applied in order to account for the fact that even a difference of 1 °C may change the pull-off strength by 5 % to 11 % in the studied temperature range. From the hyperbolic regression of the field series in Fig. 9 results Equation (1)

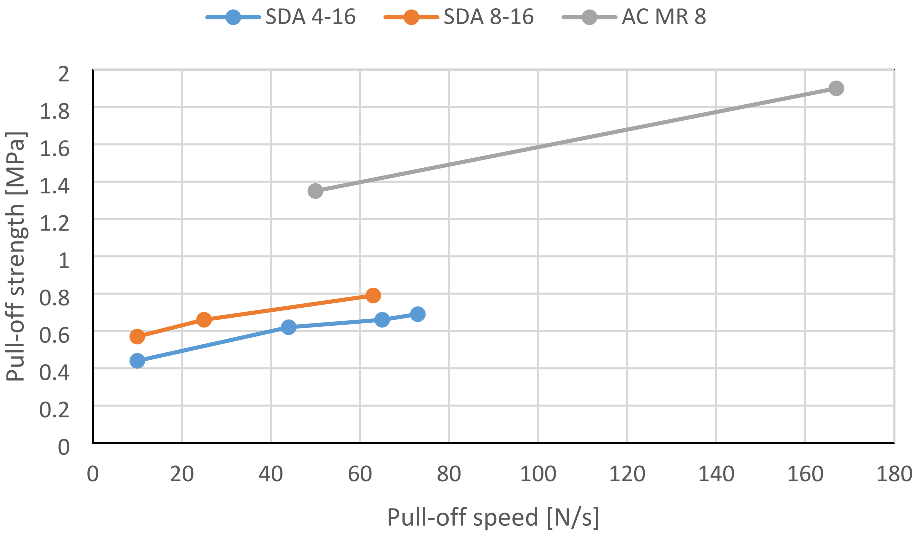

Fig. 5. Pull-Off strength-speed dependency at 18 °C, mean values of 3 measurements in the laboratory, 50 mm pull-off plates.

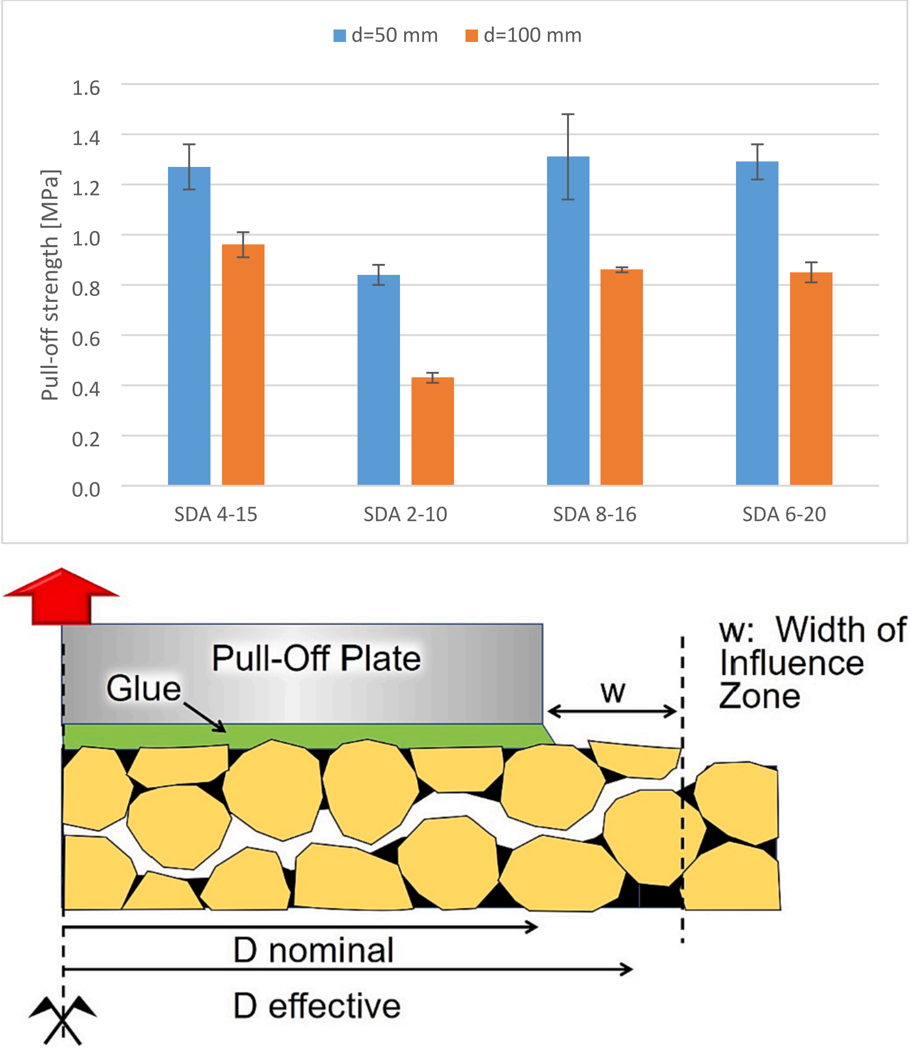

Fig. 6. **A** Influence of the plate diameter d on the on-site pull-off strength (mean values of 3 measurements at 18 ± 2 °C). **6b** Nominal and effective diameter due to formation of an influence zone.

$$\sigma\sigma_T\cdot\left(\frac{T_R}{T}\right)^{-17.02}[\text{units MPa, K}] \tag{1}$$

which is used to estimate the strength value σ_R at a reference temperature T_R from the strength σ_T at an actual testing temperature T. The low R^2 value is due to the fact that series 1 and 2 consisted of considerable variety of sections and materials as presented in Tables 2 and 3.Further, according to Fig. 9, field and laboratory pull-off data appear shifted in parallel and, comparing the regression exponents, the hyperbolic trends follow similar strength-temperature rates. The shift may be explained by the fact that for laboratory tests the whole specimen was conditioned to the same temperature whereas in the field only the surface temperature could be measured. This surface temperature might slightly overestimate the temperature at which fracture occurs since the temperature gradient below the surface cannot be taken into account. Another reason for the higher strength values in the field may be ageing and other environmental effects.

5.5.3. *Effectiveness of the Pull-off test to capture the tendency to raveling*

It is a well-accepted fact that the raveling potential of in situ pavements is directly influenced by their age in connection with the binder ageing and the traffic intensity. As previously mentioned, two different in-situ series were included in the pull-off measurements: six sections with SDA 4 pavements which at the time of testing were five to six years old and showed clear signs of distress (see Table 3); the other series consisted of different, only two years old SDA pavements (see Table 2).

The pull-off results depicted in Fig. 10 were corrected with Equation (1) to a reference temperature of 20 °C. They clearly show the differences regarding the pull-off strength between the SDA products of the different sections in correlation with the visual inspection, thus, demonstrating the suitability of the method for the in situ evaluation. Considering the results of series 1 (section 1–6) a tendency of agreement can be observed: sections with no visible raveling reached higher pull-off values than those with slight or heavy raveling, which is promising. The same tendency holds for the results of series 2, when ranking the two different low noise products (blue 7,8,11 and green 9,10,12) placed by different construction companies. However, when comparing both products, clear differences in pull-off strengths are visible, leading to rankings on different pull-off strength levels. This means that it may be too early for generally proposing a minimum acceptable threshold value for standardization (e.g. around 1.3 MPa at 20 °C) but that the required pull-off strengths may have to be adjusted to individual products.

6. Comparison with Darmstadt scuffing device DSD

In order to validate the pull-off test and to connect it to the European standard, the Darmstadt Scuffing Device DSD was chosen. In a first step,

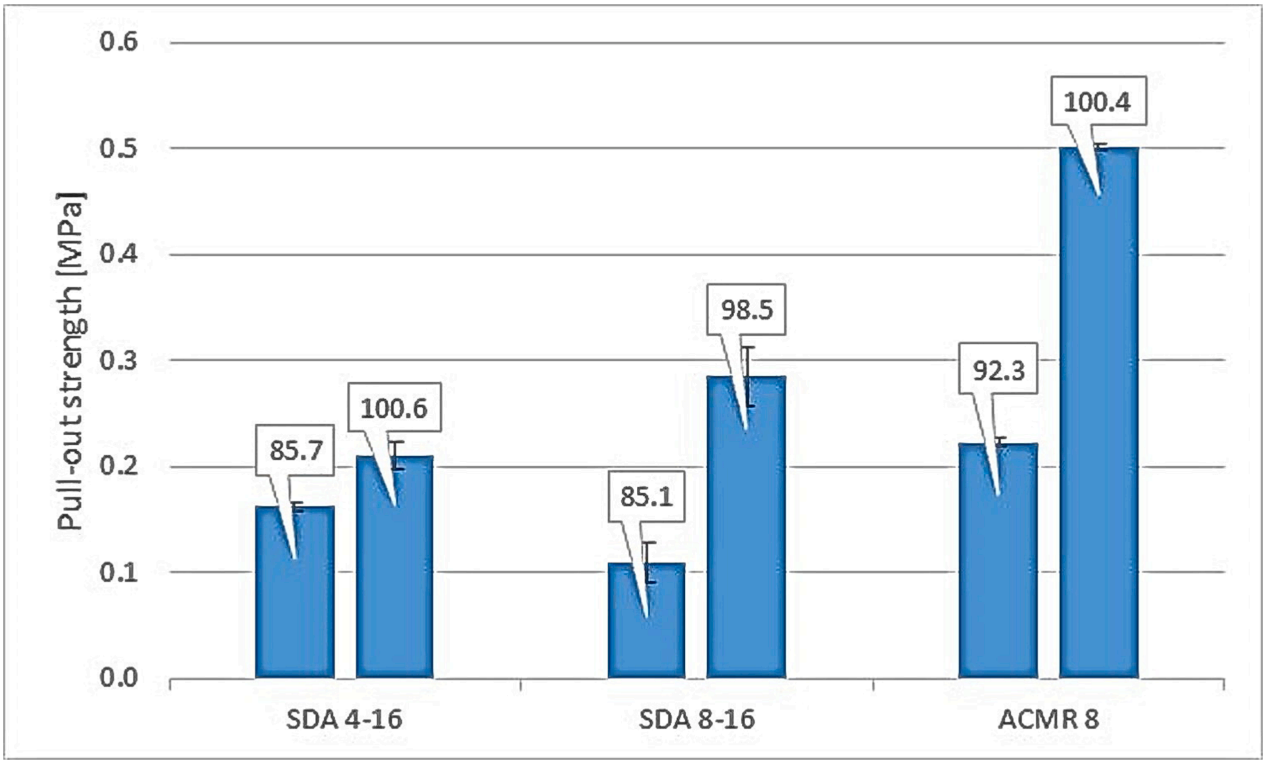

Fig. 7. Gain in pull-off strength with compaction; strength measured on sufficiently and poorly compacted slabs at 20 °C; plate diameter 100 mm; mean values of 3 measurements; labels indicate the degree of compaction in [%].

Table 4
Reproducibility between two handheld devices and repeatability; mean values and standard deviations of 3 pull-off measurements; sections according to Table 2 and Table 3.

Section	2	4	6	7	8	9	10
Surface Temperature [°C]	17.0	14.5	16.0	19.0	22.0	24.0	23.0
Device 1 Strength [MPa]	1.80	1.43	1.50	0.73	0.94	1.03	1.05
Std. Dev. [MPa]	0.07	0.14	0.08	0.04	0.04	0.07	0.06
Device 2 Strength [MPa]	1.66	1.52	1.50	0.69	0.96	0.99	1.04
Std. Dev. [MPa]	0.33	0.13	0.11	0.09	0.02	0.05	0.07
Deviation in [%] between device 1 and device 2	4.1	3.1	0.0	2.8	1.0	2.0	0.5

specimens for DSD testing were sent to the Technical University TU Darmstadt. Later, the Karlsruhe Institute of Technology KIT was also involved in the testing. Both laboratories had the same testing device produced by the same manufacturer.

When sending slabs from the same batch to both laboratories, significant differences were found. Hence, in order to exclude the influence of slab production, a second test campaign was conducted with SDA 4–20, SDA 8–16 and PA 8 specimens only, but this time each laboratory received half of the same slab (i.e. a specimen with identical compaction and homogenous air void content). The overall results are depicted in Fig. 11. It shows the average values of the 2 and sometimes 3 tests performed on each mixtures as well as the minimum and maximum values.

Fig. 11 does not show the distinction between same batch and same slab. The detailed results can be found in [5]. However, it is worth noting that results from the same slab are generally not fundamentally different from those of the same batch. In other words, they confirm the fact that the laboratory in Darmstadt provides systematically higher DSD results than the laboratory in Karlsruhe. Leaving aside AC MR 8 with very limited loss of material, the mean relative difference between the laboratories is 32 %, a value that meets the findings of the previously mentioned European interlaboratory program [4]. The reason for the differences could not be detected despite scrutinized testing procedures at the two laboratories.

In Table 5, the DSD results from Fig. 11 are ranked from smallest (1) to largest aggregate loss (5) for both Darmstadt and Karlsruhe laboratories, the goal being to observe a possible agreement. For comparison, also the ranking from pull-off tests at 20 °C is presented. The principle of this ranking is based exclusively on the criterion of overlapping scatter bars. Note that on that basis the ranking of the PA tested in Darmstadt could either be (3) or (4) due to the wide scatter bar that results from the large difference between the first and the second testing campaign in that case.

The rankings are only comparable between AC MR 8 and SDA 4–16; i.e. between strongly compacted slabs with respectively 3.9 and 12.5 vol-% air voids. In contrast, the rankings of the less compacted slabs are not consistent. On the one hand, DSD appears subject to not satisfactorily evaluated operational uncertainties revealed by a strong scatter of the results when the compaction is lower than 100 % and/or the air voids content is high, not leading to a clear ranking. On the other hand, pull-off does not discriminate between SDA 4–16, PA 8 and SDA 8–16. These observations as a whole may be explained by the fact that the mechanisms, the test parameters (such as temperature) and the measured properties (mass versus force) are significantly different between DSD and pull-off.Regarding the measured properties, it is important to note that DSD determines only the total mass of aggregate loss, not considering their number and size. For example, the loss of one big single aggregate could lead to the same result in mass [g] as several small aggregates; a qualitative distinction that would be important for

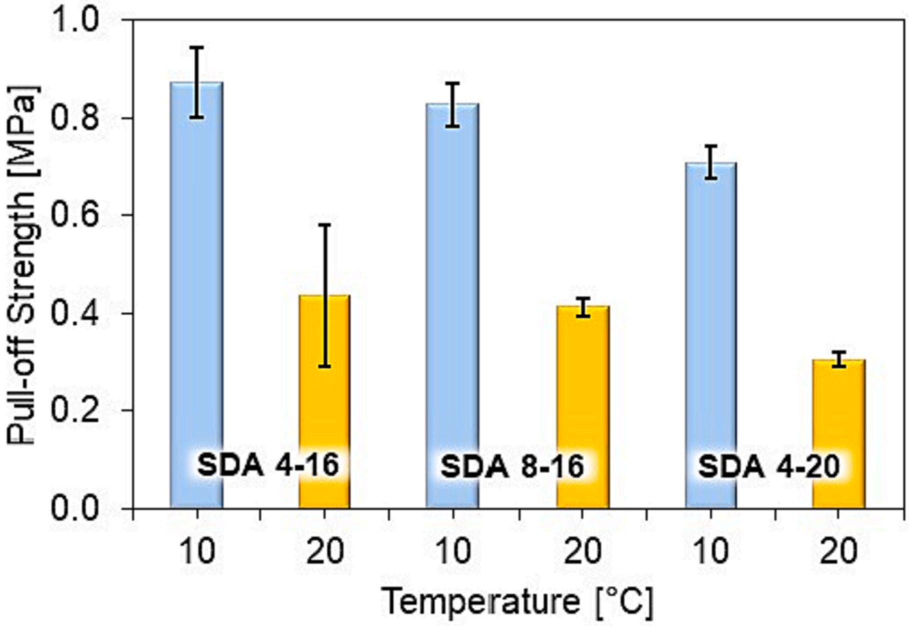

Fig. 8. Influence of temperature on pull-off strength for all SDA slabs tested with counter-frame, 20 N/s, diameter 100 mm (mean values of at least 10 measurements).

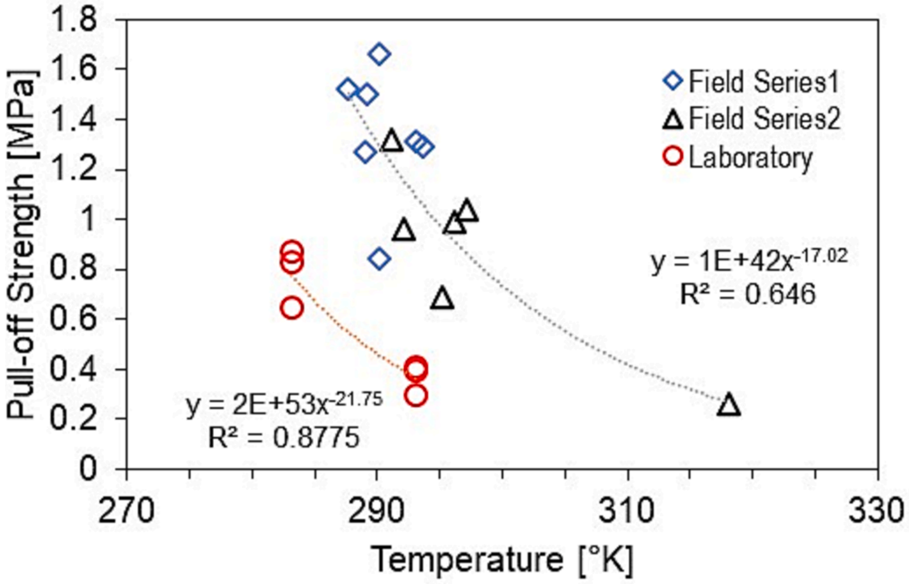

Fig. 9. Influence of temperature on pull-off strength for all pull-off tests carried out in the laboratory and in the field.

the assessment of raveling. The pull-off test on the other hand measures a mechanical adhesion-related property. Therefore, since the SDA 4–16, PA 8 and SDA 8–16 specimens were produced under ideal laboratory conditions with the same high performance binder, it is not surprising that the overall tensile behavior is only slightly affected by small changes in grain size, degree of compaction and/or air voids content. Thus, from a pull-off strength point of view, SDA 4–16, PA 8 and SDA 8–16 are equivalent and not as susceptible to raveling as claimed by the heavily scattering DSD results.

7. Conclusions and outlook

The investigation of the raveling susceptibility by pull-off testing showed the advantages of this test in comparison to the methods described in the European test specification.In the laboratory, when the pull-off test is carried out on slabs supposed to represent a wearing course but without bonding to the layers beneath, an uplift around the tested area occurs. Similar deformation has not been observed on-site where the surface course is strongly bonded to the base. When uplift occurs, the measured pull-off strength is biased. Therefore, it is of utmost importance to fix a counter-frame to prevent deformations of laboratory specimens, whether in the universal testing machine or during measurements with the handheld device.It has been shown that handheld devices may not precisely regulate the pull-off speed. The higher the target speed, the greater the difference between the target and the actual speed. Hence, verification of the test equipment is fundamental. From a series of measurements conducted around 20 °C, it appears that the pull-off speed should not exceed 50 N/s.Another parameter of influence is the

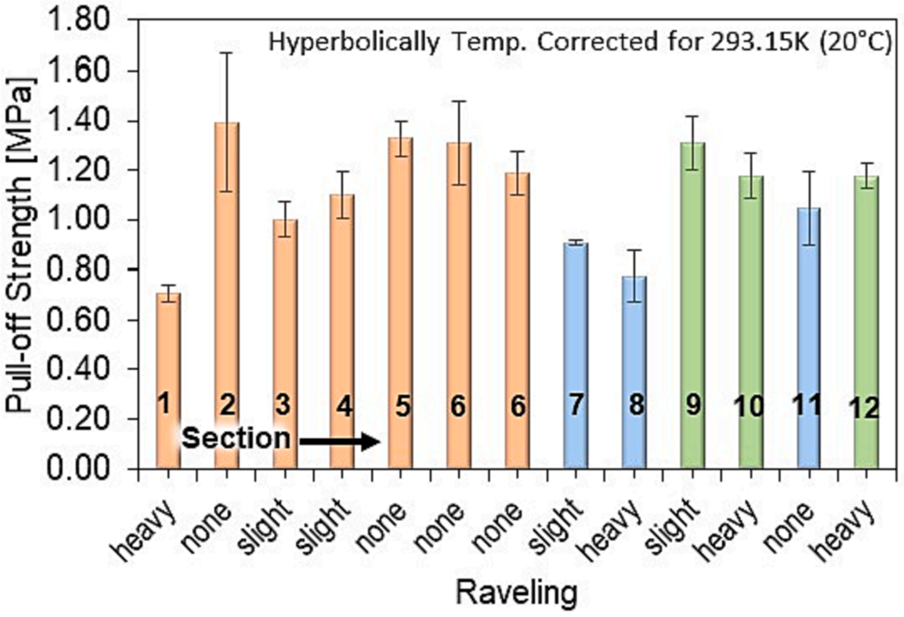

Fig. 10. Visual estimation of raveling versus pull-off strength at reference temperature 20 °C for all pull-off tests carried out in the field, mean values of 3 measurements; orange: series 1 test sections (see Table 2); blue and green: series 2 test sections (see Table 3); the colors blue and green reflect two different low noise products and construction companies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

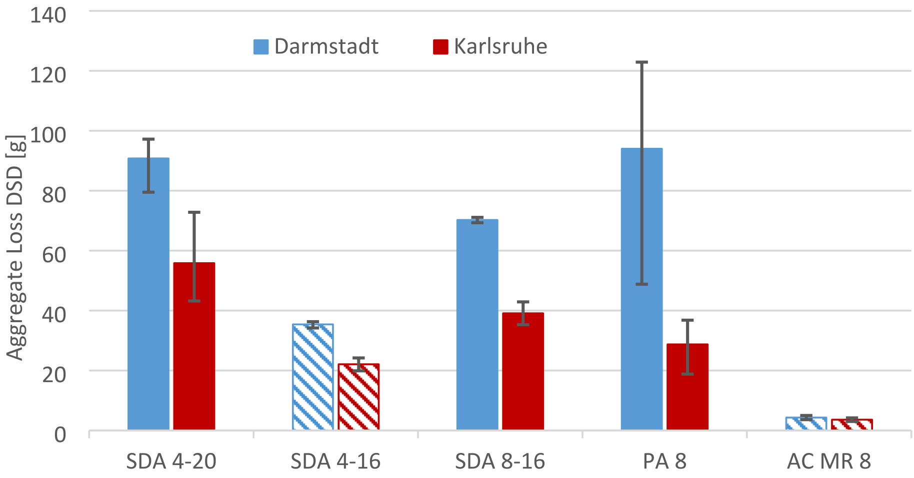

Fig. 11. Comparing aggregate loss results from the laboratories in Darmstadt and Karlsruhe after 10 double cycles for all asphalt mixtures listed in Table 1. Full columns: average of 3 tests carried out on specimens of the same batch and same slab (SDA 4–20, SDA 8–16 and PA 8); hatched columns: average of 2 tests carried out on specimens from the same batch; scatter bars indicate max and min values.

Table 5
Ranking of results from DSD in Karlsruhe (KA) and Darmstadt (DA) and pull-off; DSD ranking from Fig. 11 and pull-off ranking from Fig. 4.

	AC MR 8	SDA 4–16	PA 8	SDA 8–16	SDA 4–20
DSD (KA)	1	2	2	4	5
DSD (DA)	1	2	(3) 4	3	4
Pull-off	1	2	2	2	5

plate diameter because of the effect of the influence zone around the plate where aggregates adjacent to the nominal pull-off area participate to the overall pull-off force. It may be useful to be aware that results from plates of different sizes are not comparable. In this context, one should keep in mind that axial symmetric pull-off loading must be assured such that no tilting of the plate occurs.Regarding the capacity of the method to differentiate between good quality and poor quality slabs it has been shown that pull-off behavior is sensitive to variations of the degree of compaction. This laboratory result indicates that the pull-off method on-site should all the same correctly predict the occurrence of raveling when a new wearing course has been insufficiently compacted. Furthermore, differences were found between two company products leading to qualitative raveling assessments on different pull-off strength levels. This means that for the time being, it may be too early for generally proposing a minimum acceptable threshold value for standardization (e.g. around 1.3 MPa at 20 °C).In order to be able to compare results, the influence of temperature must be taken into account for interpretation. By applying a hyperbolic temperature correction for calculating pull-off strength values at a comparable reference temperature, a correlation between visual assessment and pull-off strength was found. The observation that pavement sections with no visible raveling reached higher values than those with slight or heavy raveling, can be considered promising.With the introduction of a second handheld device, it could be demonstrated that the reproducibility of the method is good. This result should be considered as very satisfactory given that the DSD method (as well as the 3 other methods mentioned in the CEN/TS 12697–50) is not performing well in this respect.When comparing reproducibility of DSD it was found that the device of the laboratory in Darmstadt provided systematically higher results than the laboratory in Karlsruhe, leading to different, non-conclusive rankings. For the open graded mixtures investigated in this study, the mean relative difference between the laboratories is 32 %, a value that meets the findings of an earlier European interlaboratory program. The rankings for porous asphalt PA and the coarser open graded SDA were not consistent between the different laboratories. They were also not consistent with the ranking from the pull-off tests due to the fact that DSD determines only the total mass of aggregate loss, not considering their number and size, whereas the pull-off test measures a mechanical adhesion-related property.Therefore, and because of the complexity of the scuffing test, this research led to the conclusion that the DSD method used in Europe is not recommendable and ready for standardization.The pull-off method meets most purposes. It is a practical test method without the need for expensive equipment and machinery, easy to operate and applicable on-site provided that an appropriate temperature correction is applied to the results.

Funding

This work was supported by the Swiss Federal Roads Office [Grant No VSS 2015/312].

CRediT authorship contribution statement

Françoise Beltzung: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing, Funding acquisition. **Christiane Raab:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Supervision, Project administration, Writing – review & editing, Funding acquisition. **Manfred N. Partl:** Validation, Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank Christophe Marendaz and Hans Kienast for developing and constantly improving the pull-off test procedure and Bernard Schmid, head of Laboroute SA, for providing comparative pull-off measurements on site.

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