1. INTRODUCTION

Numerous factors influence the durability of asphalt pavement constructions: Besides a good resistance to permanent deformation, to crack formation and to oxidative aging, the adhesion of bitumen to the mineral aggregate surface is essential. Specifically under wet conditions this adhesion may decrease and lead to problems such as stripping (loss of a bitumen film from a stone surface), stone loss, water infiltration in the construction, which will consequently increase the adhesion problems and lead to a loss of mechanical strength.[1]. Literature, and practical experience have shown that the properties of the aggregate such as its mineralogy and elemental composition, the porosity, the micro-texture or roughness, the presence of dust (cleanness) and play an important role for the adhesion under wet conditions. Regarding the bitumen type the important factors are less obvious; in most test methods the viscosity of the binder plays an important role, it has also been indicated that the presence of natural wax may have adverse effects, while polymer modification has beneficial effects. Apart from the properties of the particular materials, a large influence on the adhesion properties of an asphalt mixture are governed by the properties of the asphalt mixture, such as its bitumen content, and the bitumen film thickness around the aggregates, the void content, and the overall permeability and connectivity of these voids.

Moisture damage in asphalt can be investigated in many different ways and can be based on different test methods.
Three standardized European approaches to quantify the affinity between aggregate and bitumen are described in EN 12697-11: the rolling bottle test (RBT), the static immersion test and the boiling stripping water test. Despite being standardized methods, the determination of the bitumen coverage degree by visual observation is subjective, at least for the rolling bottle test and the static immersion test.

Recently, with the development of digital image processing tools, different proposals to improve the determination of the bitumen coverage on the aggregates have been published. Methods can be different in the way or the conditions the images are acquired, or in the way the images are analysed afterwards: in the image acquisition, differences in the light source, the camera or the sample position are possible. For example, in [3] a camera with a polarizing filter was used, this allowed to get rid of light reflected by the bitumen surface, and that allowed to use a stronger lightning so that surface texture could be captured in the images. In Mulsow [4], illumination was conducted with a laser light diode at a wavelength of 660 nm, this allowed to highlight the reflectance of bitumen which was different or not present on the stone surface. Another option is to take pictures from different angles or directions, or after turning the sample [5] at different angles, this also allows to separate bitumen reflectance from the stone reflectance. Digital image processing is used to separate the picture into a bitumen and an aggregate portion, which allows a quantification of both phases by counting the pixels. Again different options are available, images can be simply evaluated based on the colour difference between bitumen and stone [6] or prior to this software manipulations can be applied, for example a differentiation based on the YUV values (Y stands for the brightness and UV stands for the colour difference) **Error! Reference source not found.** or RGB-values (red, green, blue) **Error! Reference source not found.**. Moreover, in ref 8, the authors explain that strictly speaking the visualization should be taken in a stereoscopic way (i.e. images acquired from two view sources) to cope with perspective effects, as the aggregate faces are usually not parallel to the image plane. But monoscopic tests (i. e. images acquired from one point) could still be efficient as long as the sample group is large enough, so that errors due to perspective effects can be considered negligible.

In a previous project, the authors have already used their digital image method on aggregates that were subjected to the boiling water test [9]. The intention was to compare DIP results, with the more objective bitumen coverage test based on titration results from the boiling stripping water test. In fact, the plan was to use the titration results as a calibration for the DIP results. But unfortunately, such a comparison was not possible, because the titration results themselves turned out to be not reliable at all times. They were influenced by contaminations or rests of bitumen even after stripping off the coating. This contamination was observed as a discoloration, which was very clear when using a white stone. For example, in Figure 1, a white stone is shown before and after conducting the boiling stripping water test, and in the right figure, a close view of such a stone surface after the boiling water test is presented. The titration test considers the discoloured regions on the stone as a partly coated area. This problem was in fact the main reasons why the authors changed to rolling bottle results in the test described in this study.

a b c

Figure. 1: the surface of a virgin marble aggregate (a), the same aggregate after the boiling water test (b) and a detailed surface scan after the boiling water test by confocal laser scanning microscope (c)

This paper presents a method to measure the bitumen coverage based on digital image analysis. The method is simple and no special equipment is needed. In the paper, the procedure and different steps are explained, the method is applied to various stones types, the repeatability using one or more stones, or even photos obtained from other lab experiments are discussed.

2. EXPERIMENTAL

2.1 Materials

In this work, the same aggregates as in the Rilem round robin test "Bitumen / Aggregate affinity Rilem Round Robin Test on rolling bottle test " [10] were selected. In the round robin test, three binders and four stones types were used, giving a total of 12 combinations. The aggregates were obtained from Aggregate Industries from quarries located in the UK. According to Hicks [11] these aggregates can be ranked according to their degree of stripping. Pictures of these uncoated aggregates, in a dry and a wet form, are represented in Figure 2. For some of the aggregates there is a colour change when taking the image in a dry or a wet condition.

For the rolling bottle tests, conducted in the first part of this paper two stone types were selected; greywacke and granite. In this case greywacke tends to have a lower degree of stripping compared to granite. For the binder a 50/70 bitumen according to the EN 14023 was used.

In the second part of this paper, photographs taken during the RBT were further analysed using the DIP method. This step was applied to all the binder-stone combinations.

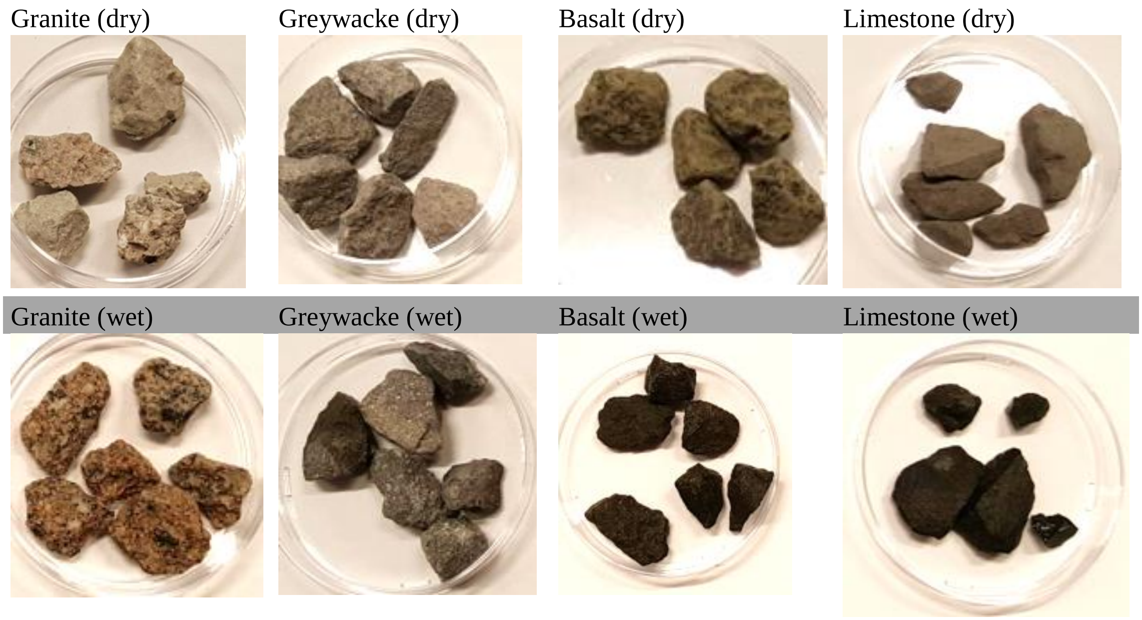

Figure 2: Used aggregates: dry & wet

2.2 Visual inspection

For the visual inspection, the estimation of the degree of bitumen coverage was determined using the scale provided in the EN 12697-11 2012 (E) Annex A (Figure 3). In the tests performed in this study, three persons were independently from each other estimating the degree of coverage.

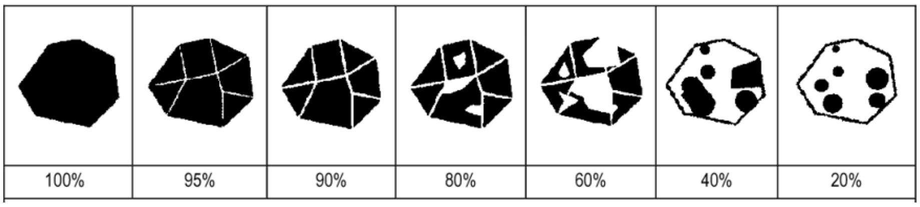

Figure 3.: Graphical help for the assessment of the degree of coating.

2.3. Image acquisition

Before being able to apply DIP, of course a picture of the aggregates is needed. In the first part of this project, a setup was used allowing to take photographs with a good background to foreground contrast, constant lighting conditions, and minimal glare and shadow effects. The setup, Figure 4, consists of an aluminium frame, led lighting and a digital camera, supplied by Imaging Development Systems GmbH (IDS). In this study the pictures were viewed in a monoscopic way, as pointed out in [8] this should be sufficient as long as enough data are taken. An IDS UI 1220 SE-camera was used, the specifications are listed in Table 1.

Table 1. Specifications of the camera

Sensor type	CMOS Mono
Resolution	0.36 Mpix
Resolution	(h x v) 752 x 480 Pixel
Colour depth	8 bits monochrome
Pixel size	6 µm
Lens	F1.4/25 mm

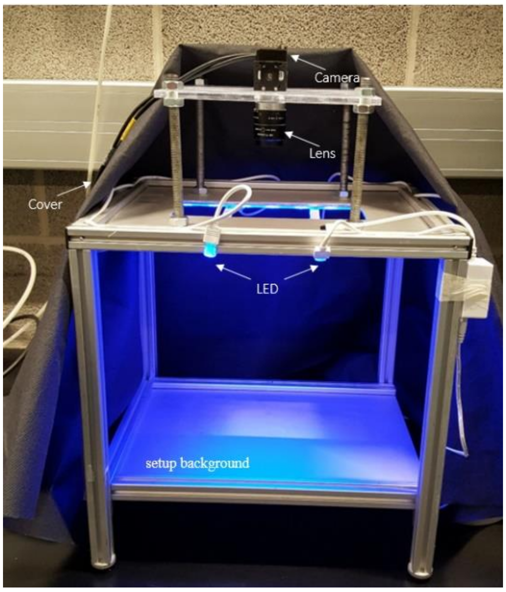

Figure 4: Experimental setup for the image acquisition.

2.4 Digital Image Processing

DIP allows to calculate the area related to the uncovered stone surface and the coated, or bitumen area. In this work ImageJ **Error! Reference source not found.** is used, no other modifications were applied to the images. Initially, the analysis was made on pictures of individual stones, afterwards, the same analysis was performed on pictures containing five stones. In the upcoming sections, these steps are described.

2.4.1 Calibration

Before starting the analysis on bitumen aggregate pictures, it was necessary to check the software's capabilities. Reference patterns, as shown in Figure 5 were used, these are optimized in order to calibrate the experimental setup. Shape and percentage of the color patterns were varied. For each reference pattern the degree of coverage was derived using the method described below. The optimisation of the calibration patterns was based on the findings published in [9]. In this case the yellow and black color scheme was chosen, it was found that a yellow color is best to mimic the stone and bitumen color.

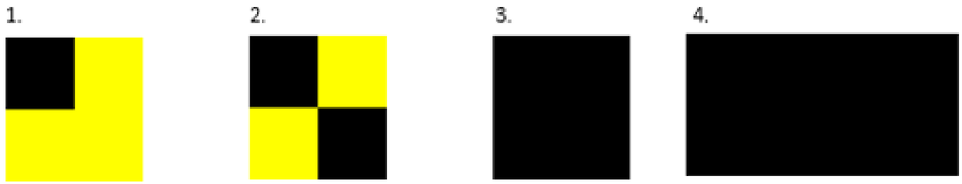

Figure 5: Calibration patterns

The results of the of the calibration procedure based on digital image processing, derived for a white illumination and a white background colour are summarised in Table 2. White light and a white background gave the best result. After processing, a small measuring error of 1,08% was obtained, for the 50/50 case, table 2. This deviation is related to the raster limitation of the sensor of the digital camera. When two black squares connect in one point, as shown in the second image of Figure 5, the camera has problems to define the image discontinuity, resulting in a slight over-estimation. By refining the imaging raster size or by rotating the image, the difference can be reduced. But as this difference was very small, the camera was believed to be ok.

Table 2: Values for reference patterns obtained by DIP

Pattern	Reference Pattern	Measured by DIP	Difference Δ
1	25%	24,66 %	0,34 %
2	50%	48,92 %	1,08 %
3	100%	100,00 %	-
4	100%	100,00 %	-

2.4.2 Focus distance

All the photographs were taken with the same distance between lens and object, and as the stones are not flat, there are always some regions on the stone surface which are "out of focus". This may give the impression that the image is not very sharp, therefore the effect of having areas out of focus on the coverage determination was investigated. The results of this preliminary test are shown in Figure 6 and Table 3. In this test a difference in sharpness of the photographs was created by changing the distance between the lens the stone surface. In the images in Figure 6, the change in this distance is reported and a difference in sharpness can be observed. Nevertheless, when computing the bitumen coverage even with a height difference of 1cm, the maximum difference in the degree of coverage between these images was only 1.35 %, Table 3.

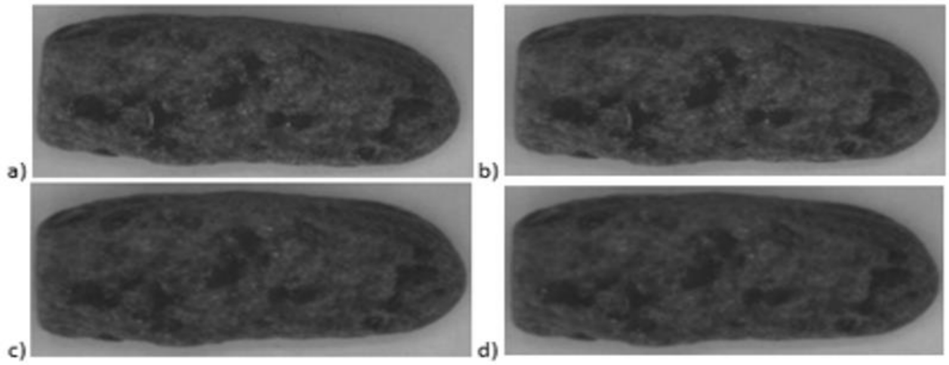

Figure 6: a: stone at bottom plate, b) height + 2 mm, c) height + 5 mm, d) height + 10 mm

Table 3: Values for Ac obtained by DIP using different focus distances

	# coated pixels*10^3	Total # pixels*10^3	Ac %
a	3.57	37.93	9.40%
b	3.76	38.76	9.71%
c	3.32	39.69	8.36%
d	3.47	40.73	8.52%
		max div.	1.35%

2.4.3. Digital image processing procedure

A first step in the analysis includes uploading the picture in the digital image processing software “Image J” **Error! Reference source not found.**, and trimming the picture, meaning removing the background and optimising of the image contrast. The second step involves the construction of a grey level histogram, and the separation of the bitumen from the stone surface, which allows a calculation of the bitumen coverage. By knowing the uncoated and the coated area, the degree of stone coverage (Ac) can be calculated according to equation 1.

$$A_c = \frac{\text{coated area [pixels]}}{\text{uncoated + coated stone surface [pixels]}} \qquad \text{eq.:1.}$$

The following section is a step wise explanation of the digital image processing procedure. In the example one stone is used, but the method is similar for a five stone batch.

Step 1: Pre-processing.

At first, an image is obtained by the digital camera, and is imported in the software. In Image J it is possible to isolate one stone from the image and to optimize the contrast. In Figure 7, an image taken by the camera is presented, before and after treating it in Image J software.

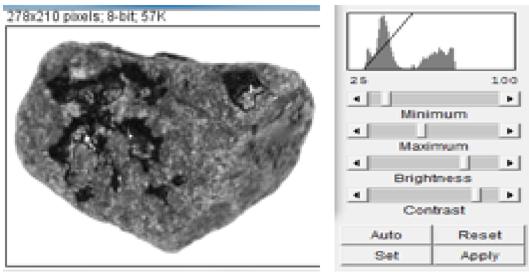

Figure 7: Stone cut out of full image **Optimizing the contrast of the image**

Step 2: Separation by thresholding.

The second step involves the transformation into a grey level histogram, and the calculation of the bitumen surface versus the total grain surface. The software allows to construct the histogram, shown in Figure 8. In this case, the distribution histogram shows two distinctive zones, the darker area represents the bitumen coating, while the stone surface is represented by the lighter area. If both areas are separated by a minimum, this can be used to set the threshold. The critical point here is to set the thresholding correctly [13]. To check if the threshold corresponds to the various areas, the software allows to visualize these areas, for example in Figure 8b the bitumen area is selected, the darker area, while in Figure 8c the stone (coated and uncoated area) is represented. In this case the correspondence seems to be very good.

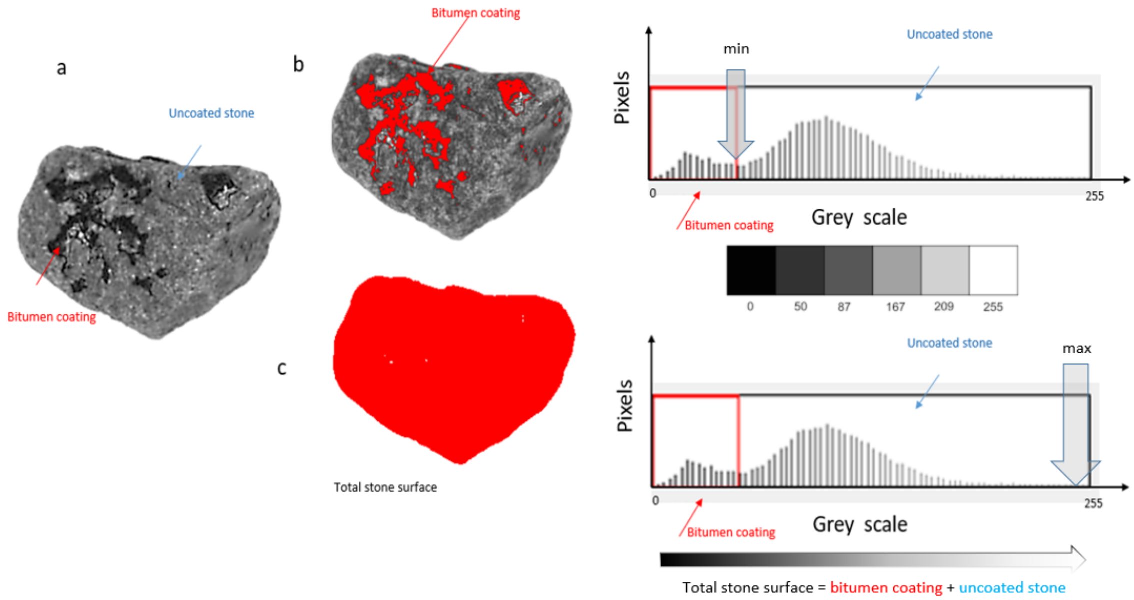

Figure 8: Separation by thresholding

Step 3: Particle analysis and calculation of Ac.

Finally, the selected areas are associated to a pixel count, this is shown in Figure 9. Sometimes, the black bitumen surface shows a reflection in the pictures, and this will be counted as a white are in the image J software. This area can be included in the bitumen part by crossing the option "include holes" as shown in Figure 9. Once the digital image processing software has recognized the particle surfaces related to bitumen and the total stone coverage, the area in pixel can be computed, and the coating percentage (Ac) calculated.

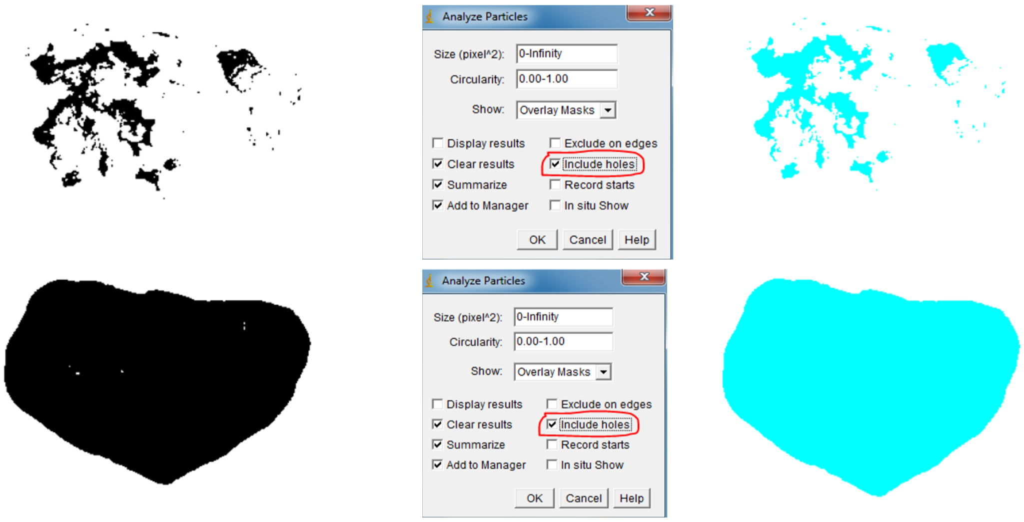

Figure. 9: Putting in settings to get pixel count

2.4.4. Digital image processing procedure used on photographs

As mentioned before, in RILEM TC 237 SIB (Sustainable and Innovative Bituminous Materials) the Task Group 1 (TG1) focused on various testing methods to assess the affinity between aggregate surface and bitumen. More specifically on the repeatability and reproducibility of adhesion tests such as the rolling bottle test or the boiling stripping water test according to EN 12697-11. For the rolling bottle test, eight laboratories participated, and the results revealed a poor reproducibility. The question was raised if it came from the visual observation as this is a subjective analysis of the coverage. As some labs had taken photographs of the aggregates, it was possible to compare these pictures directly. From this first comparison, it was clear that in some cases there was a real difference in the coverage, so the poor reproducibility of the RRT tests could not be solely explained by the variability of the visual inspection method. Nevertheless, in a second attend, a “blind test” was made, and several pictures were sent to various labs for a visual inspection. A total of ten laboratories made their own visual determination based on the same pictures. The analysis of this visual inspection test showed a variability in reading between 10 % to 30 % in absolute value, and between 5 % and 12 %, in relative value.

For the comparison between a visual inspection and DIP, those pictures were also used here in this study. After importing these photographs into image J, the software allowed to cut out separate stones out of the images. In this case, for each image five stone, being representative, were selected, this is shown in Figure 10. By using the digital image processing procedure as described above, the bitumen coverage of these stones could be derived.

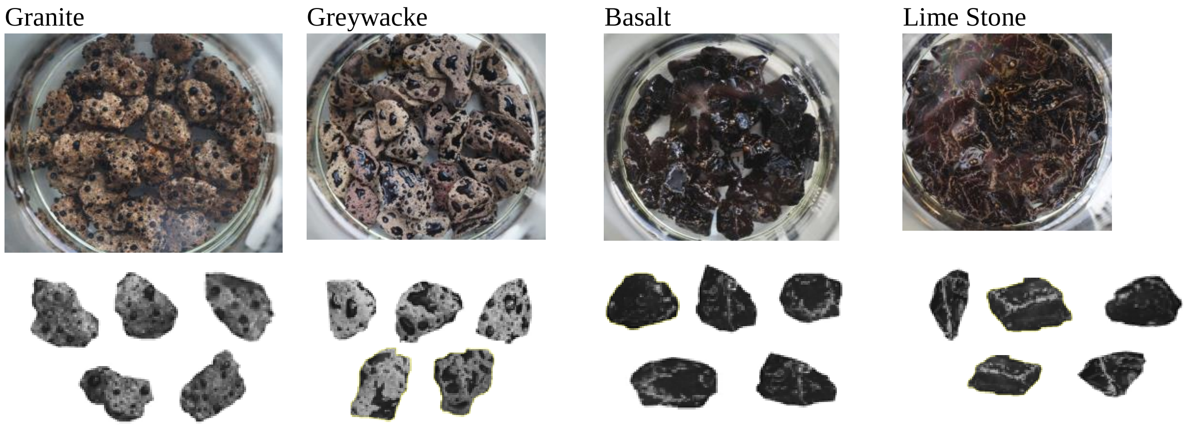

Figure 11: Single stones taken by using Image J from full image

As basalt is a dark stone, problems were expected when trying to separate the bitumen from the stone surface. Therefore, the histogram as it was obtained from the software is shown separately, Figure 12. And as expected the separation of both areas is much more challenging compared to the case of greywacke. The large peak in the histogram represents the darker area which corresponds to the bitumen, and the small bump in the curve presents more grey area corresponding to the stone surface. In this case the threshold was set manually in the picture.

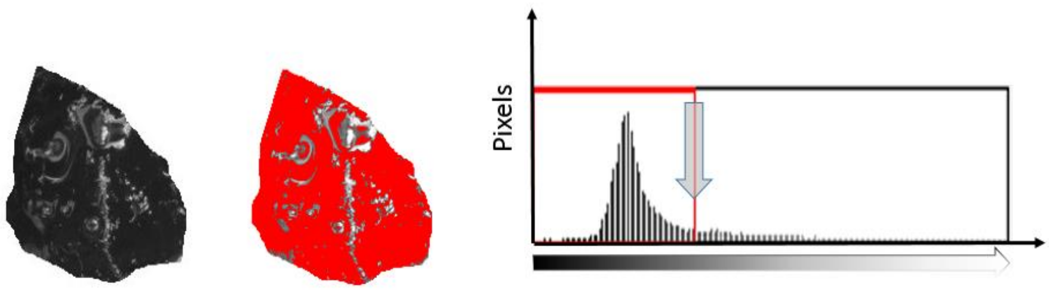

Figure 12: Thresholding histogram obtained for Basalt

3. RESULTS AND DISCUSSION

3.1. Results after rolling bottle tests

The rolling bottle tests were performed according to EN 12697-11. The standard was followed, but after the visual inspection, five stones were taken out from each bottle, and used in the alternative digital image processing method. Three bottles were tested per sample, and bitumen coverage was analysed after 6, 24 and 48 hours rolling time. The selection of the stones was performed by selecting the most and the least coated stone and three intermediated coated stones. The five stones, selected from each test bottle; were first measured separately, resulting in 15 images for each specific rolling time and bitumen stone combination, referred to as “DIP-one”. These 5 stones were also photographed together in one picture, which was repeated 3 times after shaking the stones. This procedure is referred to as “DIP-five”. So, the DIP-five procedure is for a specific rolling time and bitumen-aggregate combination, based on 9 images, three repeats from three test bottles.

Results greywacke

In Figure 12, results for greywacke are presented, in the first bars the visual inspections and next to it DIP results. The error bars correspond to the minimum and maximum value. When comparing the averages of the DIP method to the averages of the visual observations, there is a difference after the 24h test. This difference is not unexpected, as the degree of coverage is in that case intermediate, and according to the Rilem RRT that is the most difficult case to determine visually. When comparing the variation in results, the DIP results using 5 stones in one photograph have a the lowest variability. The result from the Rilem Round robin test for this bitumen stone combination is also represented in the last two bars of the diagram, only to indicate that these measurements are within the variation obtained in the RRT.

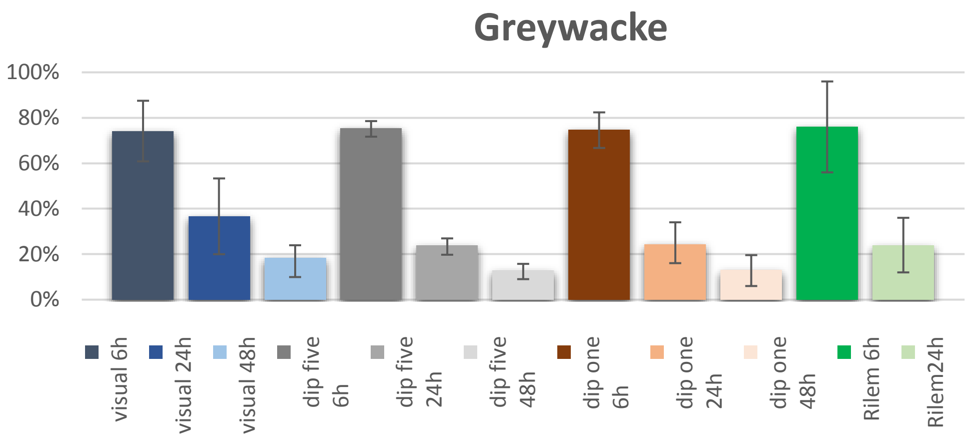

Figure 12: Rolling bottle test results for greywacke, by the standard method (visual) and the DIP method

Results granite

The results for granite are presented in Figure 13. The observations are very similar as for the greywacke sample. Average values for visual inspection and DIP results are similar, except after 6h there is a somewhat larger difference. For the visual inspection, the variation is again larger as compared to DIP, indicating the major drawback of the visual method. This emphasizes the need of a more reliable method to determine the bitumen coverage. Looking to the DIP results again very similar results whether one stone or five stones were investigated using DIP, although differences in the variation van be observed.

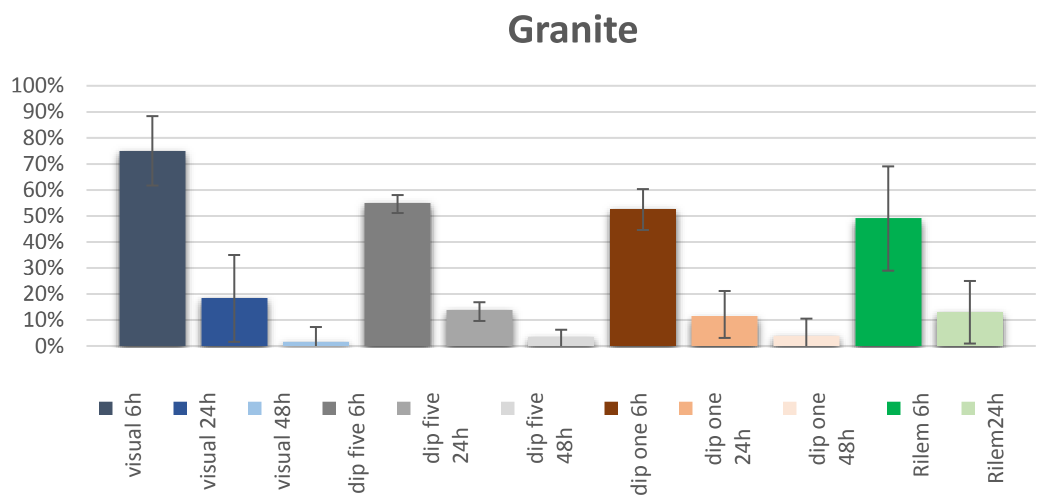

Figure 13: Rolling bottle test result for granite, by the standard method (visual) and the DIP method

3.2. Digital image processing result obtained from images from the RRT

In this section, photographs, which were visually determined in a blind round robin test, were investigated by the proposed DIP method. In this part, only stone by stone images were analysed, these were cut out from the overall image, Figure 11. In Figure 14, the results of the blind RRT test are compared to the DIP results. The average values obtained for DIP correspond to those from the round robin test, but the variability is lower.

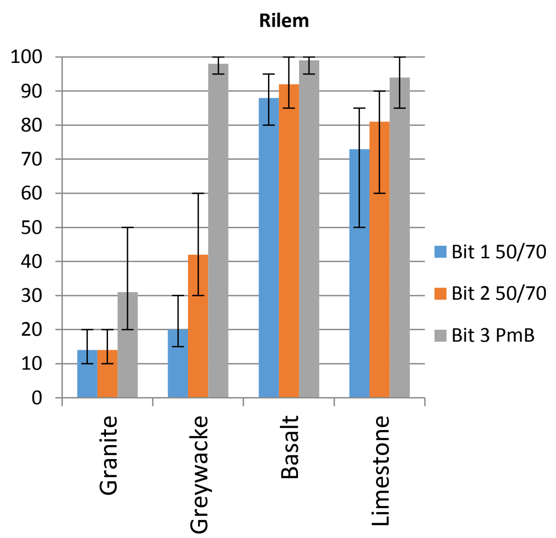

Figure 14 a: Ac results blind test Rilem by using standard method

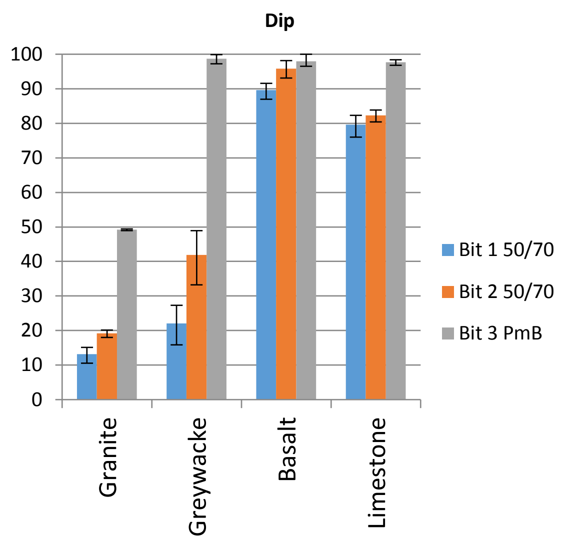

Figure 14 b Ac result obtained by DIP

4 CONCLUSIONS

A digital analysis method to determine bitumen coverage is proposed. In part 1, it was shown that the method can be used to determine the bitumen coverage, by taking photographs of single stones or a set of five stones. This was demonstrated for two stone types, greywacke & granite. Compared to the results of the visual determination, described in EN 12697-11, the DIP method resulted in a smaller variation, and a more objective determination of bitumen coverage. To record the photographs, a special setup was constructed, allowing to optimise the background versus aggregate contrast, and to reduce unwanted reflections.

In a second part, photographs taken by other laboratories (without the special setup) were investigated using the same DIP method. The results indicate that this can also give reliable results. In addition, it indicates that the special camera setup, proposed in the first part is not a necessary requirement, it is sufficient for the method to take pictures of the full batch, provided the contrast is good. Although the analysis time to be performed afterwards on the picture is shorter if small stone batches are photographed.

In general, the method based on digital image processing shows results with a lower variability compared to the visual method described in EN 12697-11. Nevertheless, the method still has some drawbacks; especially for dark stones where selecting the bitumen and stone area is challenging. For such a case, improvement would be recommended. Further improvements would be helpful, such as some automation of the image analysis step to reduce the analysis time.

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