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Image Based Modeling Technique for Pavement Distress surveys: a Specific Application to Rutting

L. Inzerillo, G. Di Mino, S. Bressi, F. Di Paola and S. Noto

Abstract— **Image-based modeling (IBM) is a well-known technique to obtain high quality 3D models based on multi view images. IBM started being used in several applications such as inspection, identification of objects and visualization, due to the user-friendly approach, the low cost and highly automated technique.**

This paper focuses on the investigation of the potential application of IBM in the diagnosis of road pavement distresses and in particular rutting. Indeed, the evaluation of the rutting distress is a fundamental step to define the whole state of a pavement as demonstrated by the calculation of Present Serviceability Index (PSI). Currently, the permanent deformation is measured monitoring visually the rut depth with the approximations that this procedure involves. Nevertheless, the exact measure of the rut depth is necessary to evaluate precisely the cause and the severity of this distress and be effective in the maintenance and rehabilitation of the pavement structure.

The objective of this study is to apply the IBM technique on a laboratory rutted sample, in order to verify the accuracy of the method in determining the rut depth. To achieve this, a comparison has been made between the 3D model obtained with IBM and the one obtained with blue led 3D scan (Artec Spider) of the same rutted asphalt concrete. The metric accuracy of the model is then defined and its validity is assessed, in terms of distress diagnosis.

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Using the IBM it is possible to obtain three-dimensional digital models with accuracy higher than with the traditional monitoring. Therefore, the higher control on the distresses may lead to an improvement of the road pavement management, which addresses the challenge to improve the overall quality of the transportation system.

Index Term— **Accuracy, distress, Image-based modeling, rutting, survey.**

I. INTRODUCTION

A. *Rutting in flexible pavements*

Two of the most common causes of failure of flexible pavements are rutting and fatigue. When a pavement structure suffers of rutting problems, then the material under the wheel path flows to form a groove or rut [27]. This type of distress in asphalt pavements increases progressively if the number of load cycles increases. Two phenomena within the pavement materials contributing to rutting are the further compaction, due to the traffic flow, and shear plastic deformation. Rutting may be caused by several aspects such as poor compaction of Hot Mix Asphalt (HMA) layers during construction, inadequate mix design (percentage of voids, too soft bitumen), underestimation of the subgrade characteristics and excessive traffic loading. Rutting may occur also using Reclaimed Asphalt Pavement (RAP) in asphalt concrete, because RAP aggregates can be rounded at the end of the pavement service life, hence facilitating flow and further densification. The use of aggregates with a significant proportion of rounded ones can lead to higher rutting susceptibility, especially in the case of wearing courses [5]. A depression under the wheel path represents a severe irregularity of the pavement surface, which becomes even more dangerous when it rains, as the rut depth can be filled by water that causes the vehicle hydroplaning. Moreover, the reduction of the thickness layer under the wheel path increases the occurrence of other types of failures of the pavement, as for example fatigue cracking [4]. Therefore, it is evident that permanent deformation decreases pavement's service life, and rutting resistance is one of the main performances that controls the durability and structural capacity of pavements, as well as drivers' safety.

Several approaches have been developed to predict and measure the permanent deformation in flexible pavements.

As part of the Strategic Highway Research Program (SHRP) [18, 19], a number of test methods were investigated

to assess the rutting potential of different asphalt mixtures. Results showed that the most suitable accelerated test is a cyclic shear test, in which combinations of shear and normal stresses can be applied to the specimen, either continuously (creep loading) or repeatedly, with short loading durations. Later on, Collop et al. [5] developed a viscoelastic model using the theory of linear viscoelasticity to model steady-state rutting in flexible pavements. Depending on the history of environmental conditions of the pavement, the model is able to determine the viscosities characterizing the layer properties.

Mechanistic-empirical (M-E) pavement design methods (PAVEMENT M-E, kenPAVE, Alizé) include the rut depth prediction as a fundamental part of the estimation of the pavement service life. These methods combine mechanistic calculations of pavement stresses and strains with the estimation of the consequent rutting, based on empirical data.

The quantity and quality of empirical data used for the calibration of the empirical distress model are responsible for the accuracy and robustness of the model itself [18].

More sophisticated models for bituminous layers behavior are needed to rely less on empirical data and to enhance fully mechanistic distress prediction [17].

The elastic domain is not sufficient to describe the material behavior over its range of temperatures, loading rates and overall conditions. Therefore, based on prior knowledge of the nature of relationships between data, nonlinear finite element methods in three dimensions appeared being used to model the viscoelastic and viscoplastic behavior of the material [14, 26]. This approach provides more realistic simulations of the pavement response.

Nevertheless, prior knowledge of the nature of the relationship between data is not always attainable. For this reason recent studies used Artificial Neural Network (ANN) [15] and its variant, the Multilayer Perceptron (MLP) [7, 18], as a technique to recognize a pattern system.

Other studies, have applied a branch of Genetic Algorithms, namely Genetic Programming (GP) [3], and variants such as Multi Expression Programming (MEP) [21] as another alternative approach for the analysis of the rutting potential.

To understand the reason of the numerous efforts made by researchers in determining and predicting permanent deformation, it is sufficient to read the wide survey conducted in 1998 by the Federal Highway Administration FHWA. According to this, rutting is considered to be the most serious distress mechanism in pavements, followed by fatigue cracking and thermal cracking [13].

In the field the rut depth can be measured by visual inspection and straight edge, while in laboratory the phenomenon can be investigated using the Wheel Tracker Machine (WTM) [32].

The permanent deformation is not considered only at the design level, although it is fundamental to measure it, in order to define the pavement condition expressed by the Present Serviceability Index (PSI) (1).

$$PSI = 5.03 - 1.91\log\left(1 + \overline{SV}\right) - 1.38\overline{RD}^2 - 0.01\sqrt{(C+P)}. \qquad (1)$$

Where:
SV= average of slope variance over the section [-]
RD = average rut depth [in.]
C = cracking [ft/1000 ft^2]
P = patching [ft/1000 ft^2]

As shown in Equation 1, pavement distress information (rut depth, cracking and patching) is basically converted into a condition index. Indeed, the PSI, which is developed as a result of AASHO road tests [1], converts the information gathered from all distress types, severities, and quantities into a single number. Equation 1 shows that PSI largely depends on the rut depth (RD exponent=2).

Therefore, the exact measure of the rut depth is necessary to evaluate the severity and the cause of this distress, and consequently to establish an optimized strategy of road maintenance and rehabilitation.

Different severities of rutting could be evaluated (Fig. 1), depending on the cause of the distress:

1. Insufficient compaction of the asphalt concrete during the construction and/or high voids content. This can cause further densification during the service life (Fig. 1a). The resistance of HMA to rutting is significantly affected by in-place density. In this case the asphalt milling is necessary, as well as the installation of a new asphalt layer.

2. Uplift creation, shear flow. The total rut depth (Peak-to-Valley) does not correspond to the downward (Baseline-to-valley) (Fig. 1b). The rutting in this case appears to be related to high binder contents and/or high Voids in Mineral Aggregates (VMA) values, in combination with low mastic stiffness. The mix design of the asphalt concrete is not adequate and should be improved to provide higher rutting resistance.

3. Structural rutting. Subsidence of all the pavement layers caused by the deformation of the subgrade (Fig. 1c). The upper layers should be removed and a specific treatment and compaction should be planned to strengthen the subgrade.
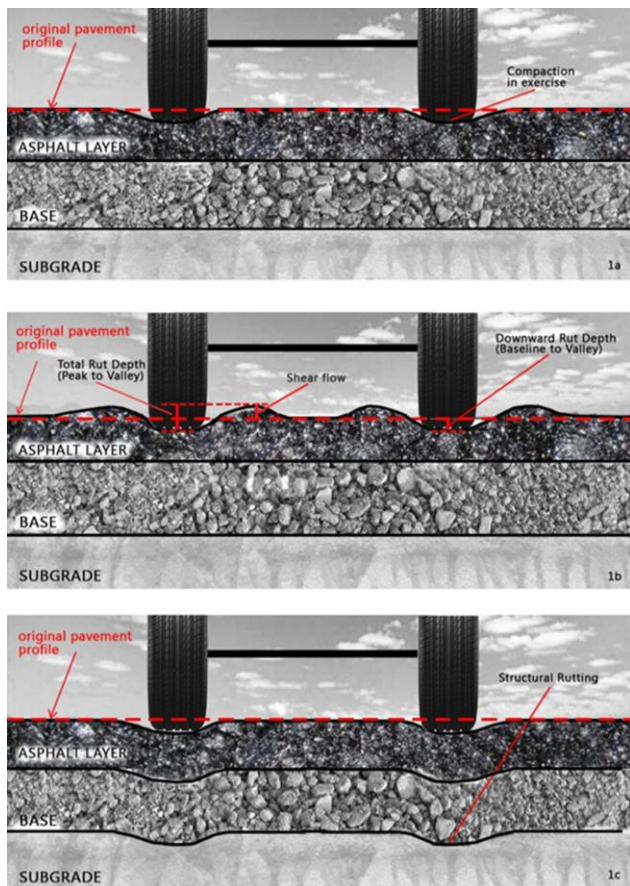
Fig. 1. Qualitative representation of different types of rutting.

Once the type of distress is defined, the main objective of the Pavement Management System (PMS) is to identify an optimal series of activities, considering the economic constraints, in order to define the most effective maintenance strategy for long-term periods.

Life Cycle Cost Analysis (LCCA) is an analytical method that allows several costs of different investment alternatives over an established period of time to be evaluated (i.e. analysis period) [10].

B.   1.2.   Distresses surveys

Most pavement condition surveys use conventional visual rating systems. This approach to detect the pavement distress is time-consuming, subjective, it has high degree of variability, it is unable to provide meaningful quantitative information, and on average leads to inconsistencies in distress detail over space and across evaluations [6].

Despite the fact that the majority of reported advances are made for the development of automated distress detection that reduces the subjectivity of visual measurements, certain issues remain unsolved. The necessity of special devices for instance (special lights, laser, etc.) increases the costs and limits of the application of automated distress detection methods. Moreover, certain systems have low processing speed/low accuracy and they can only be effective with certain types of distresses [6].

Recent advances in image spectrometry led to the consideration of digital images as an interesting technique for the monitoring of surface conditions of asphalt pavements.

Precise information regarding the chemo-physical properties of the materials was obtained using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) [16]. References [11], [12], [23] and [24] showed that through the use of high spatial resolution images, it is possible to compute a quality index representing the condition of the asphalt pavement from the remote sensing images.

Wang and Smadi [31] explained that recent 3-D imaging technique has certainly shown promising results for comprehensive and fully automated survey of pavement condition. However, coordinated research in this area is still needed.

Recent literature studies regarding the application of Image-based modeling technique in road domain are limited and certain problems emerge: the detection of the distress location might be distorted due to the presence of shadows and brightness, different textures and noise and tree leaves. Moreover, the system could be also affected by inaccuracy due to possible lens distortions and not reliable perspective projection [33]. Additionally, the metric accuracy of the IBM technique for pavement distress analysis has been not investigated.

II.   OBJECTIVES AND RESEARCH STAGES

Rutting is very frequent mostly in urban areas and it is identified due to slow traffic. Generally, in the urban road network, the distresses analysis is based on visual monitoring; on the contrary in highways and motorways it is possible to carry out the survey using the terotechnology such as Automated Road Analyzer (ARAN) and Sideway-force Coefficient Routine Investigation Machine (SCRIM). The objective of this research work is to introduce an innovative method for pavement distress survey, in order to implement a technology-based analysis of the pavement damages that overcomes the several problems and limitations of the visual monitoring, especially in urban areas. This will allow in near future, to move towards a new way of conceiving the road distress surveys, and to ensure an innovation in the process and in human resources management. High level of automation could be implemented, relying on the high degree of detail of the distress description.

IBM technique has high potential in the diagnosis of pavement distresses; however its application in road pavement domain is quite limited, while it is mostly used for architectural and archeological studies [25, 22, 9].

IBM is based on the acquisition of a set of images of an object. The elaboration of these images generates a 3D model that allows obtaining an interactive rendering of the object itself.

Therefore, IBM technique could become crucial for the evaluation of road pavement distresses. It would represent a further improvement in the analysis of rutting that is currently carried out through visual survey.

This approach would lead to several advantages, such as the

reduction of subjectivity and variability, as well as the high level of automation, since it does not require personnel's training. It is straightforward that this technique is extremely less costly and time consuming.

IBM method would lead to the precise identification of the cause of distresses and, consequently it allows intervention, so as to determine an optimized maintenance that combines lower costs and maximum effectiveness.

A first approach of the IBM application has been carried out to evaluate the permanent deformation on laboratory rutted samples of asphalt.

The metric reliability of the IBM 3D model is evaluated by comparing it with the model obtained using a 3D scanner (Artec Spider). The latter model was used as 3D virtual reference, closer to a more realistic reconstruction. The metric accuracy is calculated measuring the deviation between both models through the Root Mean Square (RMS) value.

III. METHODOLOGY

The following steps were carried out:
1) fabrication of the samples,
2) application of Image Based Modeling technique on laboratory rutted samples: data set and images processing,
3) comparison of the 3D models obtained with IBM and 3D scanner Artec Spider and computation of metric accuracy,
4) metric interpretation of the results and geometrical investigation of the reconstructed model.

A. Fabrication of the samples

Asphalt concrete with maximum nominal size diameter 15 mm (AC-15) has been produced. The target grading curve and the reference grading envelope are presented in Fig. 2.
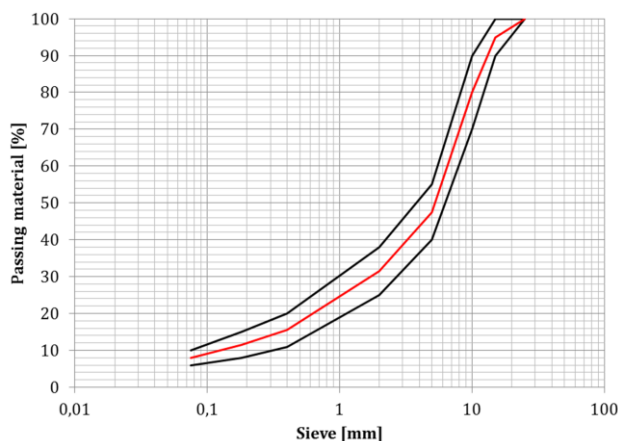

Fig. 2. AC-15 grading curve.

The mix design optimization was carried out according to SUPERPAVE methodology and using the Gyratory Compactor [2]. The optimal bitumen quantity resulted equally to 6.5% of the weight of the mixture. Bitumen with penetration grade of 50/70 has been used. Samples manufacturing was carried out according to standards UNI EN 12697-33 [28] and UNI EN 12697-35 [29] (mixing and compaction in the laboratory). Roller Compactor (UNI EN

12697-33) has been used for the samples compaction.

The aggregates were washed, dried and heated at fabrication temperature (160°C). Subsequently, they were mixed with the pre-heated (160°C) bitumen, then the bituminous mixture was poured into a mold (350 x 350 x 50 mm) and compacted at 145°C.

The slab thickness was 50 mm. Once the slab of asphalt concrete was produced, it was tested with the WTM according to the standard UNI EN 12697-22 [30]. The test was carried out at 60 °C and for 10000 cycles.

B. Image Based Modeling technique on rutted sample

The software that allows achieving the higher metric accuracy, among all the currently available, is Adobe Agisoft PhotoScan®. Therefore, this has been selected to define the 3D model of the rutted sample according to the following steps:

1) Generating the network of images (data set). The correct sequence of photos is very important to achieve satisfactory results. If the sequence changes, then the result will be altered. The pictures should be taken following a continuity path surrounding the object and with the same focal length. The procedure to be followed for the right sequence of pictures, is described in detail in the next paragraph.

2) Import the data set in PhotoScan and set the parameters, according to the scale of the object and the resolution of the expected 3D model. Exploiting the photogrammetric approach and the algorithms of computer Vision, PhotoScan is able to reconstruct the internal parameters of the digital camera and the position in space of the homologous points. Through the correspondence pixel by pixel, the 3D coordinates of all the points were found and the polygonal model was reconstructed.

Detailed descriptions of the aforementioned stages are presented in the following paragraphs.

1) Data set

In order to create a data set, it is necessary to solve the critical aspects raised during the procedure, due to the nature of the object. The dark color of the asphalt sample, the uniformity of the material, and the homogeneity of the surface are some of the aspects that can cause alignment errors.

For this reason, chalk markers were drawn on the top of the sample as shown in Fig 3.
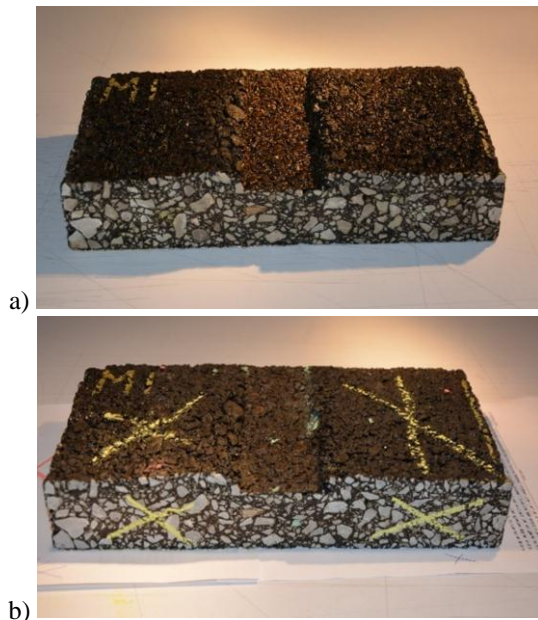
a)

b)

Fig. 3. a) Laboratory rutted sample and b) laboratory rutted sample with markers application.

Afterwards, the data set could be acquired. It is necessary to capture a sequence of photos of the object ensuring that the angle between one shot and the next, is between 5 and 10 degrees and the overlap is approximately 70%. An example of photographs data set taken to be generated with PhotoScan, is shown in Figg. 4 and 5.
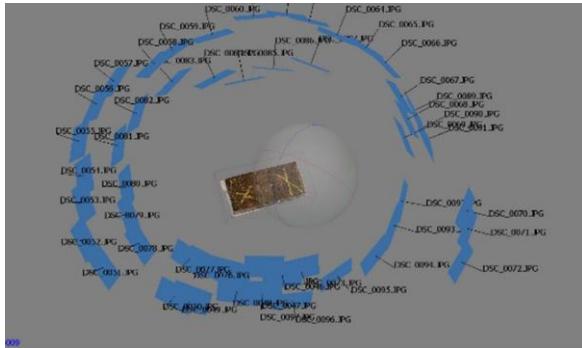

Fig. 4. Overtop view of the data set in Agisoft Photoscan.

Fig. 5. Frontal view of the data set in Agisoft Photoscan.

2) Images elaboration: Agisoft PhotoScan®

Agisoft PhotoScan® is an advanced software that creates professional quality 3D models from images. Based on the latest multi-view 3D reconstruction technology, it is efficient in both controlled and uncontrolled conditions. The image alignment and 3D model reconstruction are both fully automated. In the photos alignment stage, PhotoScan searches for the common points and matches them. Moreover, it finds the position of the camera for each picture and refines the camera's calibration parameters. All four available algorithms in PhotoScan, were applied for 3D mesh generation: Arbitrary - Smooth, Arbitrary - Sharp, Height field - Smooth and Height field - Sharp methods.

After the construction of the mesh, an editing process is necessary. The refining of the raw mesh can be effectuated with PhotoScan: mesh decimation and removal of detached components. Afterwards the mesh can be textured as shown in Fig. 6.
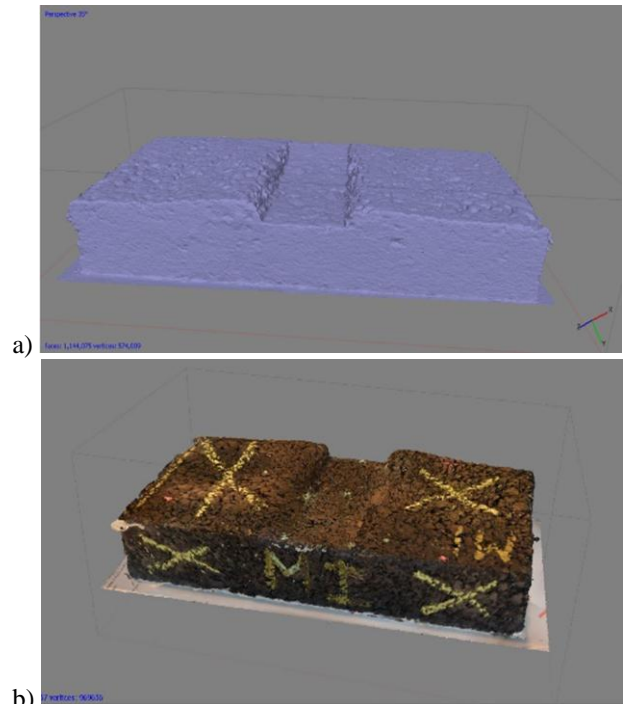

a)

b)

Fig. 6. a) Geometrical and b) geometrical-texturized 3D model in Agisoft Photoscan.

C. Comparative analysis and metric accuracy

Using Meshlab software®, the obtained model has been scaled and aligned with the corresponding model obtained with the 3D scanner Artec Spider (3D point accuracy: 5x10-3 mm).

The characteristics of the 3D scanner are summarized in Table I.

Table I
3D scanner Artec Spider characteristics.

Property	
Texture resolution	1.3 mp
Light source	blue LED
Working distance	0.17 – 0.35 m
Data acquisition speed, up to	1 mln points / sec.

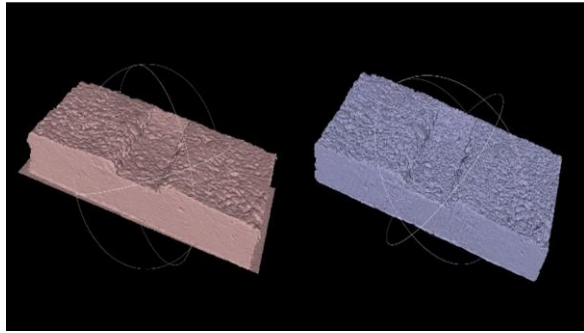The two models during the alignment phase are shown in Fig. 7.

Fig. 7. Meshed IBM 3D model on the left and 3D scanner Artec Spider model on the right: alignment phase.

The Hausdorff distance between the aligned model and the reference scanned sample was calculated. The Hausdorff distance is an algorithm that measures the distance between two subsets of a metric space. The calculation range related to the Hausdorff distance was assigned according to the objects size: 0.000-0.001 m for the rutted samples (GSD= 0.1 mm/pixel).

Fig. 8 shows the graphical representation of the Hausdorff distance results. The vertexes are colored-scaled, from red corresponding to the perfect alignment (deviation equal to 0), to blue that corresponds to a deviation higher or equal to 1 mm. The blue color corresponds to vertexes that are outside the calculation range, and which represent the points where the scan and 3D reconstructed model do not overlap. Furthermore, Fig. 8 shows the distribution of the deviations in terms of number of vertexes per color.
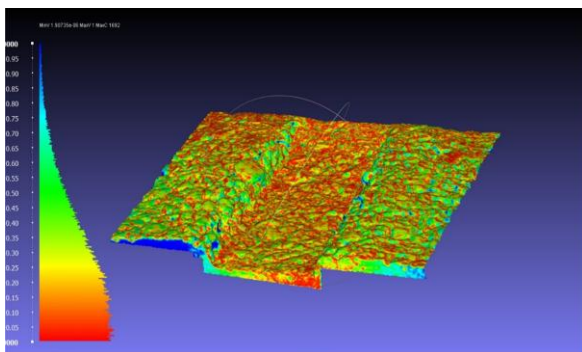

Fig. 8. Graphical representation of Haussdorf Distance.

The same methodology was applied for six laboratory rutted samples, which were tested with the same device (WTM) and conditions. The results are summarized in Table II. The average of RSM is equal to 329 10^{-3} mm.

Table II
Parameters related to the rutted samples reconstruction.

	S1	S2	S3	S4	S5	S6
Number of photos [-]	50	46	51	49	53	45
Mesh faces [millions]	2.000	1.880	2.000	1.989	2.016	1.853
Processing time	3h 9min 9s	3h 6min 34s	3h 10min 15s	3h 8min 54s	3h 12min 34s	3h 6min 15s
RSM [10^{-3} mm]	329	331	327	330	326	330
GSD [mm/px]	~0.1	~0.1	~0.1	~0.1	~0.1	~0.1
Rut depth [mm]	7.8	8.2	8.3	7.7	7.8	7.5

Symbols. S: Sample; Camera: Nikon D520; Focal length: 18 mm; Camera resolution: 6×4 kilopixel.

D. Metric interpretation of the results and geometrical investigation of the reconstructed model

In order to emphasize the potentials of the model, a geometrical analysis and an interpretation of the acquired 3D model were carried out, considering the most significant parts that allow important aspects of the distress to be highlighted. The Computer Aided Drafting (CAD) tools allow the measurement and evaluation of deformations and deviations of the model's surface, between the geometry of the sample, before and after rutting deformation.

The file has been imported into the advanced modelling software NURBS (Non-Uniform Rational B-Splines), Rhinoceros. The acquired 3D model has been scaled and rotated, in order to move and align the object in an absolute reference system, and scaling it to 1:1 (units set in cm).

An initial integrated review of the network polyhedral mesh topology (faces, vertices, edges) was conducted to identify and correct the possible occurred errors: the elimination of the abnormal and irregular faces, the identification of intersections, gaps, and open edges shared by more than two faces.

Once these preliminary steps were completed, horizontal and vertical planes were defined to intersect the mesh and extract the curvilinear profiles of certain sections.

Series of spaced planar curves (i.e. parallel longitudinal sections distant from each other 1 cm) were then created.

Fig. 9 shows the profile curves of sample 1, which was obtained from the intersection of different planes.
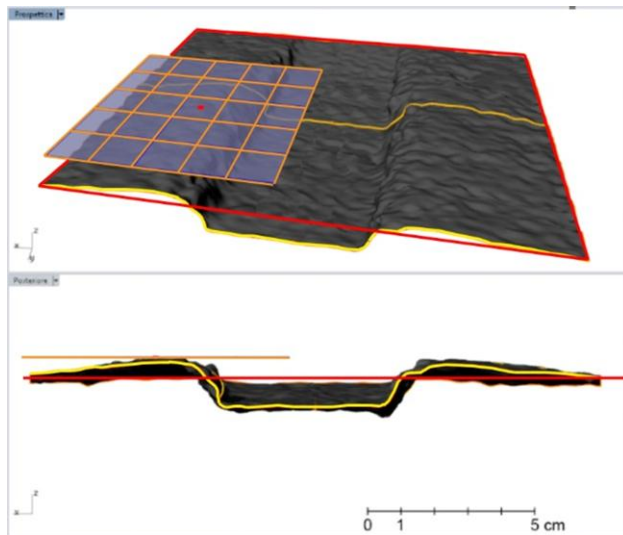
Fig. 9. Allocation of the red and orange planes on the rutted sample.

In order to measure the deformation, it is necessary to construct two horizontal fundamental planes: the first one at the level of the surface before the deformation, and the second one at the level of the highest point of the rutted sample (the red and orange planes in Figg. 9, 10 and 11 respectively). For the allocation of the orange plane, Grasshopper Rhinoceros plug-in has been applied. This algorithm allows automatic allocation of the horizontal plane at the highest point of the uplifts formed along the sides of the rut. The red plane has been selected as the plane that passes from certain meshed vertices-points, which belong to the sample surface that was not affected by the deformation (boundaries).
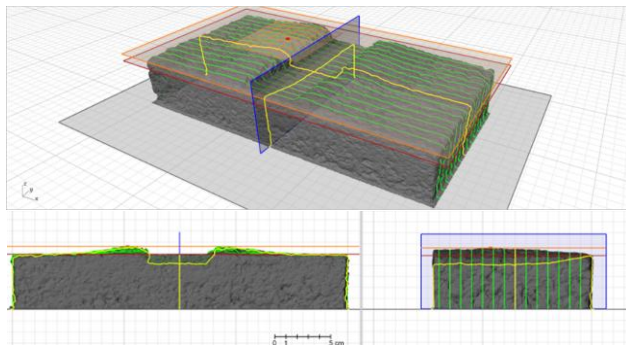

Fig. 10. Definition of the horizontal and vertical planes of the mesh and extraction of the curvilinear profiles.
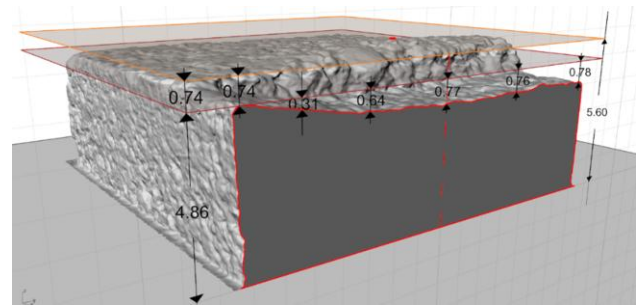

Fig. 11. Truncated mesh and analysis of the rutted surface to evaluate the severity and the shape of the deformation.

In order to extend the geometrical investigation, the 3D model of sample 1 was divided into two symmetric parts, with a vertical plane following the centerline as shown in Fig. 10 (blue plane). If the model is cut along this line it is possible to investigate the truncated mesh and analyze the rutting profile (Fig. 11).

IV. CONCLUSIONS AND PERSPECTIVES

The present paper aims to verify the metric accuracy of Image Based Modeling applied to the pavement distress survey.

Six samples of asphalt mixture were produced and tested with the Wheel Tracker Machine. Then the deformations were analyzed.

The network of images (data set) was created considering the necessary technical steps and overcoming the problems due to the nature of the object. Adobe Agisoft PhotoScan® was then used to create the 3D models of the laboratory rutted samples.

The 3D scanner Artec Spider was used to define the virtual references closer to the most realistic reconstructions.

The models obtained from the IBM and scanning technology were aligned to determine the deviation of the homologous points. The results show high accuracy in the rutting distress reconstruction (average RSM=329 10^{-3} mm)

Furthermore, the geometrical investigation of the model shows that this technique allows a detailed analysis of the distress in an innovative manner. Under this technique, it is possible to gather quantitative information, such as:
•   the measurements in each point of interest;
•   the profile of the pavement cross section.

This information is particularly relevant to identify the cause of rutting (see Fig. 1). The configuration of the test indicates the appearance of only one type of possible profile (Fig. 1b), however the potential application of IBM technique in a full scale survey offers the possibility to detect every type of rutting. The geometrical analysis highlighted the presence of two uplifts along the sides of the rut. The possibility to determine the height of the tangent plane to the highest point allows the definition of the actual depth to be taken into account for water accumulation, and therefore for hydroplaning risk. Determining the cause of distress is fundamental in order to establish the correct maintenance treatment for the optimal rehabilitation strategy, in terms of

costs and service life.

The application of IBM technology on the laboratory samples represents a first step towards a new technology-based process, for the survey and evaluation of pavement distresses that will accomplish the strategic objectives of road pavement management system. The procedure allows saving costs, time and requires simple devices (camera with minimum resolution of 4000 ×3000 pixels) in comparison to other automated systems for the pavement distress evaluation.

Based on the results of this study, IBM suitability is considered successful, as this technique provides high metric accuracy and allows an advanced geometrical analysis of the distress. The analysis relies on quantitative data and removes the subjectivity that exists in current practice, without increasing the survey's costs.

Nevertheless, additional research is needed to verify the suitability and the metric accuracy of such technology in full scale applications. It might be applicable also to different types of distresses such as cracking, corrugations and shoving, raveling etc. This procedure will be applied on the full scale pavement distress to verify the reliability of IBM in the field and increase the degree of automation of this technology.

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