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Three-Dimensional Characterization of Concrete's Abrasion Resistance Using Laser Profilometry

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This paper presents development of three-dimensional characterization of concrete abrasion using the ASTM C1138 test method, which simulates underwater abrasion. To this effect, a measuring system was designed based on laser triangulation with linear illumination of the surface measured. The system allows for contactless, quick and precise measuring of average wear and other topological characteristics dependent on the type of the tested concrete. Validation results show that the system's precision is better as conventional weighting method (<15 gram) and furthermore it allows us to analyze the spatial distribution of wear.
Keywords: concrete's wear, abrasion resistance, 3D measurement, laser triangulation

Highlights
- *Concrete's abrasion measurement is improved using laser profilometry.*
- *Depth of wear and relief of abrased surface are measured in 3D.*
- *Upgraded system has higher precision compared to the conventional method.*
- *Analysis of spatial distribution of the wear is enabled.*

0 INTRODUCTION

The damage of the concrete surface due to the abrasion of the bed load transported by the flowing water is one of the main problems to be addressed in the operation of hydraulic structures. The problem of concrete's abrasion resistance was given special attention in the construction of the Sava river hydropower plants. During the construction of the dams on the Sava, the quality and resistance of concretes to the abrasive action of waterborne particles was specified using standard and non-standard abrasion resistance test methods, and field tests, by conducting test plot measurements in the Vrhovo hydroelectric power plant spillways. From the abrasion resistance tests of the concretes used on the Sava River it was concluded that the ASTM C1138 was the most appropriate test method [1] and [2]. The test method is designed to simulate the abrasive action of waterborne particles [3] and [4]. Circulating water moves the steel grinding balls on the surface of a concrete sample, producing the desired abrasion effects (Fig. 1). The water velocity and agitation effect are not sufficient to lift the steel balls off the surface of the concrete sample to cause any significant impact action against the surface. The test method can only be used to determine the relative resistance of the material to the abrasion action of waterborne particles. The standard procedure of the investigation provides for the measurement of the wear of specimen surface at 12-hour intervals; the total investigation time is 72 hours [5]. The result of the test is the average depth of wear expressed by the average volume of wear on the surface of the specimen in the duration of the test [6]. The method is highly selective in analysing poor-performance concretes. The Sava river dams' spillways are installed with high-performance concrete where the measured values fall within the measurement accuracy limits due to the extremely low wear rates. In an effort to increase method selectivity in high-performance concretes, the investigations to date included various modifications to the standard procedure, such as: intensifying water mixing in the container [7], extending the test duration [7] and [8], and studying the possibilities of increasing the accuracy of wear measurements by using a contact, three-dimensional coordinate-measuring machine (CMM) [8]. The standard procedure measures wear by weighing the specimen with an accuracy tolerance of 25 g [5], while general purpose CMMs achieve the volumetric uncertainty of 1 μm [9].

The measurements using the 3D meter provide both the data on the wear volume size and the worn surface relief. In fact, the relief image of the concrete specimen's surface wear facilitates interpretation of the physical processes characteristic of the device's functioning and the movement of steel balls during the test. The accuracy of such a procedure depends on the size of the point data acquisition and increases with the densification of data acquisition; on the

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other hand, the procedure using contact, high lateral resolution is extremely time-consuming.

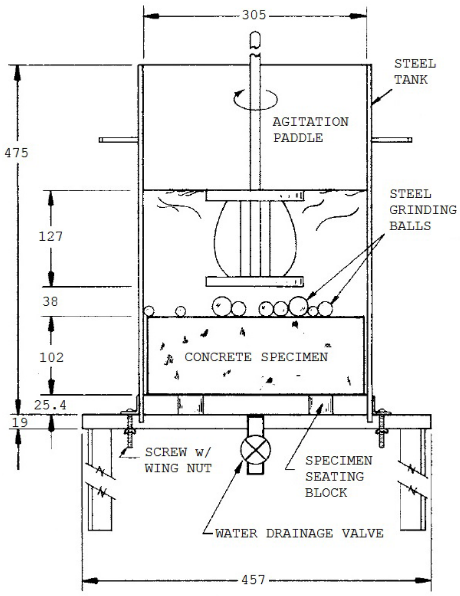

Fig. 1. *The test apparatus using the ASTM C1138 test method; all dimension are in mm* [3]

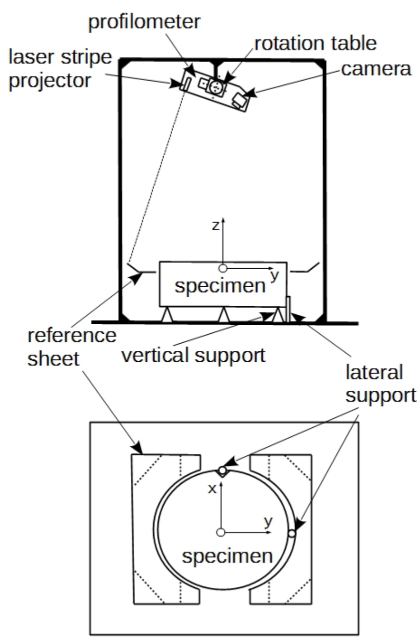

Fig. 2. *Experimental system for 3D measuring of concrete wear using laser triangulation*

In our study the method of measuring the specimen's surface wear was upgraded using a continuous 3D measurement based on laser triangulation and an advanced measurement analysis. The advantage of three-dimensional profilometry against point acquisition is that it provides contactless, high-speed, and high-precision measurements. Because of the characteristics listed above, these methods can be used in geometry control of products with complex geometry [10] in medicine to monitor wound healing [11], regularity of breathing [12], foot shape [13] and [14], and for digitally archiving cultural heritage in 3D [15].

Below we describe the measuring system adapted to the requirements and needs of the ASTM C1138 test method, the measuring procedure, the analysis of measurements, the validation of the method in terms of repeatability of measurements, and the comparability of the results with those obtained using the standard prescriptive method.

1 MEASURING SYSTEM

The three-dimensional measuring system is based on the principle of laser triangulation [16], where the laser projector illuminates the surface along a line, while the camera aligned at a triangulation angle takes images of the illuminated surface. The shape of the surface is reflected in the laser contour curvature on the captured image. The entire surface is scanned while the profilometer rotates around the turntable axis (Fig. 2). The profilometer has an in-built camera with a sensor size of sensor size of 4.15 mm × 2.88 mm, pixel resolution of 752 × 480, and refresh rate of 64 Hz which allows for on-site processing of the captured image. The laser line projector allows for a line width of < 0.1 mm, output power of 3.5 mW, and wavelength of 670 nm. The profilometer is positioned 800 mm above the worn surface of the specimen. At this distance, the resolution is 0.66 × 0.3 mm^2 in the X and Z directions. The rotation is performed via a turntable whose resolution is 0.6 arc minutes. This means that the resolution on the 800 mm arm is about 0.14 mm in the scanning direction. To measure a 500×370 mm^2 surface, which corresponds to the specimen's surface, the profilometer must rotate by 26°. In doing so, the surface is measured in approx. 400,000 points over 8.2 seconds.

The system for measuring the wear of concrete specimens consists of a massive base plate onto which the stand with the laser profilometer and the reference sheet metal are attached (Fig. 2). The reference sheet metal is used for positioning and orienting the global coordinate system. This helps to compensate for any deformations of the laser profilometer stand due to thermal elongation, or due to any accidental impact that could cause permanent displacement of the profilometer relative to the reference sheet metal.

The concrete specimen is a cylinder with a diameter of 295 mm and a height of 100 mm. Before the measurement, the specimen must be washed with a mild water jet and dried. Such a specimen is inserted into the measuring device and precisely positioned in the vertical direction with three point supports. Two lateral supports ensure repeatable positioning along the main coordinate axes in the horizontal plane (X-Y coordinates) and the rotation around the vertical axis (Z coordinate). In the C1138 test method the specimen's surface wear is measured in 12-hour test periods for a total of 72 hours, which is the full duration of the abrasion resistance test. In our study, the measurements of surface wear of the specimen were condensed by shortening the test periods to 3 h increments. The precision was also increased by performing a set of 10 stand-alone, independent measurements during each measurement period. This means that the specimen was reinserted into the measuring device. The final surface wear measurement per individual test period is the average value of all repetitions. The example of a three-dimensional concrete surface measurement and the reference sheet metal is shown in Fig. 3. The figure nicely illustrates the topography of the concrete surface and of the reference surface. The protrusions on the reference sheet metal are the heads of the mounting bolts.

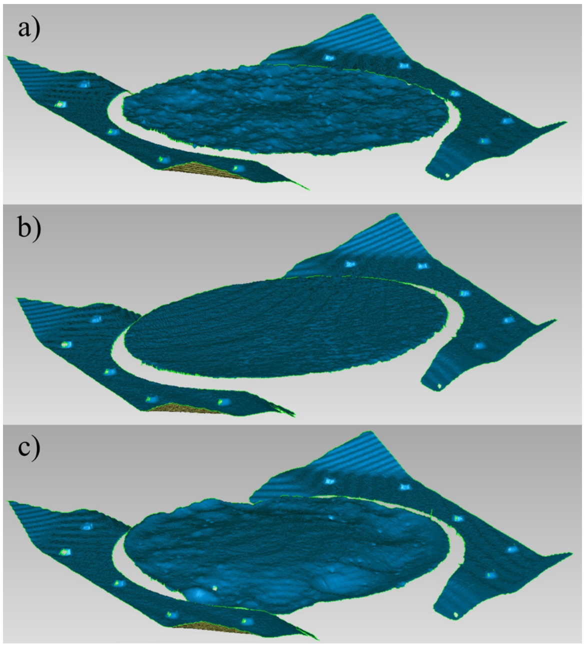

Fig. 3. *Examples of 3D measurements of concrete specimens; a) specimen with rubber aggregate, b) unworn specimen, and c) equally worn specimen*

2 PROCESSING OF MEASUREMENTS

The 3D measurements' processing procedure is schematically represented using a block diagram in Fig. 4. The testing of wear of concrete specimens takes a total of 72 hours, where the wear measurements using the abovementioned system are performed at 3-hour time increments. 10 repeated 3D measurement are performed and then averaged to improve the measuring accuracy at each time increment. The processing of measurements consists of the following steps: (1) spatial adjustment of all measurements according to the reference sheet metal; (2) calculation of the average shape based on repeated measurements; (3) calculation of wear over the entire surface, and (4) analysis of wear images, where the value and the position of the maximum wear, average wear on the chosen radius of the sample, and the total volume of the material lost are calculated. Steps (2) to (4) are carried out after each time increment, providing the time course of wear. These steps are described below.

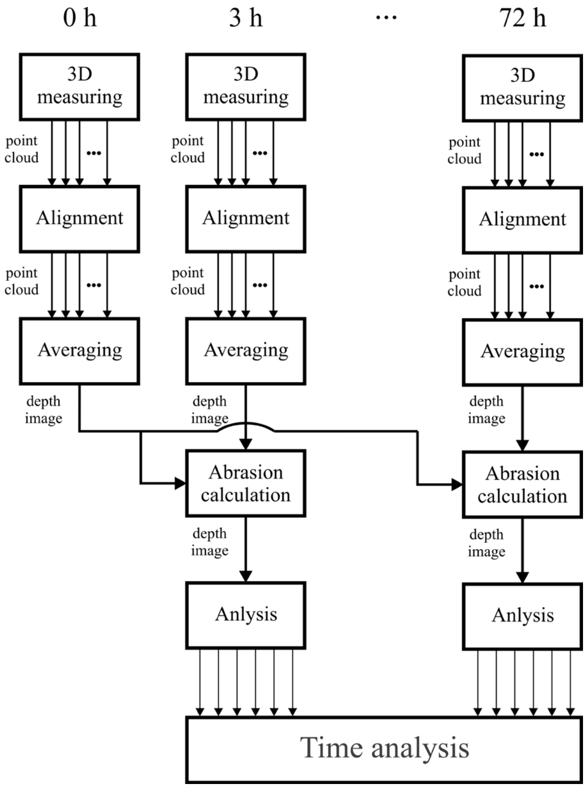

Fig. 4. *The block diagram of the characterization of concrete's abrasion based on 3D surface measurements*

The spatial adjustment is based on the minimization of the deviation between the first measurement of the reference sheet metal, and the current measurement, where the deviation is calculated as the sum of squares of distances between the points along the Z axis. Only the points lying on the reference sheet metal are taken into account. Hence, this procedure makes up for any displacements of the profilometer relative to the reference sheet metal.

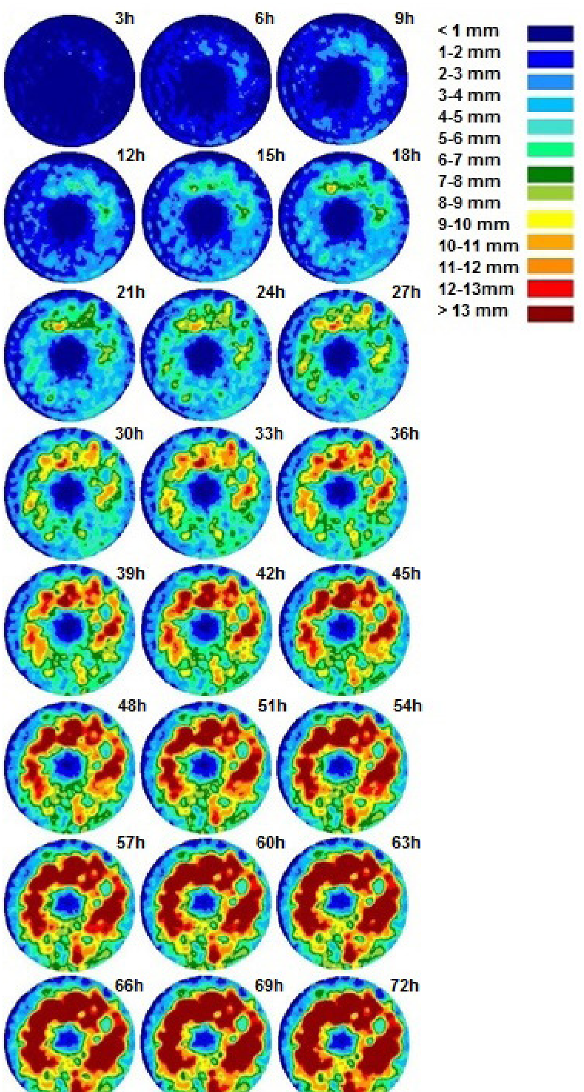

Fig. 5. *Color indication of increasing concrete's wear as a function of the time of wear*

The concrete surface's average 3D shape in the individual points is calculated in such a way that all the measurements that were performed at the same time increment are segmented in the horizontal plane (X-Y coordinates) to $2 \times 2\,\text{mm}^2$ square areas. The points within the individual areas are used to calculate the area's average height (Z coordinate), and the standard deviation. In order to exclude statistically inconsistent points (outliers) we must calculate the difference between the height of the individual point and the average height. If the difference is more than 3-times the standard deviation, the point is excluded from the new calculation of the average height. Thus, we obtain a sequence of depth images which represent the shape of the concrete surface before the wear test and across the individual time increments of the abrasion resistance test. Notably, the depth images are aligned in the direction of the main X-Y coordinate axes.

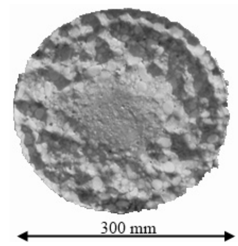

Fig. 6. *Photography of the concrete surface after 72 hours of the test*

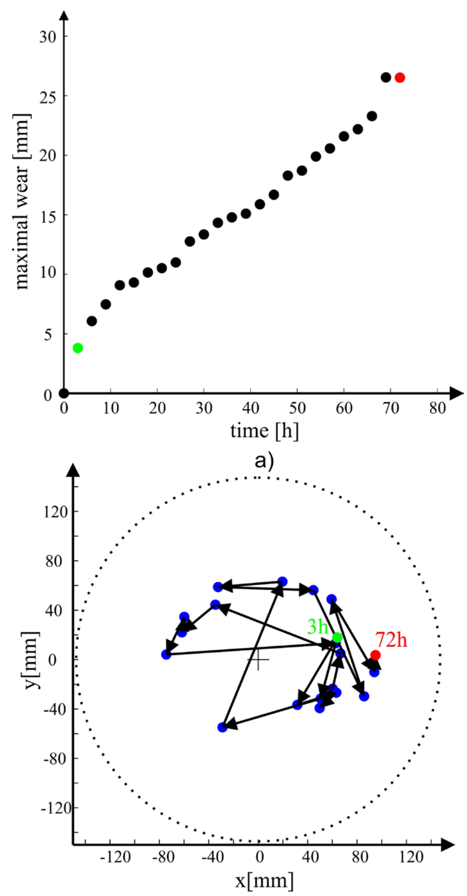

Fig. 7. *a) time course of maximum wear increase, and b) its location on the surface of the specimen*

This is followed by the calculation of surface wear, calculated as the difference of depth images of the specimen surface before the test, and the specimen surface in the individual time increments of testing. The example of the specimen's surface wear as a function of the duration of the abrasion resistance test is shown in Fig. 5, while the specimen after the completion of the test is shown in Fig. 6. The 3D illustration of the eroded surface gives considerably many more possibilities of interpreting the results of abrasion resistance measurements than the standard procedure, which only allows for qualitative interpretations of the damage to the surface based on photo documentation – such as position, depth, and the severity of wear. By contrast, the 3D measurement allows for a quantitative comparison of the results. An example of such analysis is shown in Fig. 7, where we analyzed the greatest depth of wear occurring on the surface of the specimen in the individual time increments of testing. Fig. 7a shows the time course of the increase of maximum wear, and Fig. 7b the position of the point where the wear was detected.

As seen in Figs. 5 and 6, surface wear is not uniform, but rather it changes with the distance from the center of the specimen. This can be explained with the operation mechanism of the abrasion resistance test using the ASTM C1138 test method. Due to the rotating agitation paddle in the container a potential vortex occurs as a combination of rotational and irrotational flows. Rotational flow occurs in the core of the vortex, limited by the operation area of the agitation paddle, while irrotational flow occurs outside of the vortex's core. The water's velocity in the core of the vortex increases directly proportionally to the distance from the axis of the container towards the rim, reaching its maximum at the outer rim of the container. In the area of the irrotational flow, the water's velocity decreases inversely proportionally to the distance from the core of the vortex towards the rim of the container where it reaches its minimum.

The wear propagation in radial direction shows Fig. 8, where the curves show the average wear of the specimen in the radial direction in the individual time increments. In the area of the paddle's operation, the wear of the concrete surface is smaller than that in the area of the irrotational flow where the damage to the surface increases over time, reaching its maximum approx. at the rim of the area of operation of the agitation paddle, which is, indeed, expected given that the water velocity in this area is the highest. The figure illustrates that initially the wear occurs approximately in the center of the irrotational flow area, gradually nearing the inside edge of the area, which is reached after 72 hours of the apparatus's operation (Fig. 8).

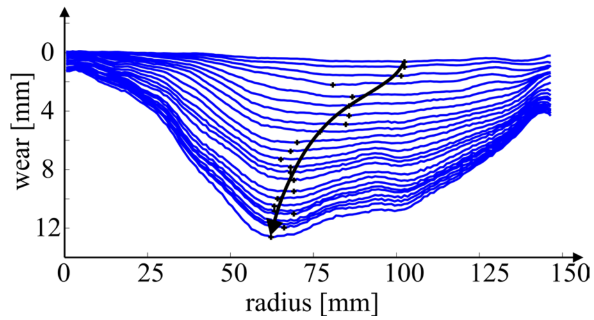

Fig. 8. Average wear in the radial direction of the specimen; the hatched arrow characterizes the wear progression over time

The volume of the material lost was determined in the last step of measurements' processing. The volume is calculated by integrating wear across the entire concrete surface. An example of the time course of the volume increase is shown in Fig. 9, which reveals the linear progression of the specimen wear up until approx. half of the test duration, followed by a gradual decrease of wear until the completion of the test.

The described method of measurement processing is implemented with stand-alone software that reads the series of 3D measurements from a working folder and automatically performs the steps described above. The final results are visually presented as a function of the time of wear, and stored into files as raster images and tables. The time of the measurements' analysis of the complete test, consisting of the results of measurements at 25 time increments or, including repetitions, 250 measurements, is approx. 5 minutes.

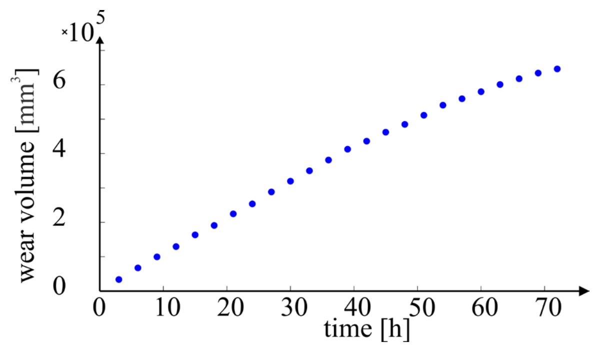

Fig. 9. *Plot of wear volume increase versus time*

3 VALIDATION

The precision of the measurement method was tested in two ways: (1) with assessment of repeatability, and (2) by comparison with the conventional weighing method. In stage 1 we analyzed the repeatability of the measurement of the specimen surface at the same time of wear. To that end, we selected three specimens with typical worn surfaces (smooth, rough, and eroded surface – Fig. 3), and we repeated the measurement of the specimen surface 10 times, while each time the specimen was reinserted into the apparatus. First, all measurements were spatially adjusted, as described in the previous chapter, then the standard deviation in the vertical Z direction in individual points and the standard deviation of the average height of the entire surface were calculated.

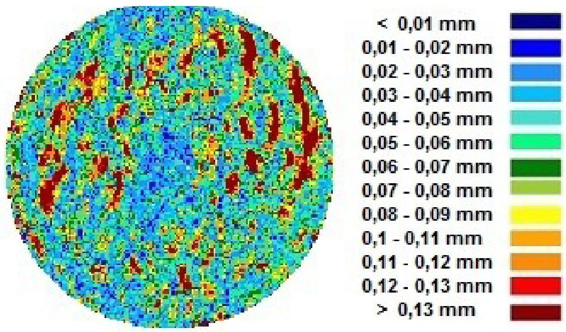

Fig. 10. *Standard deviation of the depth measurement across the surface; it is calculated for 10 repeated measurements*

Fig. 10 shows the standard deviation values in the individual points of the depth measurement for the case of the specimen with rough surface (example in Fig. 3a – concrete with rubber aggregate). It is apparent that at no point the standard deviation exceeds the value of 0.14 mm, which is more than one size class less than the expected depth of wear during the individual time increments (Fig. 5). The reason for the relative variability in the standard deviation mainly lies in the limited resolution of the profilometer, and the positioning unreproducibility of the concrete samples in the cross-direction (X and Y).

The diagrams in Fig. 11 show the average height of the measured surface as a function of the consecutive repetition of measurement. It is apparent that the positioning in the vertical direction is another size class more precise, as the standard deviation of average heights is between 3 and 6 µm. The slope of the regression line also indicates that the average height is decreasing, i.e. by approx. 1 µm per measurement. The reason for this is probably that the contact area of the specimen is worn after each placement of the specimen on the point supports.

During the abrasion resistance test of concrete using the ASTM C1138 standard test method, the loss of material during the individual time increments was assessed by weighing. For this purpose, we used a scale with a measuring range up to 20 kg, and with an accuracy of ±1 g. The measured wear volumes, acquired using the 3D profilometer, were converted to mass of the material lost based on the known material characteristics of the specimens. The comparison results are given as the Bland-Altman plot in Fig. 12. The abscissa shows the average measurement values based on 3D measurements and weighing, and the ordinate the value differences between weighting and 3D measuring method. The plot reveals that the difference increases with the increase of wear: at the

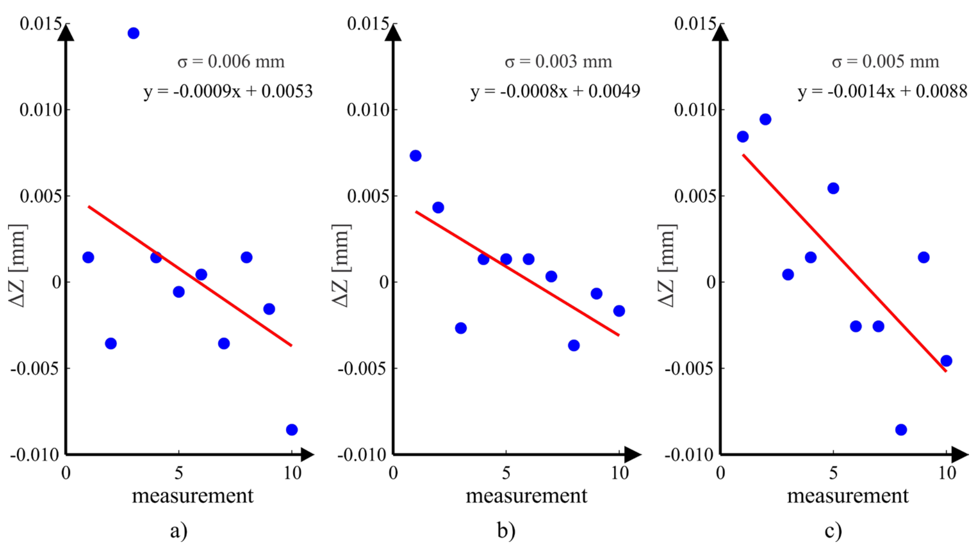

Fig. 11. *Average height of measured surfaces according to the consecutive measurement at the same duration of wear; a) specimen with rubber aggregate, b) unworn specimen, and c) equally worn specimen*

maximum wear of 1360 g it is approximately 15 g. According to our estimate, the systematic deviation is the consequence of the error in determining the diameter and density of the material in the volume-to-mass conversion of the material lost. If the mass of the material lost is converted into the average decrease of the surface height, the sample is on average worn by 10 mm, while the maximum height difference is 0.1 mm. We can conclude that the precision of the 3D method is completely comparable to the well-established method of weighing, while the 3D method also allows for topological characterization of abrasion.

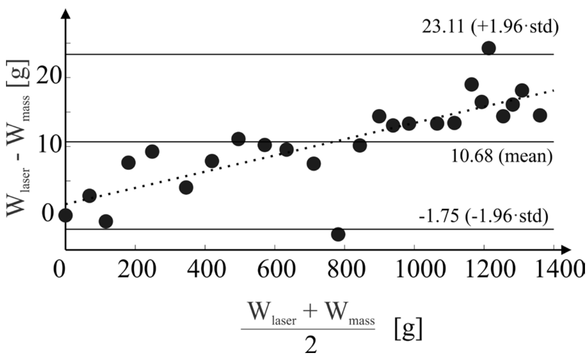

Fig. 12. *The comparison of wear measured using the laser profilometer (W_{laser}), and a scale (W_{mass})*

4 CONCLUSIONS

The paper demonstrates a new method of characterization of concrete's abrasion resistance based on laser 3D profilometry, and the analysis of the measured surfaces of concrete specimens as a function of the duration of wear. The method was developed for contactless, precise, and fast measurements compared to conventional methods. The entire measurement procedure (placement of the specimen and 3D measurement) takes approx. one minute. The measurement resolution is 0.66 mm, 0.14 mm, 0.3 mm in X, Y, and Z directions, respectively. The results of the measurements consist of three-dimensional images of surface wear, position, and size of maximum wear, average depth of wear on a specific radius of the sample, and the total volume of the material lost. All the data are measured as a function of wear duration. Repeatability tests of the measurement of the same concrete specimen show that it is approx. 0.005 mm. Compared to the weighing method, the results of average wear across the entire surface provide equivalent precision. There is a systematic bias (up to 15 g or 0.1 mm) due to the imprecisely determined density of concrete. Based on this it may be argued that the method involving weighing can be replaced by the 3D measurements of wear. Moreover, the new method allows for the acquisition of data on the topography of the worn surface.

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