Indian Journal of Engineering & Materials Sciences
Vol. 21, December 2014, pp. 692-700

Application of three-dimensional optical laser triangulation method for concrete surface morphology measurement

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Received 18 November 2013; accepted 24 July 2014

The proper preparation of the surface of concrete is an important stage in the construction and renovation of building structures. Before placing a concrete topping it is essential to determine the morphology of the concrete base surface. This paper describes a novel application of three-dimensional (3D) optical laser triangulation method for investigation of the concrete surface morphology. It is demonstrated that the 3D optical laser triangulation method is highly suitable for the fast exploration of large stretches of concrete base. In this paper large size concrete floors specimens with the substrate surface prepared with different roughening techniques are considered. The novel 3D scanner is used to precisely analyze the morphology of a 50 × 50 mm surface for the purposes of the nondestructive identification of the pull-off adhesion of concrete layers in layered building elements. Height parameters are used to describe the concrete surface morphology.

Keywords: Concrete, Concrete floor, Surface morphology, Interlayer bond

Surface morphology is one of the properties describing the structure of a surface. The surface of the concrete elements formed horizontally, is defined as a series of asymmetrical waves[1-3]. The durability of concrete elements is determined by the adhesion of the topping to the base concrete which significantly depends on proper base concrete surface preparation described by surface roughness parameters. The role of surface preparation in concrete elements and the effect of morphology on interface bond have been evaluated by many researchers[4-8].

In the civil engineering industry the conventional technique for measuring concrete surface irregularity has been to place a straightedge on the surface and to measure the maximum deviation between the straightedge and the surface of concrete floor[9]. This method measures the maximum amplitude of the surface, however, no surface roughness data has been obtained. Eurocode[10] indicates that surfaces may be classified as very smooth, smooth, rough or indented. ACI 318[11] specifies two categories of roughness. American National Standards Institute[12] classifies the techniques of morphology measurement into three types. BS 8110[13] only considers the equipment that should be used for this purpose. To analyze the effect of surface roughness on the bond in concrete elements the morphology of the surface needs to be measured. It is proper to note that Nemoto *et al.*[14] developed a morphology measurement standard of asymmetrical surface topography for improving 3D surface texture measurement. In this study the software data with 3D surface texture using the 2D model have been presented. On the other side a sort of methods are available for measuring the surface morphology of concrete pavements in the highway field. Nowadays no standard technique for measuring surface morphology of concrete surfaces has been developed.

An interesting application of a two-dimensional analysis has been realized by Thomsen-Schmidt[15]. It is equipped with a linear moving stylus which is guided by precision air bearings. A traceable profiler instrument for areal morphology measurement has been presented. Roughness was measured by the profile method. The analysis of the dependence between surface morphology and the adhesion strength in concrete structures was the subject of Santos and Julio[1]. It has been presented that there is dependence between the concrete roughness parameters and adhesion strength measured by the pull-off method[16]. In the following article, the parameters were determined on the basis of a single profile and the geometry of the specimens was concrete blocks of size a 200 mm × 200 mm × 400 mm. The main conclusion of this article was that an optical procedure would be probably the most adequate

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technique rather than based single profile analysis. The aim of the Franck and De Belie[17] research was to study the impact of concrete floor surface roughness on a bovine claw model and to assess the deformation of the bovine claw model under load. Roughness parameters were determined by the profile method of the surface with a high-precision laser beam. It is proper to note that a single profile does not sufficiently characterize a 3D surface like the surface of concrete. The measurements performed by Schwall and Courard[18] dealt among the dependence between base concrete morphology and parameters determined by the impact-echo method[19]. Authors used 3D parameters but the specimens were smaller than potential size of the concrete elements[20]. The idea of the studies by Maerz *et al.*[21] was the bond behavior between the concrete and epoxy using laser striping and image analysis. The specimens consist of six concrete blocks of size 300 mm × 300 mm × 100 mm with two sets of concrete surface preparation.

In the last few years two-dimensional analysis of concrete surface morphology has come under criticism and new solutions have been proposed. Abu-Tair *et al.*[22] proposed a destructive technique that requires the extraction of a concrete specimen. A set of needles is placed over the concrete surface and fixed. After that the concrete specimen is removed and the set of needles is photographed against a high contrast surface. The obtained image is digitally treated and the roughness profile is assessed. The determination of the dependence between concrete surface roughness parameters and concrete pull-off adhesion strength and the evaluation of the usefulness of standard and fractographic roughness parameters for the description of concrete surface topography were the subject of the studies performed by Siewczynska[23]22. In this work virtual 3D models of sandblasted and non-sandblasted concrete surfaces were made using a surface scanner and surface roughness parameters were calculated on their basis. It was shown that the greater the pull-off strength and the lower the values of the parameters defining the roughness of the sandblasted surface. It appears from author works that the 3D optical laser triangulation method is valuable to assess the pull-off adhesion of the concrete layers since it can contribute the values of the 3D roughness parameters characterizing the surface of the base layer[24-27].

A 3D optical non-destructive scanner has been employed in this study. The 3D scanner is able to measure the point coordinates of concrete elements from a few millimetres to a few tens of meters in size. Two 125 mm thick 2500 × 2500 mm concrete specimens, constituting the concrete floor base, were investigated. For the reason that a single profile analysis does not sufficiently characterize a 3D surface like the surface of concrete in the following article the parameters acquired from the surface have been used. The values of the 3D surface roughness parameters obtained on the base were compared with the values of the pull-off adhesion *fb* between topping and the concrete base. The idea of this paper was also to find the reliable correlation for the purposes of the nondestructive identification of the pull-off adhesion of concrete layers in layered building elements.

3D Roughness Parameters

Initial important work dealing with the 3D roughness parameters has been established by Stout *et al.*[28] in 1993. In the last few years the first international standard ISO 25178 taking into account the specification and measurement of 3D surface texture has been published[29]. It seems that height parameters are likely to be most useful for the evaluation of concrete surface morphology[30,31]. In order to distinguish the parameters acquired from the surface from the ones determined on the basis of a single profile, the former are denoted with the letter *S*: root mean square height *Sq* – a root-mean-square deviation of the surface from the reference surface; the numerical formula for this parameter is as follows:

$$Sq = \sqrt{\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M} z^2(x_i, y_j)}. \qquad \ldots (1)$$

where z is the height of the measured point in the coordinates i and j.

Skewness of 3D surface texture height distribution *Ssk*:

$$Ssk = \frac{1}{MNS_q{}^3}\sum_{j=1}^{N}\sum_{i=1}^{M} z^3(x_i, y_j) \qquad \ldots (2)$$

Kurtosis of 3D surface texture height distribution *Sku*:

$$Sku = \frac{1}{MNS_q{}^4}\sum_{j=1}^{N}\sum_{i=1}^{M} z^4(x_i, y_j) \qquad \ldots (3)$$

Maximum height of peaks *Sp*:

$$\mathrm{Sp} = \sup\{\mathrm{Z}(\mathrm{x}_i, \mathrm{y}_j)\} \qquad \ldots (4)$$

Maximum height of valleys *Sv*:

$$Sv = \left|\inf\{Z(x_i, x_j)\}\right| \qquad \dots (5)$$

Surface bearing index *Sbi* – being a ratio of surface roughness mean square deviation *Sq* to $\eta_{0.05}$, where $\eta_{0.05}$ is a level separating the peak surface irregularity from the core for a default value of 5%:

$$Sbi = \frac{S_q}{o.o5}\ . \qquad \dots (6)$$

Core fluid retention index *Sci* – defined as a ratio of the volume of voids in a unit sampling area between levels $h_{0.05}$ and $h_{0.08}$ to mean square surface deviation *Sq*:

$$Sci = \left(\frac{V_v(h_{0,05}) - V_v(h_{0,8})}{(M-1)(N-1)\Delta x \Delta y}\right) / S_q \qquad \dots (7)$$

Valley fluid retention index *Svi* –, defined as the volume of voids in a unit sampling area below level $h_{0.08}$ to mean square surface deviation *Sq*:

$$Svi = \left(\frac{V_v(h_{0,8})}{(M-1)(N-1)\Delta x \Delta y}\right) / S_q \qquad \dots (8)$$

Novel 3D scanner

There are a group of optical methods of measuring the coordinates of surfaces and a number of ways of qualifying them, mainly for passive and active methods. Passive methods work in uncontrolled natural light and in particular do not need any additional artificial light sources. On the other side active techniques employ additional light sources: incoherent and coherent light sources. One of the most promising active techniques for concrete surface morphology measurement is optical laser triangulation method. Optical laser triangulation method based on the measurement of light reflected from the surface of an examined object. This method presents major advantages: it is non-destructive, it is not sensitive to colour contrast between aggregate and cement paste and contact between equipment and surface is avoided[30-34].

The test set-up for the optical laser triangulation method of surface morphology comprises a laser profile scanner mounted on a linear drive together with a guide bar, an encoder and a portable laptop (Fig. 1a). As described in ref.[30], in this method scanning is effected by manually shifting the head above the measuring area during which several surface profiles, separated from one another by a distance of 0.07 mm, are being recorded with a resolution of 0.074 mm. As a result of the scanning one obtains a cloud of points modelling the morphology of the concrete surface with a vertical resolution of 0.015 mm. The data from the intelligent camera after prefiltration are sent to the laptop to be archived and later processed in order to determine the 3D roughness parameters[30].

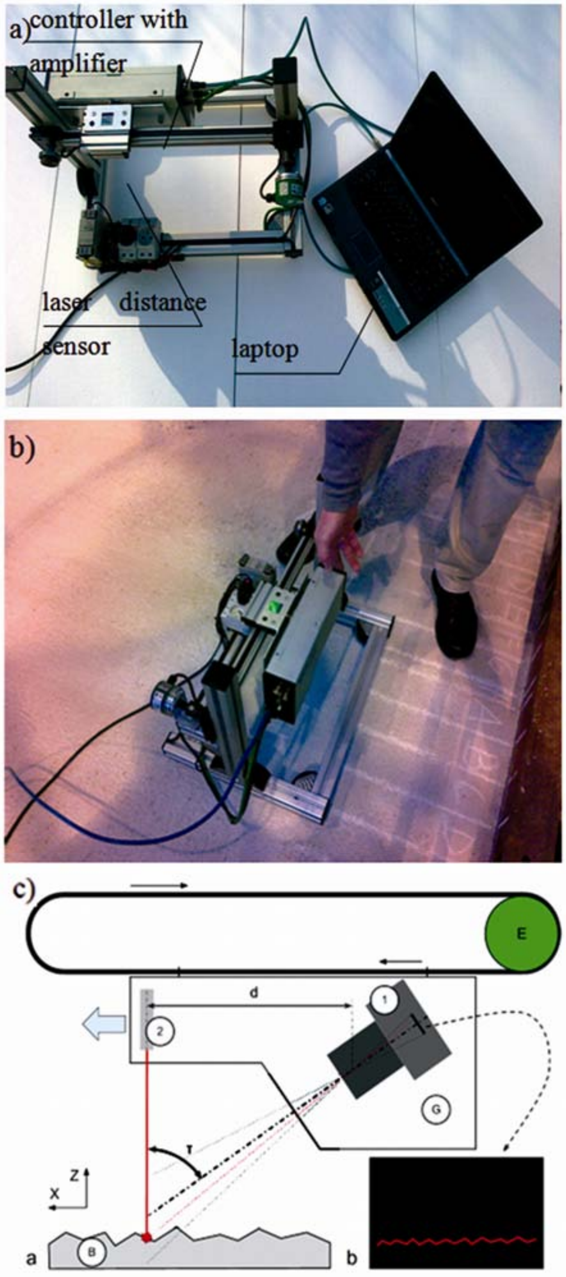

Fig.1—View of (a) measuring set used in laser triangulation method, b) testing by nondestructive laser triangulation method, (c) schematic of laser triangulation method: (1) camera with lens, (2) laser line generator, (B) concrete, (G) head, (E) encoder[30].

This method is based on triangulation by means of a line of light[35]. According to Hola *et al.*[30], it consists in taking photographs at an angle relative to the direction of lighting (Fig. 1b). The photographs depict the deformation of the-line-of-light profile caused by the shape of the illuminated object (Fig. 1c). Because of its high concentration of energy, a laser equipped with a special optical system is used as the illuminator and a low power (=658 nm ± 15 nm) diode laser was employed. According to 30 the recorded image of the line contains information about the 3D geometry of a single section of the scene by a plane of light. As presented in literature this method is referred to as 2½D, as opposed to the methods capable of activating the full geometry of the whole measuring area[36]. Therefore, it is necessary to effect relative movement, which was achieved by means of the linear drive. During the relative shift of the object being scanned the discrete acquisition of photographs, synchronized by the encoder, takes place. Although the camera system offers a maximum scanning speed of 5000 profiles/s, the actual scanning speed is limited by the exposure parameters and the profile line segmentation algorithms. In the case of the setup presented here manual shift is used instead of a controlled electric drive. The scanning time did not exceed 2 s[30].

In this method only the parts of the scanned surface which are visible from both the camera and laser perspectives are mapped. As the triangulation angle decreases so does the number of invisible areas, but also the measurement resolution along the z-axis decreases as a result. In the case of the IVC-3D scanner, both the lens and the triangulation angle (53°) have been set by the manufacturer to strike a balance between occlusion and resolution. The scanning system has been calibrated before measurement and ensures constant resolution Δz=0.015 mm along the z-axis[30].

For the 50 mm × 50 mm measuring area the following average resolutions are achieved: 0.07 mm – along the x-axis, 0.074 mm – along the y-axis, 0.015 mm – z-axis. The distances between the particular points situated on the investigated surface are measured by a camera driven by a stepper motor, whereby measurements can be performed with an accuracy of 15 µm in profiles 10 µm distant from one another. The device assigns three coordinates to each measuring point, describing its location on the examined surface. The file with measurement data is saved in the .asc format. The result of the scanning is a virtual 3D image of the morphology of the investigated surface. The image is analyzed to acquire the values of the parameters describing the surface morphology. The measurement data were exported in the csv format to be further processed by the Talymap 3D Analysis Software. Optical laser triangulation is a promising tool enabling one to quickly obtain an accurate image of the examined surface in any measuring point.

As mentioned in 31, the main advantage of the novel 3D scanner is the scanner examines a 50 mm × 50 mm surface area which corresponds to that of the area tested by the pull-off method in order to identify pull-off adhesion f_b of concrete layers. It has been previously demonstrated that the scanner is highly useful in investigations aimed at identifying pull-off adhesion f_b of concrete layers in layered elements[32,33].

Experimental Procedure

Tests were carried out on two 125 mm thick 2500 mm × 2500 mm concrete specimens, constituting the concrete base (Fig. 2a). The base layer was made of

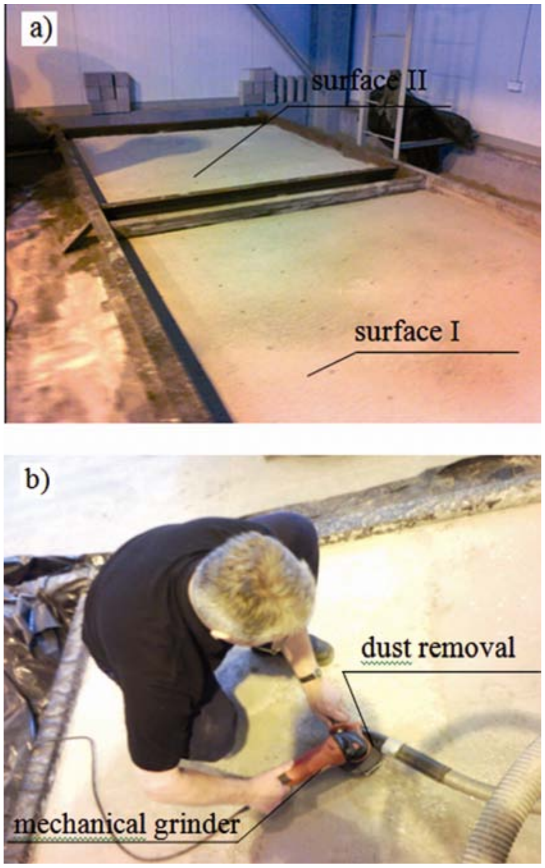

Fig. 2—Concrete floor base specimens: (a) laboratory stand, and (b) preparing the base concrete surface by mechanical grinding and dust removal.

class C30/37 concrete with consistency S3, w/c=0.5 and a maximum aggregate grading of 8 mm and was laid on polyethylene sheeting and on a 100 mm thick layer of sand. The investigations were carried out prior to concreting a 30 mm thick topping. In addition, six 150 mm × 150 mm × 150 mm specimens were made to study the physical properties of the concrete from which the concrete slabs were made. The studies were carried out after 90 days of concrete curing, except for compressive strength tests which were done after 28 days and the concrete slabs cured naturally in a laboratory hall at an air temperature of +18°C (±3°C) and a relative air humidity of 60%.

The following two ways of preparing the base were used:

- surface I: mechanical grinding (Fig. 2b),
- surface II: no surface preparation (after concreting the surface was left unchanged).

Figure 3 presents the ways of preparing the concrete base, the method of measuring surface morphology, and the measured 3D roughness parameters.

After 28 days since the base layer was concreted the concrete surfaces were labelled a 1500 mm × 1500 mm test area was demarcated on each of them and a grid of points spaced at every 100 mm was marked on each surface The grid columns were denoted from A to H and the rows from 1 to 16. Finally 256 measuring points were marked on both surfaces (Fig. 4).

The optical laser triangulation system was calibrated prior to measurements. Calibration is automatic and consists in measuring and checking the parameters of the standard in its different angular positions. As a result a precise a 3D image of the scanned surface was obtained (Fig. 5).

In order to determine the 3D roughness parameters of the investigated concrete surfaces, it became necessary to develop an algorithm for processing the measured data (Fig. 6). The application was created using the MATLAB software package which is highly suitable for numerical data analysis in research calculations. A 50 mm × 50 mm test area was demarcated around each measuring point and numerical values of the particular base concrete surface roughness parameters were determined.

As described in ref.[33], a schematic of the rig for testing by the pull-off method is shown in Fig. 7. The tests were performed in the same points in which the three-dimensional (3D) optical laser triangulation method tests had been carried out.

Results and Discussion

The experiments have demonstrated that a novel application of three-dimensional (3D) optical laser triangulation method makes it possible to obtain a virtual 3D image of the examined concrete surfaces and to acquire the values of many surface morphology parameters specified in ref.[29] from this image. Numerical values of the particular base concrete 3D roughness parameters were determined in every measuring point. Test results for selected point B2 on surface I and II are presented in Fig. 8.

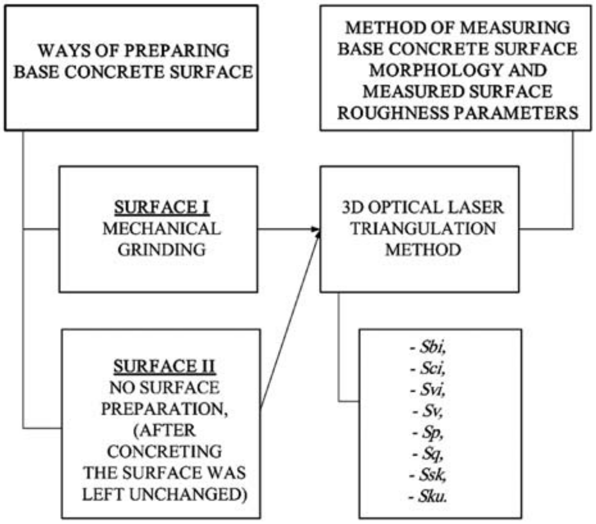

Fig. 3—Ways of preparing base concrete surface, methods of measuring its roughness, and measured 3D roughness parameters

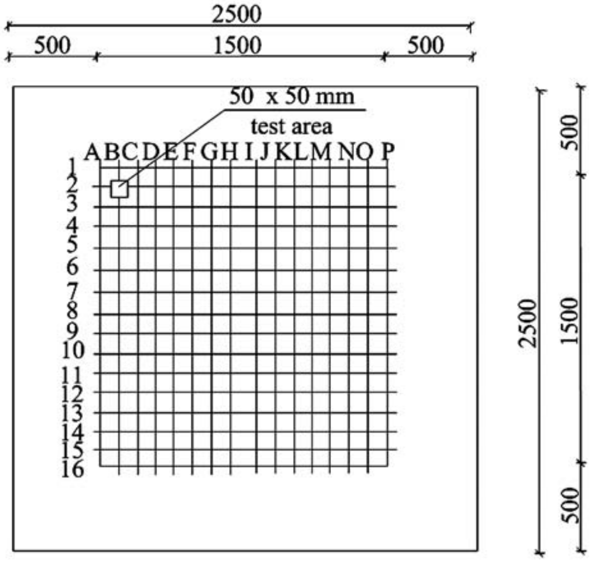

Fig. 4—Distribution of measuring points on investigated concrete slabs

Table 1 shows the statistical characteristics of 3D parameters, selected from the parameters specified in ref.[29], describing the morphology of the two model surfaces of surfaces I and II, acquired from the analysis of 3D virtual images obtained by means of the 3D optical laser triangulation method. Arithmetic mean $\bar{x}_i$, standard deviation S_x, minimum values $x_{\min}$ and maximum values $x_{\max}$ calculated on the basis of all the obtained results are calculated.

The following general observations emerge from the analysis of the results. It comes out from the 3D images of the surfaces I and II that there are important differences in the values of the 3D roughness parameters (Table 1). Regardless of the way of surface preparation, the values of all the investigated 3D parameters are higher for surface I.

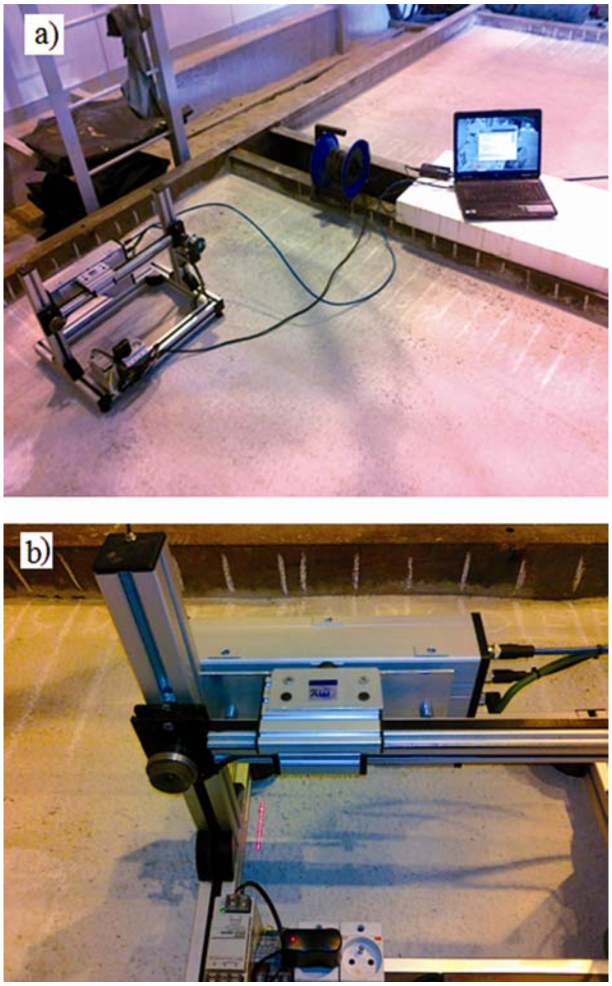

Fig. 5—Experimental study: (a) determination of the coordinates of the reference points and (b) scanning using the optical laser triangulation method

Parameter *Sq* is higher for the surface left unchanged after concreting. Also *Sv* defining the maximum height of valleys together with *Sku* and *Sci* are higher for surface I than for surface II, which indicates that larger adhesion at the interface could be obtained for the ground surface. On the other side surface skewness coefficient *Ssk, Sbi Svi and Sp* are also higher for surface II than for surface I. This could be the evidence of greater roughness of the unprepared concrete surface.

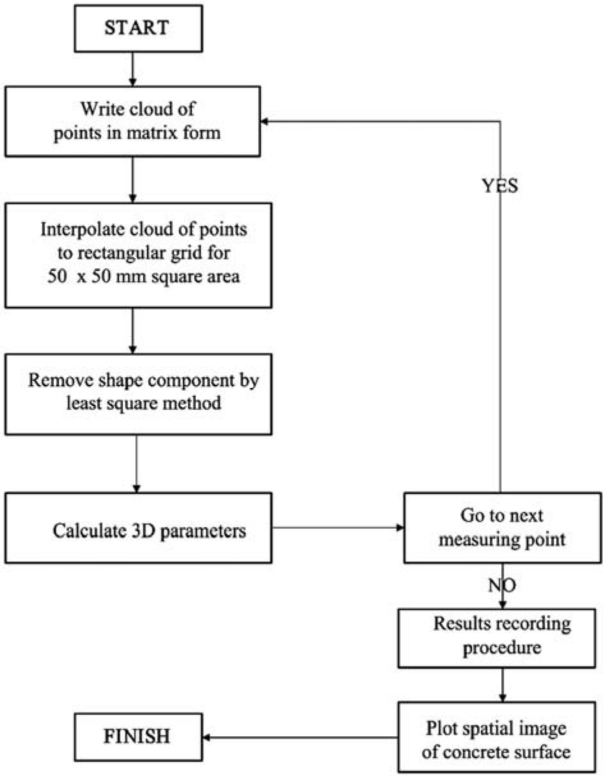

Fig. 6—Flow chart of algorithm for processing data acquired from measurements of surface roughness parameters[27].

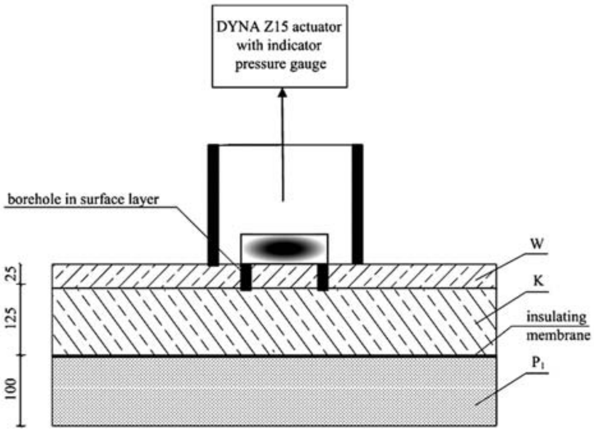

Fig. 7—Schematic of pull-off test rig[33]

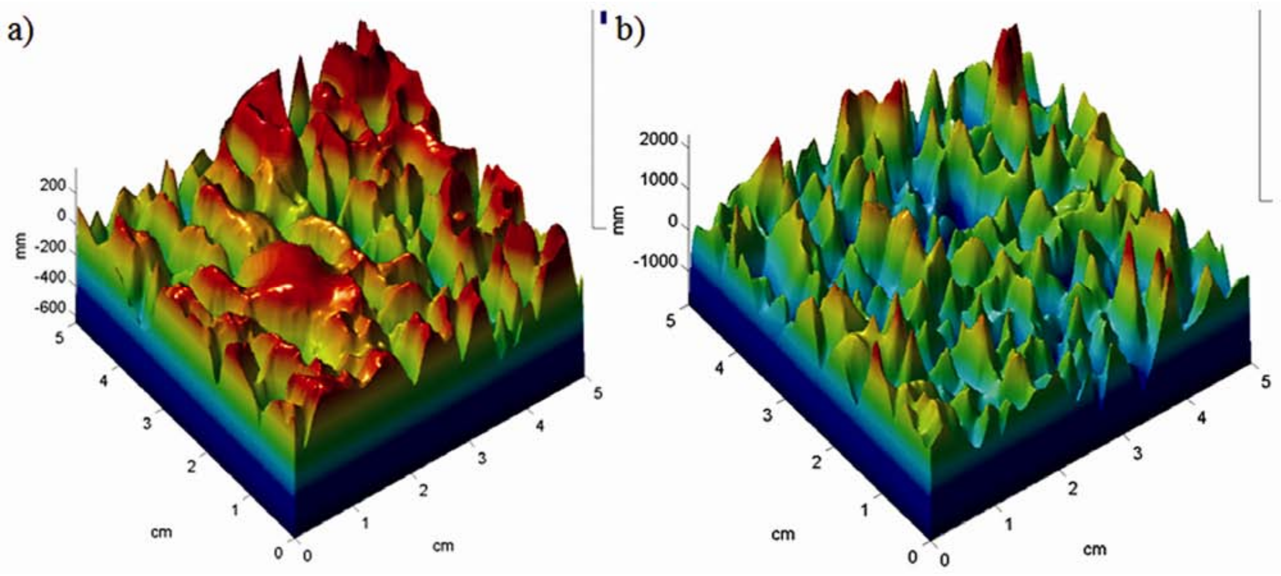

Fig. 8—3D image of scanned surface and parameters determined for test area in point B2: (a) on surface I and (b) on surface II

Table 1—Statistical characteristics of 3D roughness parameters determined by optical laser triangulation method

Symbol of characteristic	*Sq*	*Ssk*	*Sku*	*Sbi*	*Sci*	*Svi*	*Sv*	*Sp*
	mm	-	-	-	-	-	mm	mm
	Name of parameter (surface I)							
$\bar{x}_i$	0.538	-0.692	4.247	0.020	0.755	0.035	1.759	0.991
S_x	0.335	0.414	1.430	0.019	0.084	0.019	0.684	0.412
x_{min}	0.043	-2.009	1.963	0.000	0.601	0.003	0.781	0.330
x_{max}	1.421	0.219	10.975	0.086	1.013	0.093	4.776	2.609
	Name of parameter (surface II)							
$\bar{x}_i$	0.719	0.880	-0.031	3.942	0.002	0.729	0.047	3.504
S_x	0.152	0.295	0.305	0.483	0.001	0.029	0.026	1.211
x_{min}	0.405	0.171	-0.733	3.151	0.000	0.643	0.004	1.530
x_{max}	1.157	1.715	0.622	5.372	0.006	0.810	0.116	6.676

The obtained values of the pull-off adhesion f_b ranged from 0.7 to 1.2 MPa for surface I and from 0.35 to 0.7 MPa for surface II. It is evident that when the topping laid on ground concrete surface the adhesion between concrete layers is twice bigger than for unprepared surface. This influence should be also visible in analysis of the correlation between 3D roughness parameters of the concrete base and the pull-off adhesion f_b.

Considering the above, the results of determination coefficient r^2 between 3D roughness parameters and pull-off adhesion f_b have been presented in Table 2. Determination coefficient r^2 has been calculated using the formula:

$$r^2 = \frac{\sum_{i=1}^{n}\left(\hat{x}_i - \bar{x}\right)^2}{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}, \qquad \ldots (1)$$

where

$\hat{x}_i$ - theoretical value,

x_i - variable value x in point i,

$\bar{x}$ - arithmetic mean .

From the results presented in Table 2, it has been concluded that the highest determination coefficient

Table 2—Results of determination coefficient r^2 between 3D roughness parameters and pull-off adhesion f_b

Determination coefficient r^2	*Sq*	*Ssk*	*Sku*	*Sbi*	*Sci*	*Svi*	*Sv*	*Sp*
	mm	-	-	-	-	-	mm	mm
	Name of parameter (surface I)							
r^2	0.6554	0.3212	0.2210	0.0945	0.4432	0.0912	0.4501	0.1530
	Name of parameter (surface II)							
r^2	0.6341	0.3450	0.3916	0.1294	0.3091	0.1239	0.1207	0.4019

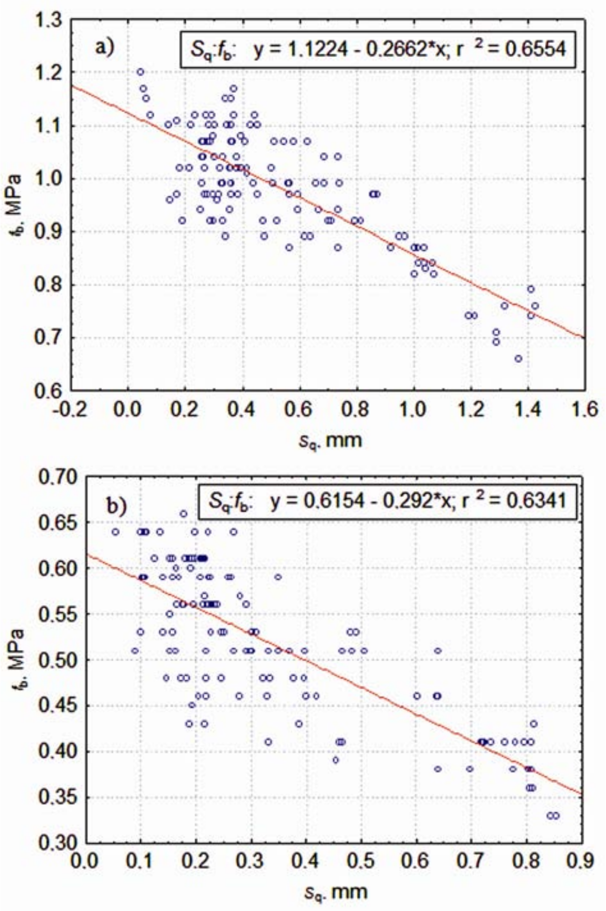

Fig. 9—Correlation between pull-off adhesion f_b and *Sq*: (a) surface I and (b) surface II

r^2 is for the parameter *Sq*. The value of r^2 over 0.6 means satisfied correlation. Following the observations from Table 2 and Figure 9 the correlation between pull-off adhesion f_b and *Sq* for surface I and surface II has been presented.

Conclusions

The paper presents the application of three-dimensional optical laser triangulation method for concrete surface morphology measurement. This study has shown that the proposed method could be used for measuring the morphology of concrete surfaces. Two concrete surfaces differing in the preparation of the concrete base, were examined. A new application of 3D optical laser triangulation method for concrete surface morphology measurement and the investigations of base concrete surface morphology have been presented.

The proposed method has the chance to be automated and used in the laboratory as well as in the field. It is proper to note that further measurements are required to terminate limitations and particularly to compare the method with a range of different methods. The 3D optical laser triangulation method could be used for measuring concrete surfaces although more sensitive equipment for modeling the surface needs to be employed.

It also seems that all of examined 3D roughness parameters will be useful for the analysis of concrete surface morphology for the purposes of the nondestructive identification of the pull-off adhesion of concrete layers in layered building elements due to the reason that there is difference between the parameter values for surface I and those obtained for surface II.

The values of pull-off adhesion f_b of the concrete layers in floors can be identified on the basis of the values of parameter *Sq* determined using three-dimensional optical laser triangulation method. High values of determination coefficient r^2, 0.6554 and 0.6431 for surface I and II respectively, indicates that it is possible to identify the value of the pull-off adhesion on the basis of value of parameter *Sq*.

These indicate that the obtained model has a theoretical value in the identification of values of pull-off adhesion f_b and has a potential practical significance and can be further enhanced by increasing the number of training samples, a wider range of the concrete's strength, another surface preparation methods and using artificial intelligence to predict the values of pull-off adhesion more reliably on the basis of 3D roughness parameters obtained by 3D optical laser triangulation method.

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