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Comparison of Methods for Texture Assessment of Concrete Surfaces

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The bond strength of the interface between concrete layers cast at different times is important to ensure the monolithic behavior of reinforced concrete (RC) composite members. The roughness of the substrate surface has a significant influence in this scope. Current design codes use a qualitative approach based on visual inspection to assess roughness. This procedure is highly dependent on the designer and, therefore, can lead to inaccurate results.

Previous studies conducted by the authors proved that it is possible to use a quantitative criterion to classify roughness. This paper describes an experimental study conducted to compare four roughness quantification methods: the processing of the digital image (PDI) and the two-dimensional (2D) laser roughness analyzer (2D-LRA) methods, both developed by the authors; an upgrade of these, using a three-dimensional (3D) laser scanner; and the sand patch test (SPT), a simple and widespread method.

The 2D-LRA proved to be the best from the four methods considered because it gives a quantitative assessment of the roughness with adequate accuracy, is nondestructive, easy and fast to use, and is cost effective.

Keywords: bond; interface; laser scanning; roughness; sand patch test; strength; surface; texture.

INTRODUCTION

The monolithic behavior of reinforced concrete (RC) composite members, such as precast members with cast-in-place parts and building slabs or bridge decks strengthened with a new concrete layer, depends on the bond strength of the concrete-to-concrete interface.

Several design codes, such as Eurocode 2,[1] ACI 318-08,[2] and CAN/CSA-A23.3,[3] present design expressions to determine the shear strength of the interface between concretes cast at different times. These expressions are based on the shear-friction theory, having always the friction (μ) and the cohesion (c) coefficients the highest influence on results. These coefficients depend on the surface roughness of the concrete substrate, which is qualitatively assessed in all of these design codes, usually classified from very smooth to very rough, or not intentionally roughened to intentionally roughened.

The classification adopted by design codes for the surface roughness is not the most adequate because, being that this approach is qualitative and limited to the characterization of the surface macrotexture, it can easily lead to inaccurate results. To reduce the possibility of misevaluation, design codes usually link this classification to the finishing treatment of the surface. Nevertheless, examples are far from covering all practical situations, taking into account the variety of methods available to remove the superficial layer of concrete and/or to increase the surface roughness.

Eurocode 2[1] addresses the following values to the cohesion and friction coefficients, depending on the surface preparation method: (a) very smooth surface, corresponding to cast against steel, plastic, or specially prepared wooden molds ($c = 0.025$ to 0.1; $\mu = 0.5$); (b) smooth surface, resulting from a slipformed or extruded surface, or a free surface left without further treatment after vibration ($c = 0.2$; $\mu = 0.6$); and (c) rough surface, corresponding to a surface with at least 3 mm (0.12 in.) roughness at approximately 40 mm (1.57 in.) spacing, achieved by raking, exposing of aggregate, or other methods giving an equivalent behavior ($c = 0.4$; $\mu = 0.7$).

ACI 318-08 and CAN/CSA-A23.3[3] adopt the same classification for the interface surface: intentionally roughened and not intentionally roughened, addressing the values of 1.0 and 0.6 for the coefficient of friction, respectively. Additionally, CAN/CSA-A23.3[3] considers the contribution of cohesion and proposes the value of 0.25 and 0.50 MPa (36.3 and 72.5 psi) for the intentionally and not intentionally roughened surfaces, whereas ACI 318-08 neglects this parameter.

Analyzing the proposed values for the coefficient of friction, according to Eurocode 2,[1] the bond strength of a concrete interface with a rough surface ($\mu = 0.7$) corresponds to an increase of 40% when compared with the very smooth surface ($\mu = 0.5$). For ACI 318-08 and CAN/CSA-A23.3,[3] an increase of 67% is observed from the not intentionally roughened surface ($\mu = 0.6$) to the intentionally roughened surface ($\mu = 1.0$). The differences in the classification of the surface roughness lead to significant differences of the corresponding bond strength.

Adding a detailed list of methods and enlarging the current roughness classification of design codes is not an alternative and would not increase the accuracy of results because, for a given method, different roughness levels of the substrate surface can be achieved, depending also on the equipment, the operator, the age of the material, the duration of the treatment, and other influencing factors. Defining a protocol for each method would further complicate a design procedure that must be simple and would not solve the problem in practice either, because it would be necessary to guarantee that this would be strictly followed on site. For all of these reasons, the need to accurately quantify the surface roughness is obvious and the logical improvement of the design expressions is to replace the qualitative approach by a quantitative one, if possible.

A first study[4] on the influence of the roughness of the substrate surface on concrete-to-concrete bond strength has indicated that it should be possible to quantify the surface roughness of the concrete substrate and to correlate this with the bond strength of the interface.

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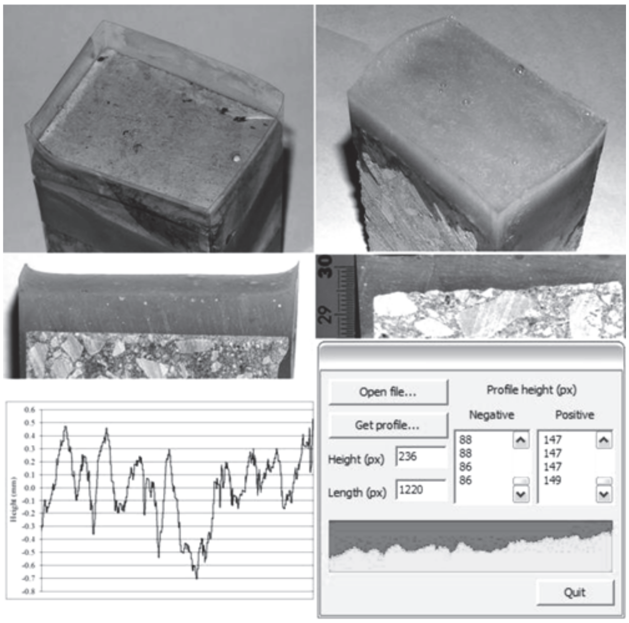

Height (px): 236

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Negative	Positive
88	147
88	147
86	147
86	149

Fig. 1—PDI method.

In a subsequent study,[5] an innovative in-place partially destructive method, based on the processing of the digital image (PDI), was developed to assess and to quantify the substrate texture. The PDI method consists of scanning or photographing a sample extracted from the concrete substrate, after submitting it to a rather complex preparation procedure (Fig. 1). It was proved that it is possible to: 1) obtain a roughness profile of the substrate surface; 2) determine roughness parameters from this profile; and 3) correlate these with the bond strength of the interface—both in shear and in tension—with high correlation coefficients. Furthermore, it was shown that a slight difference in roughness can correspond to a significant difference in the shear strength of the resulting concrete-to-concrete interface. Nevertheless, this technique presents three major disadvantages: it is partially destructive, includes laboratorial tasks, (that is, it is not completely an in-place method), and it is work-intensive and time-consuming.

In a subsequent study,[6] a two-dimensional (2D) laser roughness analyzer (2D-LRA) was specifically developed to overcome the disadvantages of the former method. Based on this portable equipment, a new method was proposed (2D-LRA method) with all of the advantages and excluding all the disadvantages of the former. In fact, this technique is really nondestructive because it does not require contact with the measured surface, it can be completely processed in-place, and it is easy and fast to perform.

Although results obtained with the 2D-LRA were outstanding, with this technique only a small part of the substrate surface is considered. Obviously, because this procedure is fast, it is easy to obtain several roughness profiles. Nevertheless, to capture a three-dimensional (3D) sample of the substrate surface and to process the data afterwards if needed seemed to be preferable. Following this idea, it was decided to conduct an experimental study—described in this paper—to develop a new method based on a 3D laser scanner[7] (3D-LS). The viability of the 3D-LS method was tested by comparing results with those from the two previous methods developed by the authors. In addition, it was decided to also carry out tests using the sand patch test[8] (SPT), selected for its simplicity and for having a widespread use, and to compare results with those obtained with the remaining methods.

RESEARCH SIGNIFICANCE

Concrete-to-concrete structural interfaces are extremely important in assuring the monolithic behavior of RC composite members. The surface roughness of the concrete substrate is one of the most influencing parameters in the bond strength of the interface. Nevertheless, current design codes of RC structures make a qualitative characterization of the surface roughness instead of a quantitative one.

This paper describes an experimental study where the performance of four roughness quantification methods is compared and contributes to the definition of an in-place methodology for the assessment of the shear strength of concrete-to-concrete interfaces.

ROUGHNESS QUANTIFICATION METHODS

Two well-known methods are currently used for the characterization of the surface texture of concrete surfaces. The first one is based on a qualitative approach and was proposed by the International Concrete Repair Institute.[9] It consists of comparing the surface in question to nine standard surface samples with increased roughness. This technique has the advantage of being fast and easy to perform, and the disadvantage of depending on the technician's subjective assessment. The second method, based on a quantitative approach, is the SPT.[8] It consists of uniformly spreading a standard volume of a specified material on the surface—usually sand—and then in measuring the diameter of the covered area from which the roughness is calculated. This method presents the advantage of being inexpensive and easy to perform, both in-place and in-laboratory, and the disadvantage of being limited to horizontal top surfaces.

The mechanical stylus[10] is the most common mechanical device used to assess the surface texture. It is composed of a stylus, a conditioner/amplifier, a mechanical unit for advancement, and a computer for data acquisition. The probe, usually with a diamond tip, is dragged over the surface—along a straight line—and the surface texture is measured.

The circular track meter[11] and the digital surface roughness meter[12] are two devices that use laser sensors to quantify the surface roughness. Both devices can be used in-place and in the laboratory. The first was developed for road pavements, whereas the second was developed to study the bond between concrete and fiber-reinforced polymer (FRP) laminates.

Methods based on microscopy,[13] such as scanning electron microscopy (SEM) or light microscopy, can also be used to characterize the external morphology of concrete surfaces. These methods are expensive but represent more accurate and reliable alternatives to the previously referred noncontact profilometers.

Table 1—Comparison of roughness quantification methods

Roughness quantification method	Type of evaluation	Nondestructive	Associated cost	Portability	Work intensive	Contact with surface
ICRI	Qualitative	Yes	Low	Yes	No	No
SPT	Quantitative	Yes	Low	Yes	No	Yes
Mechanical stylus	Quantitative	No	Medium	No	Yes	Yes
Circular track meter	Quantitative	Yes	Medium	Yes	No	No
Digital surface roughness meter	Quantitative	Yes	Medium	Yes	No	No
Microscopy	Quantitative	No	High	No	Yes	No
Slit-island	Quantitative	No	Low	No	Yes	Yes
Roughness gradient	Quantitative	No	Low	No	Yes	Yes
PDI	Quantitative	No	Low	No	Yes	Yes
2D-LRA	Quantitative	Yes	Medium	Yes	No	No
3D-LS	Quantitative	Yes	High	Yes	No	No

Different techniques have also been used by researchers to overcome the lack of a standard texture measurement method. The slit-island method[14] and the roughness gradient method[15] are two more examples.

Table 1 presents a comparison of roughness quantification methods, including: 1) the type of roughness evaluation (qualitative or quantitative); 2) the type of action produced in the concrete substrate (destructive or nondestructive); 3) the associated cost (acquisition and maintenance); 4) the equipment portability (in-place or laboratory); 5) the required human skills; and 6) the type of contact with the surface. The circular track meter,[11] the digital surface roughness meter,[12] and the 2D-LRA method[6]—all laser-based—present major advantages because these three methods perform a quantitative assessment of the surface texture, are nondestructive, have a medium cost of acquisition and maintenance, can be used both in-place and in-laboratory, are not work-intensive, and do not require contact with the measured surface.

Some of these devices only give a texture profile requiring further data processing to calculate texture parameters, whereas others already include a processor with that aim.

TEXTURE PARAMETERS

Texture parameters[10] can describe the irregularities of a surface, namely peak height, valley depth, and peak/valley spacing. If assessed directly from the measured profile, they are named primary parameters. Otherwise, they are determined from the roughness and waviness profiles, which are obtained from the primary profile by filtering, and are named roughness and waviness parameters, respectively.

Some of the most common primary parameters adopted in this experimental study, are described as follows (Fig. 2). Other parameters, namely roughness and waviness parameters, have the same definition but a different terminology and notation because they are computed from different profiles, as mentioned previously.

The most known texture parameter is the primary average P_a. It is usually adopted by its simplicity, being defined as the average deviation of the profile in relation to its mean line, being given by

$$P_a = \frac{1}{n}\sum_{i=1}^{n}|z_i| \tag{1}$$

where n is the number of measurements and z_i is the coordinate of each measurement.

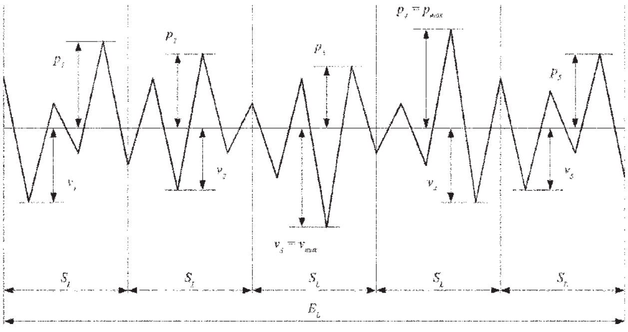

Fig. 2—Definition of texture parameters.

The root mean square (RMS) primary P_q is a parameter more sensitive to peaks and valleys and is given by the expression

$$P_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} z_i^2} \tag{2}$$

where n in the number of measurements and z_i is the coordinate of each measurement.

The primary average P_a does not provide any type of information on the local variability of the surface profile. Therefore, quite different profiles can present the same average roughness. To overcome this limitation, other texture parameters were defined, taking into consideration the location and spacing between peaks and valleys. These parameters are, in general, evaluated at five different sampling lengths (S_L), each one corresponding to one-fifth of the evaluation length (E_L), and then taken as the average values of these.

The mean peak height P_{pm} is defined as the average of the maximum peak height from each sampling length and is given by

$$P_{pm} = \frac{1}{5}\sum_{i=1}^{5} p_i \tag{3}$$

where p_i is the maximum peak height at each sampling length.

The mean valley depth P_{vm} is defined as the average of the maximum valley depth from each sampling length and is given by

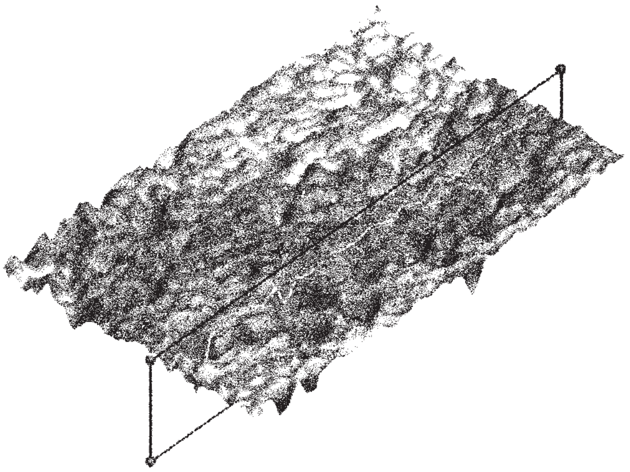

Fig. 3—3D surface, obtained by laser scanning, and 2D profile.

$$P_{vm} = \frac{1}{5}\sum_{i=1}^{5} v_i \quad (4)$$

where v_i is the maximum valley depth at each sampling length.

The mean total height P_{tm} is defined as the average of the maximum peak-to-valley height from each sampling length and is given by

$$P_{tm} = \frac{1}{5}\sum_{i=1}^{5} p_i + v_i \quad (5)$$

where p_i and v_i are, respectively, the maximum peak height and the maximum valley depth at each sampling length.

Several other parameters are based on extreme values of the profile, such as the maximum peak height and the maximum valley depth. The maximum profile peak height P_p is one of these and is defined as the maximum peak height of the evaluation length, being given by

$$P_p = \max p_i \quad (6)$$

where p_i is the maximum peak height at each sampling length.

The maximum profile valley depth P_v is defined as the maximum valley depth of the evaluation length, being given by

$$P_v = \max v_i \quad (7)$$

where v_i is the maximum valley depth at each sampling length.

The maximum primary depth P_{max} is defined as the maximum peak-to-valley height in any of the sampling lengths within the evaluation length and is given by

$$P_{max} = \max p_i + v_i \quad (8)$$

where p_i and v_i are, respectively, the maximum peak height and the maximum valley depth at each sampling length.

The maximum height of the profile P_t is defined as the height between the maximum peak and the deepest valley within the evaluation length, and is given by

$$P_t = \max p_i + \max v_i \quad (9)$$

where p_i and v_i are, respectively, the maximum peak height and the maximum valley depth at each sampling length.

EXPERIMENTAL STUDY

In the experimental study described herein, the texture of concrete surfaces was assessed with the following four methods: (a) the PDI method[5]; (b) the 2D-LRA method,[6] operated with two laser sensors with a resolution of 60 and 10 μm (0.0024 and 0.0004 in.); (c) the 3D-LS method,[7] using a 3D high-resolution laser scanner operated with a telephoto lens, leading to a maximum resolution of 39 μm (0.0015 in.); and (d) the SPT.[8]

Recent tests showed that the laser roughness analyzer presents an error in the measurements of 2.1% and 9.6% for the laser sensors with 10 and 60 μm (0.0004 and 0.0024 in.), respectively.

The selected testing samples were concrete specimens, with a surface of 200 x 200 mm^2 (7.87 x 7.87 in.^{2}), prepared with different techniques. The following surface conditions were considered: (a) smooth, surface left as-cast against steel formwork (reference situation); (b) rough, without exposing the aggregates, surface treated with wire-brushing; and c) rough, with aggregate exposure, surface-prepared with sand blasting.

For each situation, several profiles were considered to evaluate the texture properties: four 2D profiles, for the PDI method; ten 2D profiles, for the 2D-LRA method; and ten 2D profiles for the 3D-LS method, obtained by slicing the 3D sample (Fig. 3), to compare 2D results with the remaining methods.

Both 3D and 2D data were processed and several texture parameters were computed using commercial software for visualization, processing, and analysis of 2D profiles and 3D surfaces (TrueSurf[16] and TrueMap,[16] respectively).

First, the form of the profile was removed using a "best-fit" line, computed by the least-squares method, to correct misalignments between the straight surface and the measuring device. Then, three types of texture parameters were computed from all profiles. The primary parameters were determined from each profile as-measured (primary profile). Subsequently, and adopting a Gaussian filter[17] and a cut-off length of 8.0 mm (0.31 in.), the roughness and waviness profiles were extracted from the primary profile and the corresponding parameters were directly evaluated from these.

In this research study, a single filter was adopted but recent studies[18] showed that the adopted filter and cut-off length can have a significant influence on the values assumed by texture parameters. Moreover, the primary profile alone is sufficient to characterize the surface texture, thus avoiding filtering.

The following primary parameters were computed: primary average P_a, maximum profile peak height P_p, maximum profile valley depth P_v, maximum height of the profile P_t, mean total height P_{tm}, mean peak height P_{pm}, mean valley depth P_{vm}, RMS primary P_q, and maximum primary depth P_{max}.

The following roughness parameters were adopted: roughness average R_a, maximum profile peak height R_p, maximum profile valley depth R_v, maximum height of the profile R_t, mean total height R_{tm}, mean peak height R_{pm}, mean valley depth R_{vm}, RMS roughness R_q, maximum roughness depth R_{max}, valley depth R_z, and ten-point height of irregularities R_{zJIS}.

The following waviness parameters were selected: waviness average W_a, maximum profile peak height W_p, maximum

Table 2—Primary parameters

	Left as-cast, mm (in.)				Wire brushing, mm (in.)			Sand blasting, mm (in.)		
Primary parameters	PDI method	2D-LRA method, 10 μm	2D-LRA method, 60 μm	3D-LS method	PDI method	2D-LRA method, 60 μm	3D-LS method	PDI method	2D-LRA method, 60 μm	3D-LS method
Primary average, P_a	0.031	0.035	0.035	0.074	0.088	0.114	0.169	0.209	0.209	0.298
Maximum profile peak height, P_p	0.129	0.336	0.147	0.148	0.197	0.426	0.467	0.491	0.819	0.638
Maximum profile valley depth, P_v	0.240	0.113	0.156	0.783	0.558	0.368	1.119	0.665	0.579	1.622
Maximum height of profile, P_t	0.369	0.449	0.304	0.930	0.755	0.794	1.586	1.156	1.398	2.260
Mean total height, P_{tm}	0.190	0.064	0.078	0.131	0.408	0.193	0.255	0.647	0.493	0.492
Mean peak height, P_{pm}	0.076	0.034	0.035	0.061	0.150	0.110	0.113	0.287	0.261	0.243
Mean valley depth, P_{vm}	0.113	0.030	0.043	0.070	0.258	0.083	0.142	0.361	0.233	0.249
RMS primary, P_q	0.049	0.049	0.045	0.135	0.110	0.144	0.253	0.257	0.267	0.433
Maximum primary depth, P_{max}	0.301	0.327	0.220	0.833	0.713	0.413	1.167	0.837	1.066	1.714

Note: 1 mm = 0.039 in.

Table 3—Roughness parameters

	Left as-cast, mm (in.)				Wire brushing, mm (in.)			Sand blasting, mm (in.)		
Roughness parameters	PDI method	2D-LRA method, 10 μm	2D-LRA method, 60 μm	3D-LS method	PDI method	2D-LRA method, 60 μm	3D-LS method	PDI method	2D-LRA method, 60 μm	3D-LS method
Roughness average, R_a	0.024	0.008	0.011	0.032	0.054	0.028	0.058	0.100	0.061	0.105
Maximum profile peak height, R_p	0.130	0.239	0.098	0.230	0.174	0.186	0.285	0.315	0.322	0.417
Maximum profile valley depth, R_v	0.201	0.132	0.111	0.437	0.448	0.138	0.531	0.419	0.244	0.590
Maximum height of profile, R_t	0.331	0.371	0.209	0.668	0.623	0.324	0.817	0.735	0.566	1.007
Mean total height, R_{tm}	0.189	0.058	0.073	0.104	0.338	0.146	0.183	0.507	0.269	0.309
Mean peak height, R_{pm}	0.084	0.032	0.037	0.049	0.123	0.074	0.084	0.218	0.141	0.155
Mean valley depth, R_{vm}	0.105	0.026	0.036	0.054	0.215	0.072	0.100	0.289	0.128	0.154
RMS roughness, R_q	0.042	0.019	0.017	0.069	0.076	0.038	0.100	0.126	0.080	0.151
Maximum roughness depth, R_{max}	0.306	0.303	0.199	0.662	0.565	0.311	0.767	0.735	0.525	0.914
Valley depth, R_z	0.189	0.058	0.073	0.104	0.338	0.146	0.183	0.507	0.269	0.309
Ten-point height of irregularities, R_{zJIS}	0.238	0.160	0.158	0.252	0.421	0.266	0.397	0.645	0.485	0.604

Note: 1 mm = 0.039 in.

Table 4—Waviness parameters

	Left as-cast, mm (in.)				Wire brushing, mm (in.)			Sand blasting, mm (in.)		
Waviness parameters	PDI method	2D-LRA method, 10 μm	2D-LRA method, 60 μm	3D-LS method	PDI method	2D-LRA method, 60 μm	3D-LS method	PDI method	2D-LRA method, 60 μm	3D-LS method
Waviness average, W_a	0.018	0.033	0.033	0.065	0.056	0.109	0.153	0.147	0.182	0.251
Maximum profile peak height, W_p	0.037	0.127	0.107	0.110	0.136	0.266	0.419	0.244	0.600	0.467
Maximum profile valley depth, W_v	0.043	0.047	0.064	0.392	0.118	0.320	0.617	0.489	0.463	1.176
Waviness height, W_t	0.080	0.174	0.171	0.501	0.254	0.586	1.036	0.733	1.063	1.643
Mean total height, W_{tm}	0.038	0.017	0.018	0.059	0.139	0.085	0.133	0.262	0.298	0.278
Mean peak height, W_{pm}	0.020	0.006	0.004	0.029	0.068	0.054	0.064	0.108	0.155	0.138
Mean valley depth, W_{vm}	0.019	0.011	0.014	0.030	0.072	0.031	0.069	0.154	0.143	0.140
RMS waviness, W_q	0.022	0.042	0.041	0.100	0.064	0.136	0.205	0.194	0.230	0.353
Maximum waviness depth, W_{max}	0.047	0.073	0.047	0.309	0.202	0.200	0.564	0.383	0.731	1.038

Note: 1 mm = 0.039 in.

profile valley depth W_v, waviness height W_t, mean total height W_{tm}, mean peak height W_{pm}, mean valley depth W_{vm}, RMS waviness W_q, and maximum waviness depth W_{max}.

In Tables 2 to 4, the mean values of the primary, roughness, and waviness parameters, obtained from the measured profiles are presented, respectively.

RESULTS DISCUSSION

Results were analyzed according to the following methodology: 1) the variation of texture parameters with the increase/decrease of the surface texture were analyzed for each optical method; 2) in the case of the 2D-LRA method, and essentially for the smooth (left as-cast) surface, the

Table 5—Analysis of primary parameters

	Left as-cast, mm (in.)		Wire brushing, mm (in.)		Sand blasting, mm (in.)	
Primary parameters	AVG	STD	AVG	STD	AVG	STD
Primary average, P_a	0.046	0.024	0.124	0.041	0.239	0.051
Maximum profile peak height, P_p	0.204	0.114	0.363	0.145	0.650	0.164
Maximum profile valley depth, P_v	0.379	0.356	0.682	0.391	0.955	0.579
Maximum height of profile, P_t	0.583	0.303	1.045	0.469	1.605	0.580
Mean total height, P_{tm}	0.128	0.063	0.285	0.111	0.544	0.089
Mean peak height, P_{pm}	0.057	0.021	0.124	0.022	0.263	0.022
Mean valley depth, P_{vm}	0.071	0.041	0.161	0.089	0.281	0.070
RMS primary, P_q	0.077	0.050	0.169	0.075	0.319	0.099
Maximum primary depth, P_{max}	0.487	0.300	0.764	0.379	1.205	0.455

Note: 1 mm = 0.039 in.

Table 6—Analysis of roughness parameters

	Left as-cast, mm (in.)		Wire brushing, mm (in.)		Sand blasting, mm (in.)	
Roughness parameters	AVG	STD	AVG	STD	AVG	STD
Roughness average, R_a	0.021	0.012	0.047	0.017	0.089	0.024
Maximum profile peak height, R_p	0.200	0.060	0.215	0.061	0.351	0.057
Maximum profile valley depth, R_v	0.257	0.160	0.372	0.207	0.418	0.173
Maximum height of profile, R_t	0.456	0.184	0.588	0.248	0.769	0.222
Mean total height, R_{tm}	0.117	0.067	0.222	0.102	0.362	0.127
Mean peak height, R_{pm}	0.055	0.027	0.094	0.026	0.171	0.041
Mean valley depth, R_{vm}	0.062	0.040	0.129	0.076	0.190	0.087
RMS roughness, R_q	0.043	0.025	0.071	0.031	0.119	0.036
Maximum roughness depth, R_{max}	0.424	0.207	0.548	0.228	0.725	0.195
Valley depth, R_z	0.117	0.067	0.222	0.102	0.362	0.127
Ten-point height of irregularities, R_{zJIS}	0.217	0.050	0.361	0.083	0.578	0.083

Note: 1 mm = 0.039 in.

influence of the sensor accuracy was analyzed; 3) for each texture parameter, the analysis of the corresponding variation when assessed by each of the adopted optical methods; and 4) analysis of results obtained with the SPT and comparison with results from the remaining methods.

Variation of parameters with surface texture

The texture parameters should express the increase of the surface roughness from smooth to rough with aggregate exposure. Therefore, for each method, the value of each parameter (Tables 2 to 4) should increase from left as-cast to sand blasting. With the exception of the following three (Table 3), all roughness parameters presented the expected variation: the maximum profile peak height and maximum height of the profile decrease from left as-cast to the wire-brushed surface and then increase from this to the sand-blasted surface; and the maximum profile valley depth decreases from the wire-brushed surface to the sand-blasted surface. These exceptions are not significant and can be explained. Actually, all of these parameters are based on extreme values, maximum peaks, and valleys; therefore, the existence of deep air holes or very exposed aggregates can generate these abnormal values.

2D-LRA method—influence of sensor accuracy

The smooth (left as-cast) surface was measured using the LRA with two different laser sensors with resolutions of 10 and 60 μm (0.0004 and 0.0024 in.). Relative to the differences obtained with both laser sensors, (Tables 2 to 4), it was observed that the values are very similar for parameters based on mean values, but somewhat different for those based on maximum values. Therefore, especially for smooth surfaces, the selection of a laser sensor with an adequate accuracy according to the surface texture is most important.

Variation of parameters with texture measuring methods

The analysis of the texture parameters, assessed with all methods except for the SPT, was made using a statistical approach. For each numerical parameter and surface condition, the following values were computed: average (AVG) and standard deviation (STD), using the results obtained from the three methods, which are presented in Tables 5 to 7, respectively, for primary, roughness, and waviness profiles. In Fig. 4 to 6, the coefficients of variation (COV) determined for each parameter and surface condition are represented.

With the exception of three parameters, it can be stated that the variation of the numerical parameters reduces with the increase of the surface roughness. This indicates that the resemblance between readings increases from smooth to rough surfaces for the three methods. Consequently, it is advisable to use more accurate measuring devices for very smooth surfaces to reduce the variability and increase the accuracy of results. This observation corroborates the conclusions drawn in a previous study.[6]

Table 7—Analysis of waviness parameters

Waviness parameters	Left as-cast, mm (in.)		Wire brushing, mm (in.)		Sand blasting, mm (in.)	
	AVG	STD	AVG	STD	AVG	STD
Waviness average, W_a	0.039	0.024	0.106	0.049	0.194	0.053
Maximum profile peak height, W_p	0.091	0.048	0.274	0.142	0.437	0.180
Maximum profile valley depth, W_v	0.161	0.200	0.352	0.251	0.709	0.404
Waviness height, W_t	0.252	0.221	0.625	0.393	1.146	0.460
Mean total height, W_{tm}	0.038	0.021	0.119	0.029	0.279	0.018
Mean peak height, W_{pm}	0.018	0.012	0.062	0.007	0.134	0.024
Mean valley depth, W_{vm}	0.020	0.009	0.057	0.023	0.145	0.008
RMS waviness, W_q	0.055	0.040	0.135	0.070	0.259	0.083
Maximum waviness depth, W_{max}	0.143	0.145	0.322	0.210	0.717	0.328

Note: 1 mm = 0.039 in.

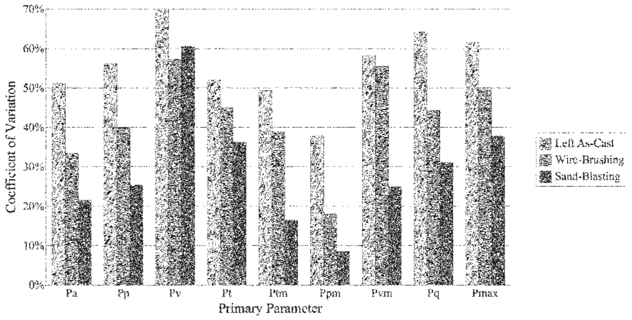

Fig. 4—COV of primary parameters.

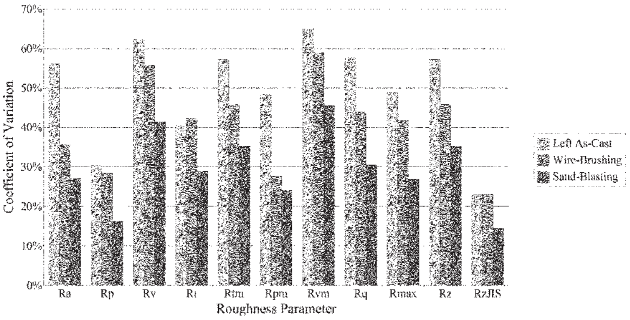

Fig. 5—COV of roughness parameters.

Further studies are needed to investigate the high values observed for the coefficient of variation and to check if these are related with the reduced number of measured profiles adopted in this study.

Discussion of results from SPT

The SPT was performed on the same three surfaces tested with the optical methods (Fig. 7). A volume of 100 mL (6.10 in.^{3}) of sand was considered. It was observed that the speed adopted for the test has a significant influence on results, namely on the diameter of the spread sand. The same average diameter was measured for the left as-cast and for the wire-brushed surfaces (125 mm [4.92 in.]), and a smaller value for the sand-blasted surface (110 mm [4.33 in.]). Therefore, the corresponding values of the mean texture depth for the three situations are 8.15, 8.15, and 10.52 mm (0.3209, 0.3209, and 0.4142 in.), respectively. Results achieved with this method do not reproduce different texture surfaces and are not in accordance with the results obtained with the remaining (optical) methods.

CONCLUSIONS

The experimental study conducted showed that the PDI method, the 2D-LRA method, and the 3D-LS method can be used to characterize the texture of a concrete surface. Contrary to these, the SPT cannot be used with this purpose because it does not reproduce the difference between surfaces with different textures, mainly if these are smooth or a little rough. Moreover, the SPT also presents the major disadvantage of only being applicable to horizontal top surfaces.

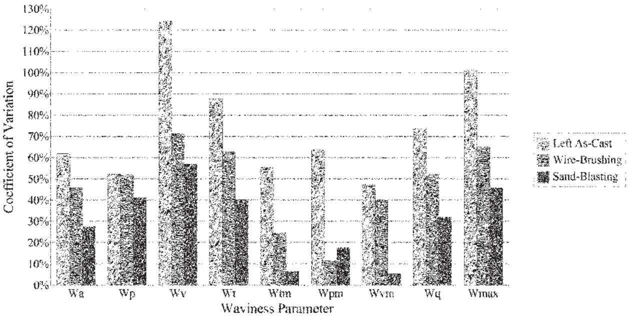

Fig. 6—COV of waviness parameters.

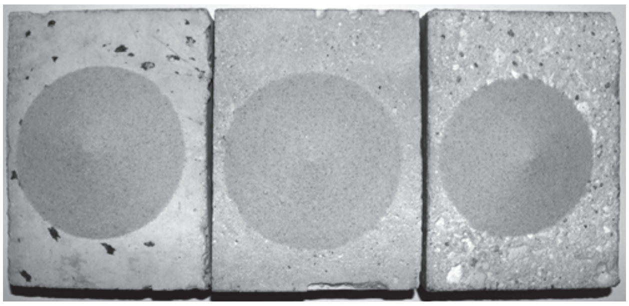

Fig. 7—SPT.

In comparison to the remaining, the 2D-LRA method proved to be the most suitable for the texture characterization of the concrete surface because it presents an adequate accuracy in opposition to the SPT; it is nondestructive, contrary to the PDI method; and it has an acceptable acquisition and maintenance cost compared to the 3D-LS method.

In what concerns the adopted parameters, it was observed that the existence of deep air holes and/or very exposed aggregates on the substrate surface can influence the measured values (in particular, texture parameters based in extreme values), originating high variability in results.

Smooth surfaces require the use of laser sensors with improved accuracy, particularly when texture parameters based in maximum values such as the highest peak and the deepest valley are adopted.

In this study, primary, roughness, and waviness parameters were determined and all of them proved to be capable of distinguishing the considered surface conditions. Filtering presents some advantages—separating texture into roughness and waviness—but also makes results dependable on the choice of the filter and of the cut-off length. If filtering could be avoided, the characterization of concrete surfaces would be much easier, faster, and simpler to perform.

Further studies are also needed to investigate the high values observed for the COV and to check if these are related with the reduced number of measured profiles adopted in this study.

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