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APPLICATION OF HE-NE LASER IN SURFACE METROLOGY OF POROUS CONSTRUCTION MATERIALS

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Summary: Application of laser radiation (He-Ne laser) in surface metrology of porous construction materials is relatively new concept. Non-contact measurement of surface alterations is based on analysis of the reflected light parameters. Although such analysis can be very complex due to highly developed roughness of surfaces they proved to be very informative. In this paper, two methods – laser speckle method and reflected light intensity method are presented and compared. The average surface modification factor, obtained from the laser speckle method and from reflected light intensity method shows a very good correlation.

Keywords: laser speckles analysis, reflected light intensity, cementitious materials

1. INTRODUCTION

Over the past few decades laser technologies have gained increasing popularity and have found many applications in different brunches of industry. Unfortunately application of lasers in construction industry is still very limited, especially in modification/metrology of porous materials, such as concrete or ceramics. It is mainly caused by the lack of comprehensive databases relating porous materials characteristics with irradiation parameters [1],[2]. The existing laser treatment of construction materials is restricted to the technological processes either during the manufacturing in the factory or directly in service conditions (real objects) [3]. The first group of applications includes mainly cutting and drilling holes, modification of near-surface layers, welding. The second group covers usually laser application in cleaning of contaminated surfaces (mainly historic buildings), removal of the radioactive layers, drilling holes and cutting rocks [4].

The application of laser beam radiation (He-Ne) in surface metrology of porous materials is relatively new concept not yet fully investigated. Non-contact measurement of surface alteration is based on analysis of the reflected light parameters. Although such analysis can be very complex due to highly developed roughness of surfaces they proved to be very informative [5], [6].

This paper presents the application of He-Ne laser in surface characterisation of cementitious mortars subjected to cleaning process. Two methods will be applied to assess the modification of surfaces – the laser speckle method and the reflected light intensity method [7].

2. LASER SPECKLE METHOD

Monochromatic, highly coherent laser light directed onto an optically rough object is partially reflected, absorbed and transmitted. Waves, reflected from such material, are phase displaced (shifted) between each other. Interference of such coherent but phase-shifted waves produces the interference pattern called laser speckles. Fig. 1 below [8] shows the principle of method.

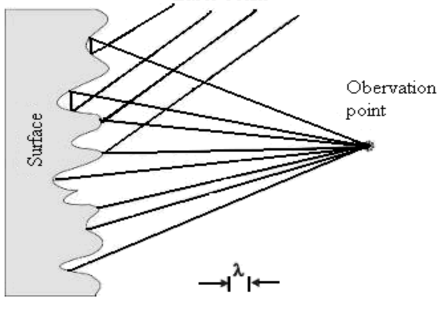

Fig 1. Speckle pattern of reflected light from the rough surface.

The characteristic grainy structure does not represent an obvious relationship with the macroscopic structure of the object and has a rather unsystematic and chaotic character with non-regular patterns, which are best described by probabilistic theory and statistics [9]. Analyses of speckle images are usually based on the analysis of distribution of light intensity of striae obtained in a selected plane and analysis of statistical parameters describing such distribution (intensity of the reflected light, skewness, kurtosis) [5],[10]. Since the intensity of reflected light depends on the geometrical microstructure of the samples, any alterations of surface result in different speckle images.

Individual images can be characterised by the following parameters:
Intensity of reflected light. Average intensity of the reflected light is obtained by an estimation of the expected value from the histogram of intensities of all recorded points of image or by using an intensity diagram. 625 lines are considered in a single laser speckle image to determine the intensity of reflected light, expressed in relative units, [r.u.]. The intensity of light is recorded along each line as shown on Figure 2.

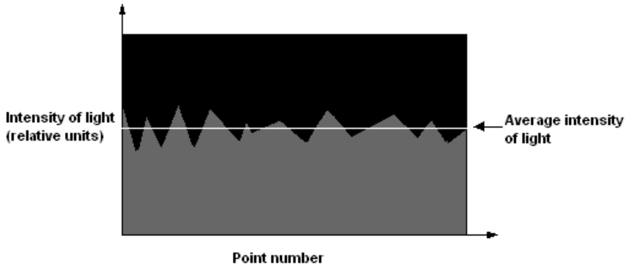

Fig. 2. The intensity of light along one line in the laser speckle image.

The area under the curve (Figure 2) is calculated for each line to find out the average intensity of light. The average intensity of reflected light is given by the following equation:

$$I_{AV} = \frac{1}{L}\sum_{1}^{L}\frac{1}{d}\int_{0}^{d} xI(x)dx \qquad (1)$$

Where: I_{av} is an average intensity of reflected light,
L is a number of all lines of image,
d is a length of image line.

The light intensity is expressed by mean of grey level (0-225). The grey level depends on the CCD camera position, time of the shutter opening and level of whiteness. The optimal position of camera can be determined from the histogram. The condition is an assumption of minimum number of points having gray level of 0 and 255. The number of such points must be significantly lower then the number of points for a mean value.
Skewness. Skewness is a measure of asymmetry of a histogram of intensities. It is calculated by using third central moment, which is calculated from the histogram of intensities of grey levels for the whole image:

$$Sk = \frac{M_3}{S^3} \qquad (2)$$

Where, S is the standard deviation.
The third central moment is given by the following equation:

$$M_3 = \frac{1}{N_0}\sum_{i=1}^{k}(\overline{x_i} - \overline{x})^3 n_i \qquad (3)$$

Where: k express a number of classes of a mean value x_i and of size n_i. N_0 is a number of all elements and $\overline{x}$ is a mean value for a specimen.

Skewness reveals whether the number of bright and dark points is the same in the speckle image. Figure 3 shows an example of a distribution of light intensity with more bright points. Here the value of skewness is positive.

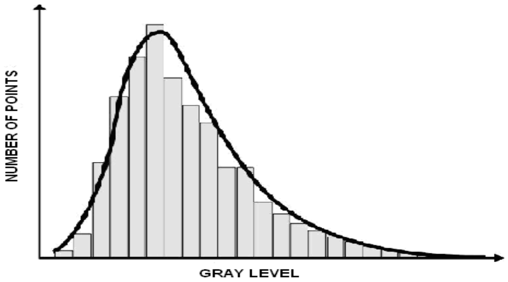

Fig. 3. Distribution of light intensity with very bright points

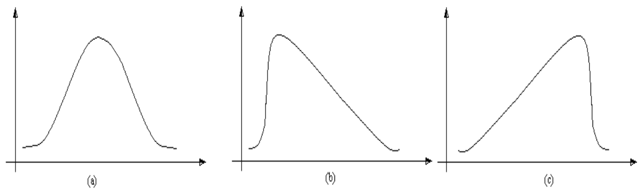

Fig. 4. Distributions of light intensity with different skewness: (a) Normal curve, (b) Positively skewed curve, (c) Negatively skewed curve.

Figure 4 shows different types of distribution of light intensity. When $Sk \geq 1$ or ≤ -1, the distribution is highly skewed; when $0.5 < Sk < 1$, the distribution is moderately skewed; when $0 < Sk < 0.5$, the distribution is almost symmetric [11].

Kurtosis. Kurtosis is a measure of "flatness" of the histogram of intensities. It can be determined from the following equation:

$$K = \frac{M_4}{S^4} \qquad (4)$$

Where M_4 is the fourth central moment and S is the standard deviation.

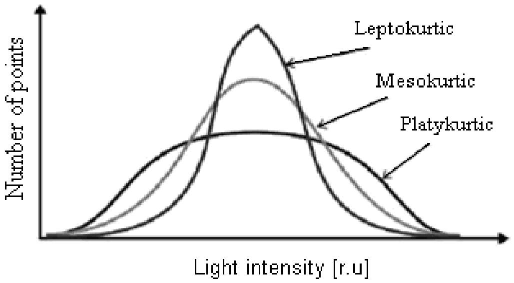

Fig. 5. Distributions of light intensity with different kurtosis.

When $K = 3$, the distribution is said to be *mesokurtic* with reference to a "normal distribution"; when $K < 3$, the distribution is said to be *platykurtic*, and when $K > 3$, the distribution is said to be *leptokurtic*.

3. EXPERIMENT

The subjects of this investigation were laser-cleaned mortar samples with different internal microstructures (H - high porosity; L - low porosity), surface roughness (A, B, C), and moisture content (wet - W, dry- D). Assessment of the effectiveness of the laser cleaning process has been performed by means of He-Ne laser with the maximum power of 70mW.

Each sample was previously subjected to laser cleaning (Nd:YAG laser) of the same laser fluence (3.06 J/cm^2) but an increasing number of pulses (N) as shown in Figure 6.

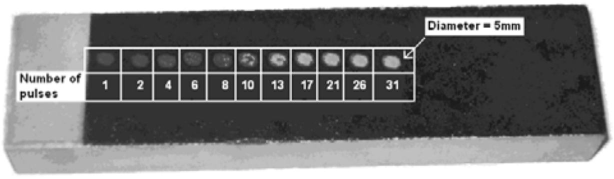

Fig. 6. Sample after the laser cleaning process; constant laser fluence (3.06 J/cm^2) and increasing number of pulses.

The effectiveness of the cleaning process was preliminarily assessed by optical microscopic examinations, followed by the detailed analyses of laser speckle images and reflected light intensities.

3.1. Laser Speckle Method

An experimental set up used in the adopted method is presented in Fig. 7. The laser beam was divided into two beams by a prism. Consequently, part of the reflected light passed through a diaphragm and reached a specimen and the other part reached the photo-sensor controlling the stability of laser work. Light reflected from the specimens was recorded by cameras and analysed.

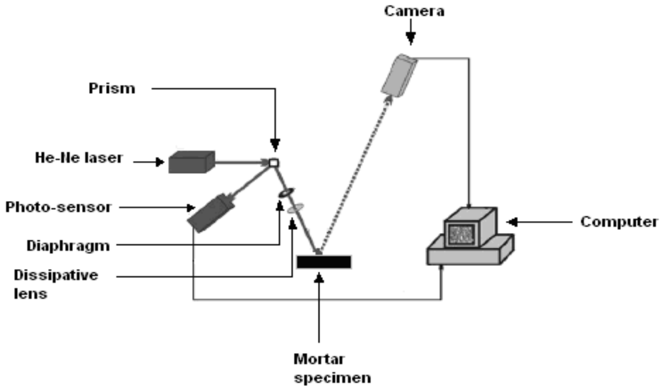

Fig. 7. Schematic diagram of measuring system.

3.2. Reflected Light Method

The intensity of light reflected from the specimen, as recorded by a photodiode detector, is directly related to the surface characteristics. Porous construction materials, such as bricks, concrete, and stone, have a high absorption characteristic. Because of the low intensity of scattering light, it is very difficult to capture it by a detector, especially when a low power laser (< 1mW) is used in an open space with several light sources (light noises). An experimental set up, was designed and built to overcome these problems (Fig. 7). Laser light was directed onto the sample at the angle of 45^o. In order to get a unique signal, low energy pulses of were produced by a chopper from the continuous laser. The frequency of the chopper was selected in a prime number. To avoid overlaps of signals, the frequency of the incident beam should not be a multiple of the frequency of light noise. A reference beam was obtained from the incident beam, using a beam splitter To eliminate the oscillation in the incident beam, the ratio of the intensity of scattered light to the intensity of reference beam was calculated. The chopper was computer-controlled, to get the reference signal of the frequency equal to the frequency of the He-Ne laser. LabVIEW was adapted in such way as to allow identification and processing of the reflected beam of only a particular frequency (frequency of reference signal).

4. RESULTS AND ANALYSIS

4.1. Laser speckle method

The analyses of the mean light intensity of reflected light were supplemented by the analysis of skewness and kurtosis. Figures 8 show variations in mean light intensity/500, kurtosis, and skewness as a function of the number of pulses applied. Kurtosis and skewness decrease gradually to a certain level, approximately equal to kurtosis and skewness obtained for the reference surface. The number of pulses corresponding to this point are marked as N_g. Beyond this point, variations in kurtosis and skewness with the number of pulses applied were smaller. These variations showed that, with the increased number of pulses, the distribution of light intensity changed from highly skewed and leptokurtic distribution to moderately skewed and mesokurtic distribution.

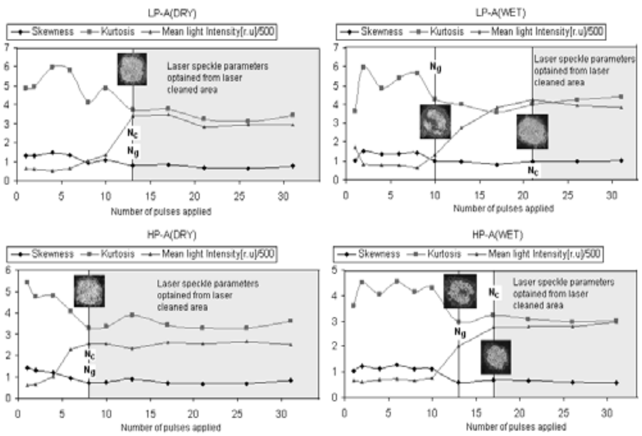

Fig.8. Mean light intensity, kurtosis and skewness of the reflected light distribution; F = 3.06 J/cm^2; Ra = 2.28-2.49 µm.

Increased number of laser pulses results in increased mean light intensity up to a certain level. Approximately equal to mean light intensity of reflected light from reference surface (point N_C). After the application of N_C number of pulses, corresponding to the minimum number of pulses required to entirely remove paint from the mortar surface, variations in mean light intensities were negligible. Differences in the number of pulses required for surface cleaning in relation to different surface conditions can be attributed to variations in mortar characteristics or/and thickness of a paint layer.

The points N_g and N_C were not always the same as shown above. That is, the number of pulses corresponding to point N_g might be smaller or equal to point N_C, so that kurtosis and skewness reached the constant value (comparable to the reference surface) before the mean light intensity. Thus, kurtosis and skewness would reach a constant value before the total removal of paint, suggesting that they do not depend on the surface colour (colour of paint and mortar). For instance, kurtosis and skewness of reflected light from partially and fully cleaned mortar surface were almost the same as shown in Figure 9.

	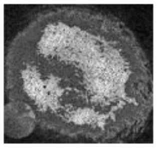	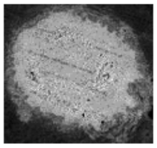
Number of pulses	10	26
Skewness	1.0	1.0
Kurtosis	4.3	4.3

Fig. 9. Kurtosis and skewness of distribution of reflected light from laser-affected area and number of pulses applied; L-A(W);

Therefore, the initial changes in kurtosis and skewness, caused by the increasing number of pulses applied, should be mainly associated with the alterations of geometrical microstructure. However, mean light intensity seemed to depend predominantly on the mortar's absorption characteristics (colour).

The values obtained from the laser speckle analysis method coincided very well with the number of pulses required for the laser cleaning, as estimated by the microscopic inspection.

It is important to note that these results should be treated with caution, due to the non-linear increase in the number of pulses required. Since the aim of this analysis is to present the application of the assessment method, rather than to determine the precise number of pulses required for efficient cleaning, non-linear increments of the number of pulses does not pose a problem.

In order to compare the modification of mortar surfaces by the laser cleaning process, surface modification factor (SMF), based only on mean light intensity, may be introduced:

$$\mathrm{SMF} = |1 - (I_C / I_R)| \qquad (4)$$

Where:

I_R – mean intensity of reflected light from a reference surface

I_C – mean intensity of reflected light from a laser cleaned area

Surface modification may be associated with change of colour, surface roughness and surface density or any combination of these. Table 1 summarises the detailed analysis of laser speckle parameters. The average modification factor was determined as 0.12. The ratio of I_C/I_R varied within the range of 0.73 - 1.20 for different surface conditions. This implies that, when the ratio between mean intensity of the reflected light from laser affected surface and the reference surface reaches the above range, the surface becomes almost free from paint. The values of mean light intensity of the reflected light from a surface partially covered by paint (I_P) are within a narrow range of 247 to 399, indicating similarity of absorption characteristics of different surfaces, and therefore the presence of paint.

Table 1. Intensities of reflected light, statistical parameters of their distribution and surface modification factor with respect to different samples

Sample code	I_R	I_P	I_C	I_C/I_R	SMF	Sk_R	K_R	Sk_C	K_C
L-A(D)	1710	304	1559	0.91	0.09	0.62	3.20	0.95	4.00
L-A(W)	1549	386	1862	1.20	0.20	0.87	4.05	0.76	3.50
H-A(D)	1286	384	1255	0.98	0.02	0.61	3.00	0.63	3.10
H-A(W)	1404	342	1327	0.95	0.05	0.75	3.46	0.76	3.44
L-B(D)	924	247	883	0.96	0.04	0.57	3.00	0.55	2.95
L-B(W)	965	281	939	0.97	0.03	0.77	3.48	0.73	3.41
H-B(D)	882	344	896	1.02	0.02	0.53	2.86	0.70	3.31
H-B(W)	1037	395	876	0.84	0.16	0.68	3.38	0.73	3.49
L-C(D)	1148	382	937	0.82	0.18	0.64	3.22	0.70	3.36
L-C(W)	1384	352	1113	0.80	0.20	0.76	3.70	0.74	3.61
H-C(D)	1150	352	932	0.81	0.19	0.83	3.69	0.77	3.74
H-C(W)	1043	277	938	0.90	0.10	0.73	3.80	0.70	3.40

Where:

I_R – mean intensity of reflected light from a reference surface

I_C – mean intensity of reflected light from a laser cleaned area

I_P – mean intensity of reflected light from a laser affected areas covered by paint

SMF- surface modification factor: SMF = $| 1 – (I_C / I_R)|$

Sk_R – skewness of distribution of light intensity reflected from reference surface

Sk_C – skewness of distribution of light intensity reflected from laser-cleaned area

K_R – kurtosis of distribution of light intensity reflected from reference surface

K_C – kurtosis of distribution of light intensity reflected from laser-cleaned area

Interpretation of the surface modification factor is very complex, since the intensity of reflected light depends on surface roughness, colour, and surface density (near surface porosity). The obtained SMF values should be treated therefore with a caution. Even though the correlation between the average surface roughness and the value of the SMF for all samples is poor, it seems that an increase in average surface roughness above certain level (Ra = 8.5 µm) leads to an increase of the SMF and therefore more extensive modification.

Furthermore, average Surface Modification Factors corresponding to wet surfaces were higher, indicating the greater possibility of surface colour changes on wet surfaces, probably due to evaporation of water.

4.2. Reflected light intensity method

The surface condition and effectiveness of laser cleaning were also assessed by application of the reflected light intensity method. Various surfaces, whether cleaned or un-cleaned have different absorption characteristics, depending on their colour and other surface parameters such as roughness. The assessment of surface condition is based on the measurement of light intensity reflected from this surface.

Fig. 10 show the relationship between the number of pulses applied to the surface and the ratio between the intensities of light reflected from laser-cleaned area I_C and the light reflected from the reference surface I_R (original mortar surface).

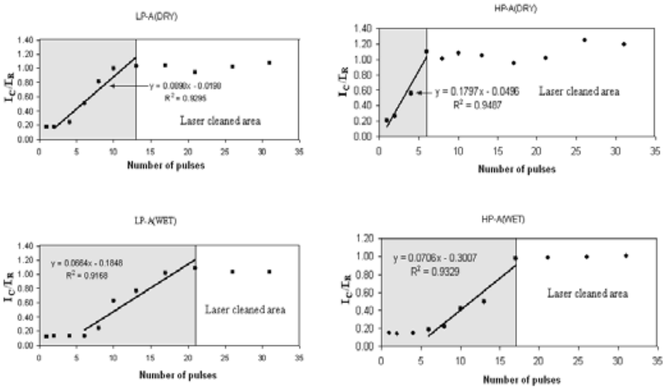

Fig. 10. Variation of I_A/I_R with the application of laser pulses; Samples A.

The intensity of reflected light from the laser-affected area remained initially nearly constant and then it changed linearly (0.99 > R^2 > 0.92), until surfaces become almost free from paint. After that, only small fluctuations in light intensity were observed.

Since the number of pulses required to clean a paint layer of smaller thickness is lower, the steeper gradient of some graphs might be attributable to the smaller thickness of paint layer. However, the gradient of a linear portion seemed to change with the surface roughness of surfaces. Higher gradients were observed for the smoother surfaces (Ra = 2.28-2.49 µm) while smaller gradients were observed for rougher ones (Ra = 15.58-17.89 µm). This leads to the conclusion that rougher surface required higher number of pulses to clean than smoother surface.

Table 2 shows values of I_C/I_R with respect to different sample conditions. When the ratio between intensity of light reflected from the laser-affected areas and from the reference surface reaches the value of 0.83-1.09, surfaces become almost free from paint.

Table 2: The surface modification factors, gradient and squared correlation of coefficient of linear portion and I_C/I_R with respect to different sample conditions.

Sample code	I_C/I_R	Gradient (m)	R^2	SMF	
				Laser Speckle method	Reflected light intensity method
H-A(W)	0.99	0.071	0.93	0.05	0.01
H-A(D)	1.02	0.18	0.95	0.02	0.02
L-A(W)	1.09	0.066	0.92	0.2	0.09
L-A(D)	0.94	0.0.90	0.93	0.09	0.06
H-B(W)	0.83	0.107	0.99	0.16	0.17
H-B(D)	0.99	0.266	0.99	0.02	0.01
L-B(W)	1.01	0.093	0.97	0.03	0.01
L-B(D)	1.02	0.118	0.96	0.04	0.02
H-C(W)	0.94	0.043	0.92	0.1	0.06
H-C(D)	0.86	0.054	0.96	0.19	0.14
L-C(W)	0.84	0.049	0.95	0.2	0.16
L-C(D)	0.84	0.031	0.97	0.18	0.16

The average surface modification factor, SMF, obtained from the laser speckle method was 0.12, while the average surface modification factor in reflected light intensity method was 0.10, showing a high consistency of the results.

5. SUMMARY

Based on experimental investigations some preliminary observations and conclusions can be formulated.

- The surface modification factor is proposed to assess the extent of alteration of mortar surfaces resulting from laser cleaning process:
  $\mathrm{SMF} = | 1 - (I_C / I_R)$
  I_R – mean intensity of reflected light from a reference surface: I_C – mean intensity of reflected light from a laser cleaned area
- The increase of average surface roughness above 8.5 μm resulted in an increase of the modification factor. Surface modification seems to be more pronounced on rough surfaces rather than smooth ones. Moreover, the surface modification on mortar surface due to laser cleaning of wet samples was more visible than of dry ones.
- Mortar surfaces became free from paint layer when the ratio between mean light intensity reflected from laser cleaned area and mean light intensity reflected from the reference area (unpainted surface) reached the values between 0.80 – 1.20.
- With the increase of number of pulses, the distribution of light intensity changes from highly skewed and leptokurtic distribution to moderately skewed and mesokurtic distribution becoming similar to the distribution of light reflected from the reference surface. Moreover, kurtosis and skewness depends on the geometrical microstructure of the surface.
- There is good correlation between SMF results obtained from laser speckle method (0.12) and reflected light intensity method (0.10).

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