Periodica Polytechnica
Civil Engineering

OnlineFirst (2018) paper 11406
https://doi.org/10.3311/PPci.11406

RESEARCH ARTICLE

Terrestrial Laser Scanner as a Tool for Assessment of Saturation and Moisture Movement in Building Materials

Czesław Suchocki[1], Jacek Katzer[1*], and Jacek Rapiński[2]

Received 22 August 2017; Revised 03 November 2017; Accepted 15 February 2018

Abstract

Non Destructive Testing (NDT) is a key element of modern civil engineering. It is especially important in civil and structural engineering helping both in quality control of produced elements and technical assessments of existing structures. Existing NDT methods are being continuously improved and new methods are developed or adopted from different engineering fields. Terrestrial Laser Scanner (TLS) method which is commonly used for geodetic applications has a great potential to be successfully harnessed in civil and structural engineering. TLS can be used for remote sensing of saturation of building materials. A research programme was prepared in order to prove this concept. Specimens representing most popular European building materials were scanned using TLS. Tested specimens were in different saturation states including capillary rising saturation. The saturation assessment was based on differences of values of intensity. The concept proved to be feasible and technically realistic.

Keywords

TLS, NDT, saturation, building materials, intensity

1 Koszalin University of Technology,
Faculty of Civil Engineering Environmental and Geodetic Sciences,
Śniadeckich 2, 75-453 Koszalin, Poland
2 University of Warmia and Mazury in Olsztyn,
Institute of Geodesy, Oczapowskiego 2, 10-719 Olsztyn, Poland,
* Corresponding author, email: jacek.katzer@yahoo.com

1 Introduction

Modern civil and structural engineering is increasingly harnessing Non Destructive Testing (NDT). So far NDT methods have been extensively used in case of concrete structures and concrete precast elements. Safety assessment of existing structures and quality control of produced precast concrete elements become a daily practice. Some NDT methods gained large popularity among civil and structural engineers. In case of concrete elements and structures the most popular NDT methods are ultrasonic pulse velocity test and Schmidt hammer test. These long-established methods are also known as a rebound hammer or a Swiss hammer [1][2][3]. These basic and old NDT methods are focused on assessing compressive strength and modulus of elasticity (E) of different types of concrete and concrete-like materials and structures. There are also other NDT methods currently used for steel rebar detection (e.g. inductive assessment) [4] or for spacing assessment of steel fibre and air pores in a concrete element (e.g. X-ray computed tomography) [5][6]. All these widely utilized NDT methods have two common properties: they are directly associated with mechanical characteristics of a structure or element; there is a need for a free access to the tested structure or element. Therefore harnessing of these NDT methods in civil and structural engineering is significantly limited.

Structural safety of old and historic urban environment depends heavily on saturation of buildings and structures. Pure strength characteristics of the material or structural element achieved through means of traditional NDT methods is definitely not sufficient to maintain structural safety. Old and historic buildings and structures are much more likely to be saturated than the newly erected ones. The saturation can be caused by bad maintenance, lack of maintenance, properties of old insulating materials, long lasting bad weather conditions, new extensions, poorly executed restorations etc. Saturation changes the performance of building materials through triggering corrosion and influencing their thermal characteristics. In this way structural safety of a building or structure is quickly compromised. Quite often deterioration of a historic building is a very fast process with little of externals signs for extended periods of time. In majority of cases the parts of the historic building prone to saturation and subsequent deterioration are impossible to access without erecting full size scaffolding. When the signs of damage caused by saturation are large enough to be recognized from a distance and scaffolding is erected the deterioration process is usually significantly advanced. Keeping in mind that the number of old and historic buildings in need of structural safety inspection is constantly growing new NDT technics are necessary for civil and structural engineering. Probably, the most promising NDT technic with high potential of successful utilization for assessing the saturation of buildings is remote laser scanning [7][8][9][10]. Some preliminary tests conducted with the help of commercially available geodetic Terrestrial Laser Scanners (TLS) proved the viability of the concept. The research programme was described in a previous publication [11][12] and was focused on remote laser scanning of multiple dry and saturated building materials. It was proven that it is possible to use ordinary TLS for quick and remote saturation assessment of building materials. The authors decided to conduct current research programme with the help of a different type of commercially available geodetic TLS. The main objective of the research programme was to prove if the proposed methodology is valid for different TLS and to test the potential of the methodology for possible other saturation related measurements (e.g. moisture movement).

2 Used equipment

An impulse TLS scanner ScanStation C10 produced by Leica was used during the research programme. This scanner is characterized by full 360˚·270˚ field-of-view, high accuracy, long range (300m @ 90%; 134m @ 18% albedo), and high scan speed (50 000 pts/sec). Laser wavelength is visible green (wavelength = 532 nm) - Laser Class 3R (IEC 60825-1). The minimum measure range is equal to 0.1 m. Scan resolution for range from 0m to 50m is equal to 4.5mm and 7.0mm for FWHH-based and Gaussian-based measurements respectively. Point spacing is fully selectable both horizontally and vertically. The minimum spacing is less than 1mm for the full range. The TLS is also characterized by single point dwell capacity. The main principle of TLS is based on power of reflected laser signal. So called "laser equation" [13] describes the relation between emitted and received power of a laser signal (see Eq. (1)).

$$P_R = \frac{\pi P_E \rho \cos\alpha}{4r^2} \eta_{Atm} \eta_{Sys} \tag{1}$$

Where: P_R - detected signal power, P_E - transmitted signal power, α - angle of incidence, ρ - reflectance of a material, η_{Atm} - atmospheric transmission factor, η_{Sys} - system transmission factor, r - range

The presented equation Eq. (1) is a simplified version valid only for situations when a laser signal is reflected from a rough surface (Lambertian scattering) and the size of a laser dot is smaller than the scanned object. This version of a "laser equation" is commonly used in case of TLS in civil engineering. There are multiple factors influencing the measurement [14][15][16] such as: the distance between TLS apparatus and the scanned object, the angle of a laser beam hitting an object and the very material of the object. There are also weather conditions and system limitations which are represented in the Eq. (1) by η_{Atm} and η_{Sys} factors respectively. The value of ρ is influenced by colour, roughness and other reflective properties of a scanned surface. All these factors significantly influence absorption and scattering of a laser signal. Some researchers noted that water is absorbing laser signal [17]. Keeping this fact in mind authors decided to prepare a research programme focused on scanning dry and saturated construction materials. In theory saturation of a given construction or building material should increase its laser signal absorption and thus influence the reflectance of a material (ρ). The prepared experiments were to closely mirror real situations in civil and structural engineering during technical inspections. Proving that TLS is a viable and precise technic for remote NDT saturation assessment of buildings and structures was the main aim of the conducted research programme.

3 Laboratory set up

The research programme covered three different experiments. All the measurements were realized in an indoor environment (temp. +20˚C ± 1˚C; r.h. 45% ± 1%) and harnessing daylight (indoor scattered light). Conducting tests in a stable environment allowed to assume that the atmospheric transmission factor (η_{Atm}) is constant and there are no incidental lighting conditions. Taking into account these stable conditions and reasonably short time of scanning one can be also sure that the system transmission factor (η_{Sys}) and transmitted signal power (P_E) would be constant, too (see Eq.(1)). The first experiment was scanning the most popular building materials used in European countries in different saturation states. There were chosen: ordinary concrete (a cube specimen), cellular concrete (a prism wall bloc specimen), red ceramic (a prism hollow wall block specimen), silica (a prism wall block specimen) and pine timber (a board specimen). The specimens were prepared in three saturation states: oven dry, saturated only by air humidity and fully saturated. The full weight saturation of used ordinary concrete, cellular concrete, red ceramic and silica was equal to 1.1%, 52.6%, 20.4% and 16.5% respectively.

Specimens in question were remotely scanned by TLS from the distance of 7 m. This distance was chosen to mirror the experiments conducted using infra-red TLS described in the previous publication [11]. The utilized setup of the specimens for scanning is presented in Fig. 1. The second experiment was focused on scanning ceramic hollow wall blocks exposed to capillary rising saturation.

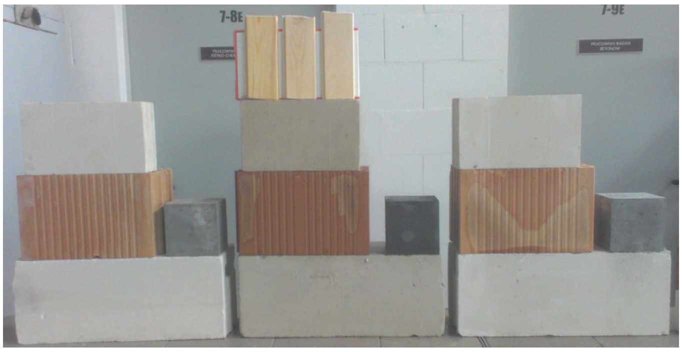

Fig. 1 Setup of specimens in three saturation states

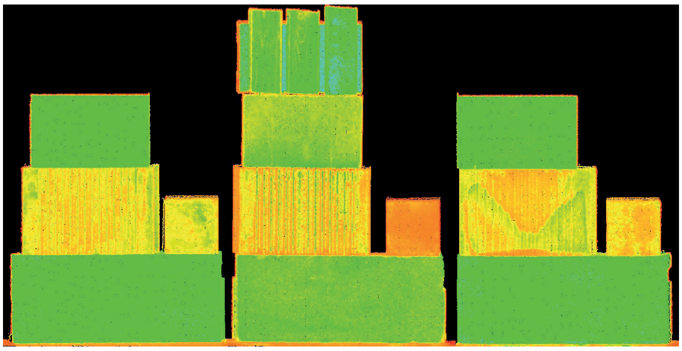

Fig. 3 Image of specimens created by TLS using artificial colours

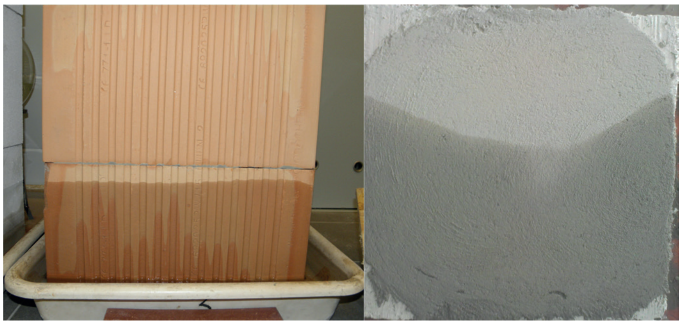

Fig. 2 Saturation of ceramic hollow blocks (left) and cement plaster on Styrofoam insulation (right)

The oven dry blocks with a layer of very fine aggregate mortar (to simulate the real wall) were placed in a plastic container with tap water. The level of the water in the container was kept constant using an autonomous hydraulic pressure system. The porous dry ceramic was sucking water and the level of saturation was rising. The whole process was scanned by TLS in time intervals for 96 hours. Time intervals were ranging from 1 hour (in the beginning of the process) to 15 hours (at the end of the test). The setup of the experiment No. 2 is presented in Fig.2. The third experiment was associated with light external thermal insulation systems. These systems are very common in Europe and they are used both during the erection of new “brick and mortar” buildings and renovation or refurbishment of old ones. The bottom part of the rectangular specimen was submerged in a water tank. In this way a full saturation of a system was enabled. The top part of the specimen remained air dry (see Fig. 2).

4 Achieved results

Experiment No. 1

Intensity of reflected laser beam was a parameter which was followed and registered during the research programme. The intensity (a dimensionless variable) is defined as a product of reflectance of a material (ρ) and unknown constant (C). The intensity was registered in multiple points for all specimens. The number of tested points (n) was ranging from 7600 to 54895. The smallest number of tested points was obtained for the smallest specimen (the pine wood board specimen) and the highest number of tested points was achieved for the largest specimen (a cellular concrete wall block).

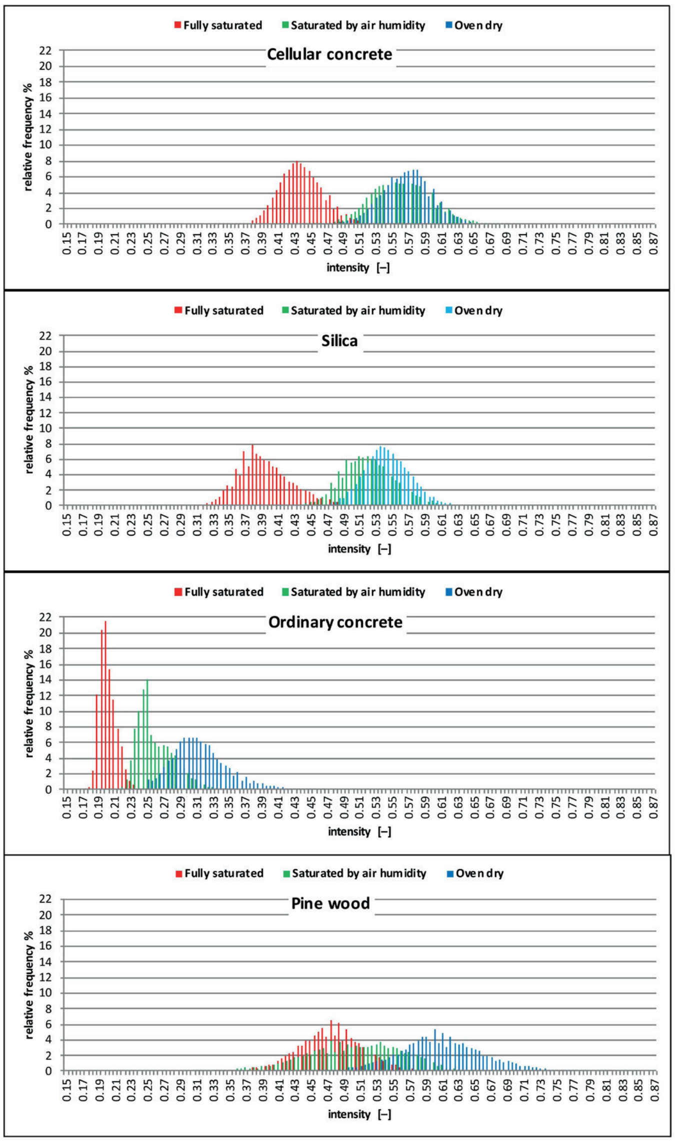

Fig. 4 Intensity for all tested materials in three states of saturation

Recorded values of n for all scanned materials are presented in Table 1. After scanning was completed all acquired data was filtered. The main aim of data filtering was to remove digital noise and edge effects resulting from reflectorless electronic distance measurement errors [18]. The sets of digital images were composed using RGB data, values of the intensity and geometric coordinates. TLS registers intensity in the scale ranging from -2047 to +2048. This scale was transformed into

Table 1 Values of intensity and number of tested points n scanned from the distance of 7 m

	Fully saturated						Saturated by air humidity						Oven dry				
	Intensity						Intensity						Intensity				
n	min.	max.	avg.	range	med.	*n*	min.	max.	avg.	range	med.	*n*	min.	max.	avg.	range	med.
Cellular concrete																	
51486	0.333	0.573	**0.438**	0.240	0.437	52722	0.442	0.707	**0.560**	0.265	0.559	54895	0.440	0.689	**0.566**	0.249	0.566
Silica																	
24384	0.250	0.557	**0.394**	0.307	0.390	24113	0.380	0.661	**0.520**	0.281	0.518	24249	0.448	0.672	**0.541**	0.224	0.540
Ordinary concrete																	
9337	0.173	0.250	**0.200**	0.077	0.198	8513	0.13	0.358	**0.258**	0.145	0.250	8992	0.237	0.465	**0.312**	0.228	0.031
Pine wood																	
7600	0.334	0.625	**0.474**	0.291	0.474	7720	0.304	0.668	**0.502**	0.364	0.504	8136	0.448	0.811	**0.607**	0.363	0.604

a scale ranging from 0 to 1, to present the achieved results in the most commonly used way of expressing the intensity. In Fig.3. an exemplary image of specimens using artificial colours is presented. Ceramic specimens were characterized by significant colour differences and local discoloration (see Fig. 1). Since colour hue impacts registered intensity, ceramic specimens were rejected from further analysis during experiment No. 1. Four sets of available data were used to create the histograms presented in Fig. 4. The relative frequency of results was used as a scale for vertical axis. In this way data collected from specimens with a different number of testing points n could be presented in the same graphic way. The values of intensity were used as a scale of the horizontal axis. The minimum and maximum values of the horizontal scale of all histograms was the same. Through this standardization, all histograms presented in Fig. 4 are easy to compare and study. Only in case of ordinary concrete there are clearly visible differences in values of intensity between all three states of saturation. The peak of fully saturated results, saturated by air humidity and oven dry are differentiated by the step of 0.05 and 0.06 of intensity respectively. Results achieved for cellular concrete and silica are divided into two groups. One group is formed by results of fully saturated specimens and the second is formed by results of oven dry and saturated by air humidity specimens. In both cases peaks for fully saturated material and oven dry material are clearly visible and apart from each other by intensity of 0.15. While analysing the peaks of results of saturated by air humidity and oven dry specimens, it is useful to keep in mind the values of full saturation percentage by weight for these materials. Ordinary concrete is characterized by the smallest full saturation of all tested materials. It is almost 48 times smaller than saturation of cellular concrete which is characterized by the largest saturation. The achieved results prove that small values of full saturation do not disable TLS saturation tests.

The phenomenon of the dense overlapping populations of results for oven dry and saturated by air humidity specimens is partially caused by the colour of a given surface which is not uniform and varies in different areas. These variations are magnified by a saturation level which eventually gives overlapping of oven dry results and results for specimens saturated only by air humidity.

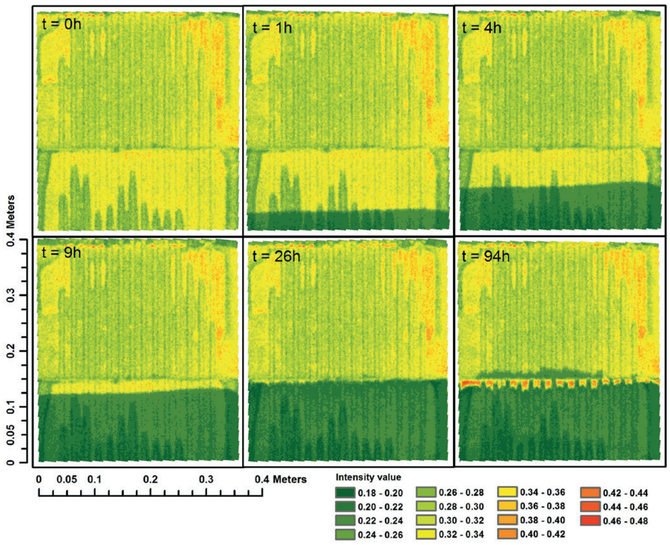

Fig. 5 Images created by TLS (using artificial colours) of a ceramic specimen being saturated

Experiment No. 2

The data was acquired and statistically treated in the same way as during experiment No. 1. In Fig. 5. images of a specimen being exposed to capillary rising saturation are presented. The images were prepared in artificial colours. The presented picture is a regular GRID model achieved through natural neighbour interpolation algorithm (definition 2mm · 2mm). In the starting image (t = 0h) significant colour differences and local discolorations of oven dry ceramic specimen can be observed. In the images, the capillary rising saturation is clearly visible. The images were taken after time intervals. Initial colour differences and local discolorations do not affect them. The border between dry and wet areas are very sharp. After 20 hours the bottom hollow red ceramic element was fully saturated. The process of capillary rising saturation was slowed down by a layer of fine aggregate mortar, but it wasn't stopped there. The experiment was ceased after 96 hours. The speed of capillary rising saturation assessed in three cross-sections of tested specimen is presented in Fig. 6

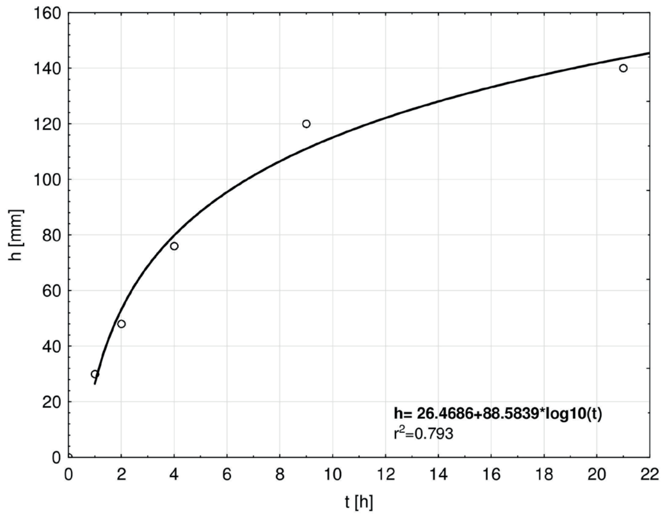

Fig. 6 The speed of capillary rising saturation in red ceramic hollow block

Experiment No. 3

Results of the experiment No. 3 are presented in Fig. 7. The same "natural neighbour interpolation" as in the experiment No. 2 was used to achieve images. The scanned surface of the rectangular specimen of a light external thermal insulation system (see Fig. 2) can be divided into three subareas: fully saturated, dry and blurred border between the above two. In Fig. 7 a scale of grey shades was used to present values of the intensity. Saturated and dry areas differs significantly. Peak values of intensity for dry and saturated areas are equal to 0.55 and 0.35 respectively.

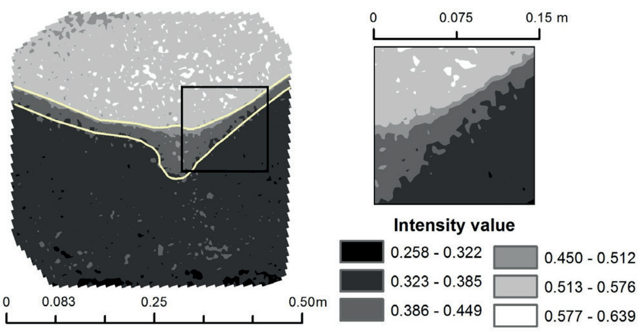

Fig. 7 Values of intensity achieved on specimen of a light external thermal insulation system

5 Discussion

The conducted research programme proved that saturation of building materials can be assessed with the help of TLS method. Some materials are better suited for TLS assessment than others. In case of tested materials ceramic specimens were characterized by significant colour differences and local discoloration which effectively disabled submitting them to experiment No. 1. Results of experiment No. 1 can be compared with the results achieved in a previous research programme [11]. Cellular concrete, silica and ordinary concrete (of the same quality) were successfully tested in homogenous conditions during both research programmes. Intensity registered with the help of infra-red TLS is always larger and the difference ranges from 0.204 to 0.388 depending on the tested material and its saturation. There are significant differences between both sets of results which were summarized in Table 2 in a form of difference described by the following equation:

$$i\Delta_1 = \text{avg.}\mathit{intensity}\ (\text{infra-red}) - \text{avg.}\mathit{intensity}\ (\text{visible green}) \qquad (2)$$

Table 2 Difference between intensity achieved by TLS based on infra-red and visible green laser

	$i\Delta_1$	
	Fully saturated	Oven dry
Cellular concrete	0.204	0.233
Silica	0.254	0.244
Ordinary concrete	0.388	0.290

The capillary rising saturation of ceramic wall elements was successfully followed during the experiment No. 2. It was possible to establish the velocity of the rising saturation over the passing time. The results of this experiment are very important from the point of view of technical assessment of old and historic structures. The results of the conducted experiment prove the viability of a concept and should be further tested and developed.

During the three described experiments feasibility of the method was proven. Nevertheless viability of the method yet has to be assessed. The basic viability assessment of the method was performed using two parameters: GRID intensity for dry and fully saturated specimens, for all tested elements. The factor $i\Delta_2$ was created and defined by the following equation:

$$i\Delta_2 = \mathit{GRIDintensity}\ (\text{dry}) - \mathit{GRIDintensity}\ (\text{fully saturated}) \qquad (3)$$

The achieved $i\Delta_2$ – GRID intensity relation is presented in Fig. 8. It is described by a linear function characterized by very high fitting ($r^2 \approx 0.94$). All results form a dense cloud with an obvious rising tendency. Prediction intervals defined for probability of 95% were also presented in Fig. 8.

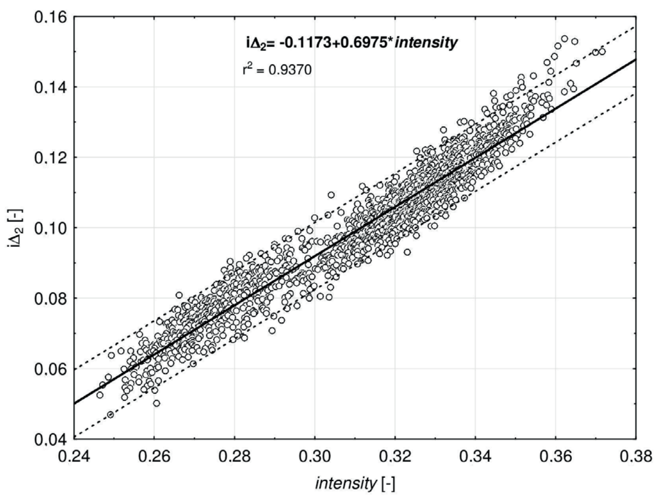

Fig. 8 The value of intensity for a dry specimen versus its $i\Delta_2$

Almost all the results are located inside the defined intervals proving high uniformity and precision of the testing method. Values of differences between dry and fully saturated GRID intensities remain the same independently from initial values of intensity for a dry specimen.

The described study is only an introduction to the topic which needs further research and analysis. The proposed application of TLS is feasible and viable. The method is also characterized by a great potential for future development and multiple qualitative and quantitative applications in civil and structural engineering.

6 Conclusions

The conducted research programme proved that saturation of building materials can be assessed with the help of TLS method. It is possible to follow capillary rising saturation of building materials using TLS but achieved results are influenced by a type of tested material. Significant colour differences and local discoloration can disable the saturation assessment, thus it is crucial to validate it in real outdoor conditions. Quality of achieved results is associated with porosity and maximum saturation of a tested material. A type of used TLS apparatuses and especially its laser beam characteristics influences the assessment of saturation level. The testing method is feasible and viable, but further tests should be conducted using different TLS apparatuses and materials.

References

[1] Bilgin, N., Dincer, T., Copur, H. "The performance prediction of impact hammers from Schmidt hammer rebound values in Istanbul metro tunnel drivages". *Tunnelling and Underground Space Technology*, 17(3), pp. 237–247. 2002. 10.1016/S0886-7798(02)00009-3

[2] Hobbs, B., Kebir, M. T. "Non-destructive testing techniques for the forensic engineering investigation of reinforced concrete buildings". *Forensic Science International*, 167(2–3), pp. 167–172. 2007. 10.1016/j.forsciint.2006.06.065

[3] Katzer, J., Kobaka, J. "Combined Non-Destructive Testing Approach to Waste Fine Aggregate Cement Composites". *Science and Engineering of Composite Materials*, 16(4). 2009.

[4] de Alcantara, N. P., da Silva, F. M., Guimarães, M. T., Pereira, M. D. "Corrosion Assessment of Steel Bars Used in Reinforced Concrete Structures by Means of Eddy Current Testing". *Sensors*, 16(1), pp. 15. 2015. 10.3390/s16010015

[5] Ponikiewski, T., Gołaszewski, J. "X-Ray Investigation And Modelling Of Steel Fibres In Self-Compacting Concrete". *Transactions of the VŠB – Technical University of Ostrava Civil Engineering Series*, 15(2), pp. 1–18. 2016. Retrieved from 10.1515/tvsb-2015-0020

[6] Ponikiewski, T., Katzer, J. "X-ray computed tomography of fibre reinforced self-compacting concrete as a tool of assessing its flexural behaviour". *Materials and Structures*, 49(6), pp. 2131–2140. 2016. 10.1617/s11527-015-0638-y

[7] Janowski, A., Nagrodzka-Godycka, K., Szulwic, J., Ziółkowski, P. "Remote sensing and photogrammetry techniques in diagnostics of concrete structures". *Computers and Concrete*, 18(3), pp. 405–420. 2016. 10.12989/cac.2016.18.3.405

[8] Suchocki, C., Damięcka, M., Jagoda, M. "Determination of the building wall deviations from the vertical plane". 7th International Conference on Environmental Engineering, ICEE 2008 - Conference Proceedings, Vilnius, Lithuania, 1488–1492. 22–23 May. 2008.

[9] Park, H. S., Lee, H. M., Adeli, H., Lee, I. "A New Approach for Health Monitoring of Structures: Terrestrial Laser Scanning". *Computer-Aided Civil and Infrastructure Engineering*, 22(1), pp. 19–30. 2007. 10.1111/j.1467-8667.2006.00466.x

[10] Previtali, M., Barazzetti, L., Brumana, R., Cuca, B., Oreni, D., Roncoroni, F., Scaioni, M. "Automatic façade modelling using point cloud data for energy-efficient retrofitting". *Applied Geomatics*, 6(2), pp. 95–113. 2014. 10.1007/s12518-014-0129-9

[11] Suchocki, C., Katzer, J. "An example of harnessing Terrestrial Laser Scanner for remote sensing of saturation of chosen building materials". *Construction and Building Materials*, 122, pp. 400–405. 2016. 10.1016/j.conbuildmat.2016.06.091

[12] Suchocki, C., Katzer, J., Panuś, A. "Remote Sensing to Estimate Saturation Differences of Chosen Building Materials Using Terrestrial Laser Scanner". *Reports on Geodesy and Geoinformatics*, 103(1), pp. 94–105. 2017. 10.1515/rgg-2017-0008

[13] Jelalian, A.V. *Laser Radar Systems*. (Artech House Radar Library) Artech House,1992.

[14] Pfeifer, N., Dorninger, P., Haring, A., Fan, H. "Investigating terrestrial laser scanning intensity data: Quality and functional relations". 8th Conference on Optical 3-D Measurement Techniques, pp. 328–337. 9–12 July. ETH Zurich, Switzerland, 2007.

[15] Kaasalainen, S., Vain, A., Krooks, A., Kukko, A. "Topographic and Distance Effects in Laser Scanner Intensity Correction". Proceedings of the workshop Laser scanning '09 : ISPRS Vol. 38 prt 3/W8, 1-2 September, Paris, France, 2009. Retrieved from http://www.isprs.org/proceedings/XXXVIII/3-W8/papers/219_laserscanning09.pdf

[16] Pesci, A., Teza, G. "Effects of surface irregularities on intensity data from laser scanning: an experimental approach". *Annals of Geophysics*, 51(5–6), pp. 839–848. 2008. 10.4401/ag-4462

[17] Tan, K., Cheng, X., Ju, Q., Wu, S. "Correction of Mobile TLS Intensity Data for Water Leakage Spots Detection in Metro Tunnels". *IEEE Geoscience and Remote Sensing Letters*, 13(11), pp. 1711–1715. 2016. 10.1109/LGRS.2016.2605158

[18] Kowalczyk, K., Rapinski, J. "Investigating the Error Sources in Reflectorless EDM". *Journal of Surveying Engineering*, 140(4), pp. 6014002. 2014. 10.1061/(ASCE)SU.1943-5428.0000130