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Some aspects of image-processing-based method of measuring lateral deformation of hardening concrete – revised measuring technique

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Abstract

The image-analysis-based measuring methods which process images of captured specimens cannot include the thin layer of the squeezed-out water to the total lateral deformation. This paper presents a revised measuring technique, which allows measurement of the lateral deformation including the contribution of the squeezed-out water. The major differences in the test configuration and image processing are described, and the applicability of results obtained is demonstrated on a real civil engineering problem.
Keywords: hardening concrete, Poisson's ratio, image processing.

Introduction

The multi-dimensional analysis of a concrete structure at the construction stage requires the knowledge of the material characteristics of concrete when it is not yet fully hardened. The minimum number of material characteristics necessary for a simple elastic or elasto-plastic analysis comprises the modulus of elasticity and the instant strengths, which can be obtained from a standard uniaxial compression test, and the Poisson's ratio, which is in the case of hardened concrete obtained by a contact device attached to the surface of a concrete specimen. At the transient stage, when concrete is neither liquid nor solid, the measurement of the lateral deformation is limited to the use of contact-free methods, such as the ultrasound, [1], laser or image-analysis techniques [2].

The work presented in [2] described a method based on analysis of a digital image of concrete specimen, which was an extension of the standard uniaxial test when the lateral deformation of the yet hardening concrete specimen was measured. The method bore a limitation related to the glistening of the squeezed-out water on surface of the specimen, which changed the conditions for the edge detection algorithm. A corrective measure was proposed in [3], which described the problem of the squeezed-out water and quantified its effect on the accuracy of the measuring method.

In this paper, a revised measuring technique is presented where the shadow of a specimen is captured and further processed. This method eliminates the issue related to the glistening of the squeezed-out water on the surface of the specimen. Moreover, it allows incorporation of the thin layer of the squeezed-out water to the total lateral deformation measurement. An example of application of the measured data to a civil engineering problem, namely a problem of the highest possible rate of placement of concrete in construction of a new Prague's subway station, is presented to show the usefulness of the proposed methods for measuring lateral deformation of hardening concrete, which is necessary for derivation of the Poisson's ratio.

Recognition of problems related to free water in hardening concrete

Concrete is a composite material whose main constituents are cement, sand, aggregate and water. Once water gets in the contact with cement, the hydration reaction sets forth. During the hydration the amount of free water, which is about 170 liters in one cubic meter of concrete, reduces as the water becomes chemically bound. At the ages between the initial and the final setting times, which are the ages of about 3 hours and 7 hours, respectively, the amount of free water present in the hardening concrete is still considerable and once a concrete specimen is compressed, the free water is squeezed out onto its surface, where it glistens. It is the glistening effect which reduces the applicability of the measuring method presented in [2]. The concrete specimen was illuminated on both sides so that the bright edges of the specimen contrasted with the dark curtain placed behind the test set. It should be noted that the heat emitted by the spotlights is considerable and therefore during the experiment, when load was monotonically increased, the squeezed-out water evaporated off the surface. That means the conditions for the edge detecting algorithm changed during the experiment which resulted in obtaining inconsistent measurements. The sequence of the change in the surface condition during loading is illustrated in Fig.1.

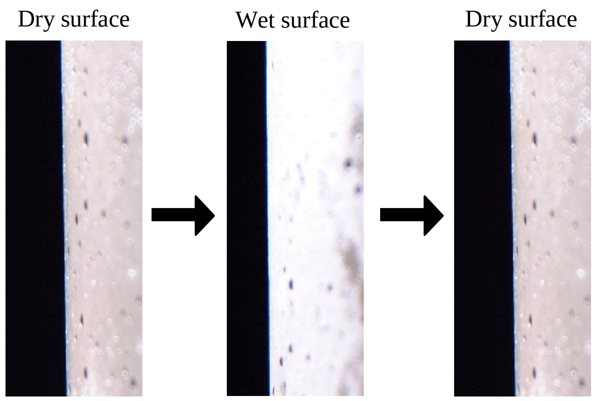

Fig.1. **Change in surface condition during experiment**

As a result, the concrete specimen appeared slimmer than it actually was. A corrective measure was derived in [3], which added the missing number of pixels to the measured value so that the realistic look of the results resumed, that is, the concrete specimen bulged under the uniaxial compressive load.

As was already written, water is one of the main constituents of concrete and so its mass should be included in the deformation measurement, whether it is inside the concrete mass or it is squeezed out on the surface of the specimen. That means the thin layer of the free water squeezed out on the surface of a specimen is a valid part of the total lateral deformation, even though the layer is relatively thin compared to the deformation of the solid part of the specimen. This reasoning leads to the rearrangement of the test configuration.

Rearranged test configuration

The test set was rearranged so that the shadow of the specimen was measured. Three issues are decisive for obtaining a shadow with sharp edges. Firstly, a whiteboard with smooth surface needs to be installed behind the test set. Secondly, a high-quality spotlight with a very narrow beam of light needs to be fixed tightly. Thirdly, the test set needs to located in a dark room. The test set is schematically depicted in Fig.2.

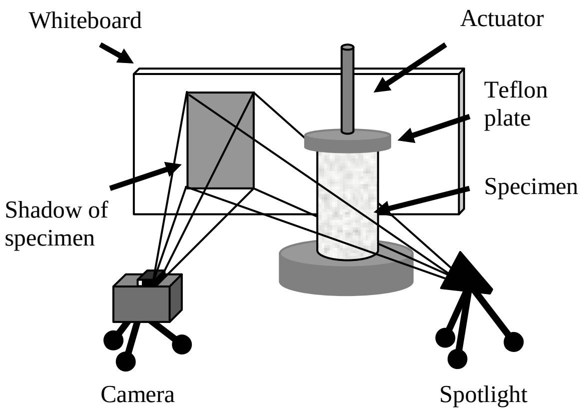

Fig.2. **Test configuration**

The distances between the specimen and the whiteboard and the specimen and the spotlight are about 40 centimeters and their ratio represents the parameter which controls the size of the shadow cast on the whiteboard. The distance between the camera and the whiteboard is another parameter which controls the size of the specimen's shadow in the captured image.

In our case, the camera used was a CMOS camera with the pixel resolution of 3456 x 2304 pixels. The longitudinal deformation, which is the deformation along the axis of uniaxial loading, was measured by standard contact equipment. The loading force induced by the electric actuator was monitored by the actuator itself and checked by a load cell.

Image processing

The image processing tools used were the same as those described in [2, 3]. The processed image, however, was this time inverted, which means the measured object was dark while the background was light. The center of gravity method used for edge detection proved efficient when dealing with the slight blur at the edge of the shadow. An example of a captured image is shown in Fig.3. The width of the specimen can be obtained by the following relation

$$r = d_2 \, . \tan\left(\frac{1}{2}\arctan\left(\frac{AB.\cos 2\alpha}{d_1}\right)\right), \qquad (1)$$

where r is the radius of specimen and the section AB is the measured width of the shadow. All parameters used in Eq.1 are defined in Fig.4. It can be noticed in Eq.1 that the camera's position does not affect the measurement. Therefore, the camera can be placed anywhere in front of the whiteboard at the distance d_1, but attention should be paid to the asymmetrical growth of specimen's shadow during loading so that the shadow does expand out of the captured frame. Also in this case, the Poisson's ratio was obtained from the differences between readings for subsequent loads. Therefore, the readings in pixels did not have to be converted to, e.g. millimeters.

Fig.3. **Captured image of specimen's shadow**

More general information on the image processing methods can be found in, e.g. [4].

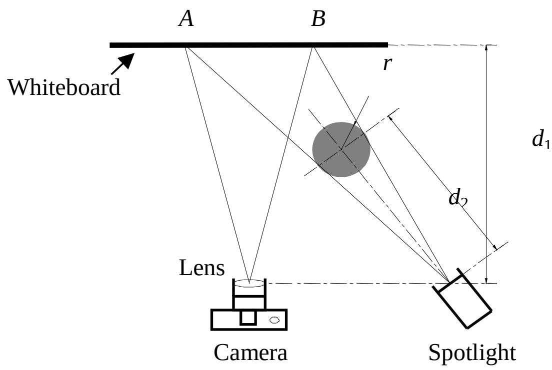

Fig.4. **Test configuration**

Results

The results obtained by the revised method are identical to those presented in [2, 3] for the stress-strength ratio above 20 %. Fig.5. shows the thickness of water layer on a specimen, when a not loaded specimen was captured once dry and once sprayed with water. It should be noted that the thickness of the squeezed-out water cannot be measured by this method separately as it is impossible to distinguish the part of the total lateral deformation, which is contributed by the deformation of the concrete mass, from the contribution of the squeezed-out water.

The discrepancy caused by the glistening of the squeezed-out water has been solved by using this method.

However, the values of the Poisson's ratio for stress-strength ratios below 15 % are affected by initial settling of the specimen, which is a commonly experienced phenomenon. Therefore, the quality of the data for stress-strength ratio below 15 % is always questionable.

The experimentally obtained relation between the apparent Poisson's ratio and the stress-strength ratio can be expressed by the following equation

$$\begin{aligned} \mu(S) &= 0.25 & & S \in \langle 0; 0.3) \\ \mu(S) &= 0.25 + 0.5(S - 0.3) & \quad for \quad & S \in \langle 0.3; 0.8) \\ \mu(S) &= 0.5 & & S \in \langle 0.8; 1), \end{aligned} \qquad (2)$$

where $S = f / f_c$ is the load level, f stands for the actual compressive stress and f_c stands for the instant compressive strength at the moment of loading.

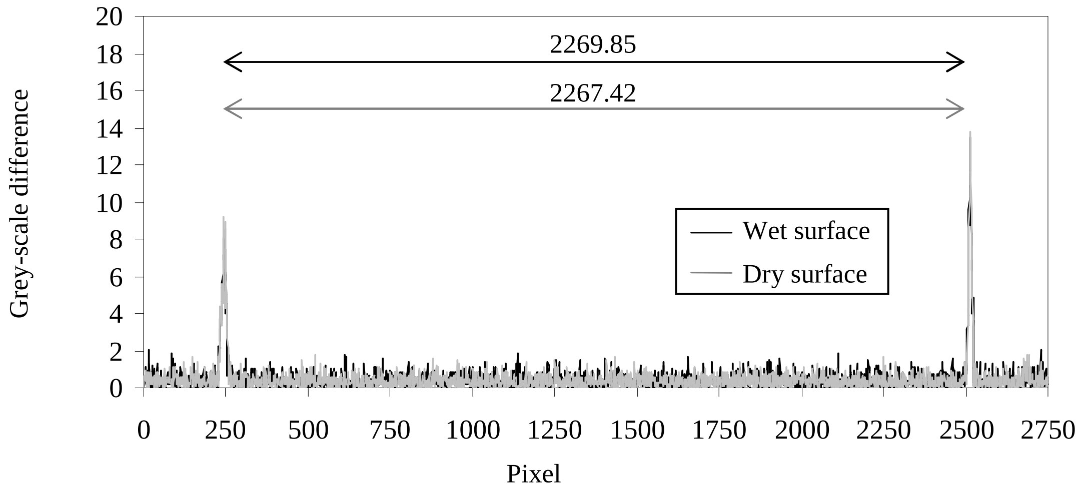

Fig.5. **Lateral deformation of specimen with wet and dry surface**

Application of obtained data

The knowledge of the Poisson's ratio is essential for a multi-dimensional analysis. A function describing the evolution of the Poisson's ratio of concrete during hydration is presented in [5]. However, this function gives only the average values of the Poisson's ratio, while dependence of the Poisson's ratio on the stress-strength ratio is also necessary. Therefore, Eq.2 can serve as an extension of the function presented in [5]. The function in [5] gives the value of the Poisson's ratio as about 0.35 for the ages between 3 and 7 hours, which corresponds to our results obtained for the stress-strength ratio of 50 %. It should be noted that the stress-strength ratio of 50 % limits the elastic region of concrete, where the Poisson's ratio of the already hardened concrete can be considered constant.

In the following, the applicability of the obtained data is demonstrated on a real-life example. A civil engineering problem which required the knowledge of the Poisson's ratio of hardening concrete occurred during construction of tall reinforced concrete walls of the subway station Letnany of the currently constructed IV.C2 line of Prague's subway system. The height of the reinforced concrete walls was 10 meters and since it was desired to construct these walls as fast as possible, the fastest possible rate of pouring of concrete into to formwork was of interest. The capacity of the concrete producing plant and the pumps allowed pouring as fast as one vertical meter per hour. But, the limited stiffness of the formwork and the strength evolution of concrete needed to be taken into account. The horizontal stress distribution was calculated with help of the model presented in [6] and Eq. 2. As a result, the contractor was advised to pour concrete at the rate of 1 vertical meter per hour for 5 hours and then to allow a 2-hour pause, or pour concrete continuously at rate of 0.5 meters per hour. This advice helped to avoid excessive deformation of formwork and excessive compression of the joint filler used.

Conclusions

A revised test configuration was presented in this paper, which was based on measuring a shadow cast by the investigated specimen on a smooth whiteboard. This arrangement allowed including the thin layer of squeezed-out water, which represents a valid part of deformation, in the total lateral deformation. Moreover, this arrangement helped to avoid the glistening effect of the squeezed-out water, when the specimen was captured directly in a digital image. That means the accuracy of the previously presented method was enhanced. The image processing tools, which were presented in the previous works, could be used also for investigation of the captured shadow, as detection of the edge of a shadow represents the inverse problem to the detection of the edge of a specimen. The applicability of the experimental data obtained by the presented methods has been already proved by their application to the investigation of the fastest possible construction of tall reinforced concrete walls of one of the newly constructed Prague's subway stations.

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