Ultrasonic Evaluation of the Pull-Off Adhesion between Added Repair Layer and a Concrete Substrate

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Abstract. This paper concerns the evaluation of the pull-off adhesion between a concrete added repair layer with variable thickness and a concrete substrate, based on parameters assessed using ultrasonic pulse velocity (UPV) method. In construction practice, the experimental determination of pull-off adhesion \( f_b \) between added repair layer and a concrete substrate is necessary to assess the quality of repair. This is usually carried out with the use of pull-off method which results in local damage of the added concrete layer in all the testing areas. Bearing this in mind, it is important to describe the method without these disadvantages. The prediction of the pull-off adhesion of the two-layer concrete elements with variable thickness of each layer might be provided by means of UPV method with two-sided access to the investigated element. For this purpose, two-layered cylindrical specimens were obtained by drilling the borehole from a large size specially prepared concrete element. Those two-layer elements were made out of concrete substrate layer and Polymer Cement Concrete (PCC) mortar as an added repair layer. The values of pull-off adhesion \( f_b \) of the elements were determined before obtaining the samples by using the semi-destructive pull-off method. The ultrasonic wave velocity was determined in samples with variable thickness of each layer and was then compared to theoretical ultrasonic wave velocity predicted for those specimens. The regression curve for the dependence of velocity and pull-off adhesion, determined by the pull-off method, was made. It has been proved that together with an increase of ratio of investigated ultrasonic wave velocity divided by theoretical ultrasonic wave velocity, the pull-off adhesion value \( f_b \) between added repair layer with variable thickness and a substrate layer also increases.

1. Introduction

The quality control of layered concrete elements, new and repaired, is the experimental determination of the interfacial bond between the layers [1-4]. This is very often carried out using the destructive pull-off method, which is not unfortunately without its disadvantages [5-6]. Recently the researchers have been trying to develop a method without these disadvantages and which is simple enough in order to be carried out also in construction practice. However, the problem of measuring the adhesion by using non-destructive testing (NDT) methods is still rare and sometimes demands many methods to be applied [7-10]. In some cases, the NDT methods have been supported by artificial intelligence [11-13]. As it is proved by Szymanowski and Sadowski, there is a possibility to predict the pull-off adhesion between concrete layers [14] and epoxy resin and existing concrete substrate [15] by means of using the ultrasonic pulse velocity method (UPV). The idea might be also used to investigate the quality of repair in concrete structures where it is obligatory to have the adhesion checked and this
adhesion has to be higher than 1.5 MPa [20]. Some of the elements are with only one side access e.g. foundations, but some of them are with two sided access e.g. walls, floors. In order to predict the pull-off adhesion $f_b$, the coefficient of determination for the regression curve $R^2$ between the pull-off adhesion $f_b$ and ultrasonic wave velocity $V$ has been calculated and presented in this article.

2. Materials and Methods

Cylindrical two-layer elements of 50 mm in diameter were the object of the test. Those elements were obtained by drilling the borehole from a large size specially treated large-scale concrete element. Those two-layer elements were made out of concrete substrate layer and Polymer Cement Concrete (PCC) mortar as an added repair layer. The substrate layer with variable thickness $h_1$ ranging from 180 mm to 210 mm was made of concrete of class C30/37 and the maximum grain size of crushed basalt aggregate was equal to 8 mm. Before applying an added repair layer, the surface of substrate was specially prepared using shot-blasting, grinding and a part of substrate was left raw after concreting [16]. The added repair layer with variable thickness $h_2$ ranging from 30 to 60 was made of PCC mortar whose average compressive strength was measured to be $54.02 \pm 3.79$ MPa and the maximum grain size was equal to 4 mm. The scheme and the view of the element and the specimens is presented in figure 1.

![Figure 1](image-url)

Figure 1. The scheme and the view of the element (a,c) and exemplary specimen $S_i$ (b,d)

In order to obtain the experimental values of pull-off adhesion $f_b$, the tests using pull-off method were performed on the whole element and as a result the map of pull-off adhesion values is presented on figure 2. The value of pull-off adhesion for each of the test was in accordance with [7]:

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[Image: image-url]
where:
$F_b$ – failure load [kN],
$D_f$ – the average sample diameter [m].

![Diagram of pull-off adhesion](image)

Figure 2. The pull-off adhesion: scheme of method (a), during the evaluation (b), the results of the evaluation (c)

The test was carried out using pull-off tester DY-2016 by Proceq. Apart from above-mentioned, slide caliper, spatula and two-microsecond measures for calibration, ultrasonic heads and industrial safety paste (ultrasonic couple agent) were used during the test. The UPV method with two-sided access was used in the test. The method belongs to the group of acoustic NDT methods and it uses the ultrasonic wave propagation effect in the tested medium. The view of the stand and its scheme are presented in figure 3.
According to [8], the length of ultrasonic wave in the medium should not be bigger than the minimum transverse dimension of the element being tested. The proper frequency of ultrasonic heads was designed according to [9] and is dependent on equation 2.

$$\lambda = \frac{c}{f}$$  \hspace{1cm} (2)

where:
- $\lambda$ – ultrasonic wave length [m],
- $c$ – ultrasonic wave velocity [m/s],
- $f$ - ultrasonic wave frequency [Hz].

The value of ultrasonic wave velocity $c$ was selected on the basis of [9]. The ultrasonic heads of 100 kHz frequency were selected according to [9] and the ultrasonic wave velocity in the tested specimens was calculated according to [9] on the basis of equation 3.

$$V = \frac{h}{T}$$  \hspace{1cm} (3)

where:
- $V$ – ultrasonic wave velocity in element [m/s],
- $h$ – height of the element [m] in this case $h = h_1 + h_2$ of each sample,
- $T$ - time of ultrasonic wave transit [s].

3. Test results and their analysis

The test results for each two-layer sample, such as: $h_1$, $h_2$ – the heights of each part of the specimen, $T$ – the time of ultrasonic wave transit, $V$ – the ultrasonic wave velocity, $V_t$ – the theoretical value of the ultrasonic wave velocity of the sample, $V/V_t$ – the ratio of difference between the ultrasonic wave value obtained experimentally and theoretically, are presented in table 1. The theoretical value of ultrasonic wave velocity of the whole element was obtained using experimental values of the ultrasonic wave velocity for both materials which were $V_1 = 4.400$ km/s for concrete and $V_2 = 4.710$ km/s for mortar.
Table 1. The results obtained using the UPV method.

| Sample | $h_1$ [mm] | $h_2$ [mm] | $H$ [mm] | $T$ [μs] | $V$ [km/s] | $f_b$ [MPa] | $V_t$ [km/s] | $V/V_t$, [-] |
|--------|------------|------------|----------|-----------|------------|-------------|-------------|-------------|
| S1     | 41.7       | 35.2       | 76.9     | 18.9      | 4.076      | 1.00        | 4.563       | 0.89        |
| S2     | 41.3       | 201.0      | 242.3    | 56.2      | 4.312      | 1.25        | 4.450       | 0.96        |
| S3     | 45.0       | 201.5      | 246.5    | 54.9      | 4.449      | 3.00        | 4.454       | 0.99        |
| S4     | 49.5       | 67.8       | 117.3    | 27.1      | 4.335      | 1.50        | 4.526       | 0.96        |

Based on the analysis of the data presented in table 1, it can be observed that the values of ultrasonic wave velocity obtained during the tests are comparable for samples S2 and S4 and are higher than the value obtained for sample S3. However, those values of ultrasonic wave velocity of samples S1, S2, S4 are respectively 4.076 km/s, 4.312 km/s, and 4.335 km/s and are less than the ultrasonic wave velocity of concrete used as substrate itself. Only sample S3 is represented by the value of ultrasonic wave velocity higher than 4.400 km/s. The reason of lower values of height of specimens S1 and S4 in comparison with height of specimens S2 and S3, is breakage of the concrete part of the sample during drilling.

Figure 4 shows the relationship between the pull-off adhesion $f_b$ and ultrasonic wave velocity $V$. Regression curves were plotted and next to it equation and coefficient of determination $R^2$ is given.

![Figure 4](image)

Figure 4. Relationship between pull-off adhesion $f_b$ and ultrasonic wave velocity $V$.

After analysis of the regression curve, it can be stated that together with an increase of ultrasonic wave velocity $V$ in two-layer repaired elements, the value of pull-off $f_b$ adhesion increases. As seen from figure 4, the coefficient of determination for the regression curve $R^2$ is equal to 0.72 and according to [10] is relatively high.

4. Conclusion and perspectives
This paper presents an attempt of prediction the value of pull-off adhesion $f_b$ by means of ultrasonic wave velocity method. In order to plot the curve of regression between the pull-off adhesion $f_b$ and
ultrasonic wave velocity $V$, two-layer specimens were obtained by drilling the borehole from a larger size element. It has been proved that together with an increase of ultrasonic wave velocity, the pull-off adhesion value $f_b$ between added repair layer with variable thickness and a substrate layer also increases. However, despite the fact that the coefficient of determination for the regression curve $R^2$ is relatively high, further research is underway. It is proper to note, that in order to obtain the higher value of the $R^2$ more samples need to be evaluated.

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