BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 63, No. 1, 2015
DOI: 10.1515/bpasts-2015-0009

Application of stress based NDT methods for concrete repair bond quality control

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Abstract. Adhesion in repair systems is one of the most important factors affecting their durability. Elaboration of a reliable nondestructive test method to perform an adhesion mapping is one of the most important tasks. A majority of NDT methods applicable for the assessment of concrete structures are based on the propagation of various types of stress waves. In this paper, the influence of the repair material type (polymer-cement or polymer) and quality of the concrete substrate (roughness, microcracking, not cleaned surface) upon propagation of stress waves in a repair system was studied in view of developing a reliable NDT procedure for the field assessment of bond quality in concrete repairs.

Key words: concrete structure, repair durability, repair quality control, NDT techniques, substrate and interface quality.

1. Introduction

As a result of repair or protection of the building structure a composite system (concrete substrate in contact with repair material) is produced [1]. Adhesion in this system is one of the most important factors that affects the reliability and durability of repair [2–5]. According to the many standards and guidelines, e.g. new European Standard EN 1504 "Products and systems for the protection and repair of concrete structures" and ACI Concrete Repair Manual [5], a pull-off test is recommended for assessment of a bond quality in repair systems. The use of the pull-off test, due to its semi-destructive character, is restricted by owners and managers. Therefore, elaboration of the reliable nondestructive method for an adhesion mapping could provide a quite advantageous alternative. Recently, a growing interest has been noted in the application of nondestructive techniques (NDT) for evaluation of concrete structures [6–8]. A majority of NDT methods mentioned in EN 1504-10 and ACI Concrete Repair Manual for assessment of concrete structures are based on propagation of stress waves. In particular, ultrasonic methods (UPV), impact echo (IE) and impulse-response (IR) methods are recommended for evaluation of repair quality. However, these investigations are rarely focused on evaluation of the bond strength (eg. [9–12]).

The repair system is difficult to test with NDT methods, because of the many factors influencing the stress wave propagation. Taking into account the classification proposed by Adams and Drinkwater [13], two main types of defects can occur in this system that can affect stress wave propagation (Fig. 1):

- adhesion type (at the interface zone: overlay - substrate): various types of "non-zerovolume" disbonds (e.g., voids, delaminations) and "zero-volume" disbonds – weak adhesion areas(e.g. due to a presence of dust, oil, etc.);
- cohesion type (in repair material or/and concrete substrate): porosity, cracks, honeycombing, partially non-hardened resin in the case of polymer material.

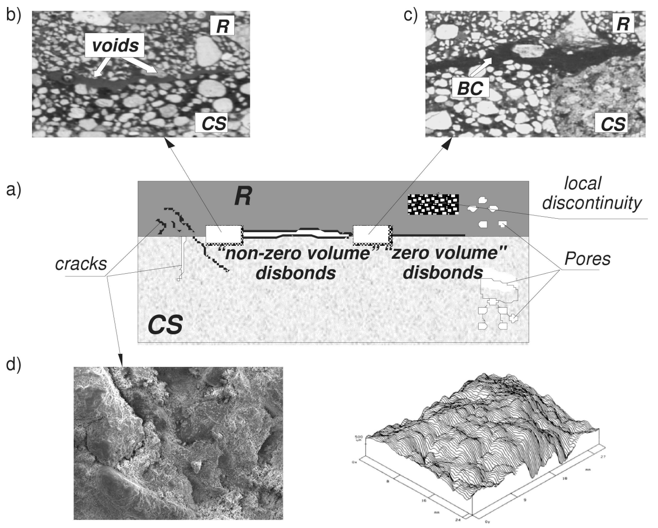

Fig. 1. Possible defects in the system: repair material (R) – concrete substrate (CS): a) Scheme and examples of different quality of interface, b) voids at interface, c) quality improvement by using bond coat (BC), d) concrete substrate after treatment prior repair (adopted from Ref. 14)

To select the appropriate NDT method for repair quality control, the following factors should be taken into account [13–15]:

- type and size of defects at the interface zone to be investigated;
- thickness of overlay;

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- type of repair material (cement based or polymer composites);
- quality of concrete substrate (roughness, microcracking, saturation level).

The first two factors depend mainly on the NDT method used. For example, the depth and size of detectable defect depends on a diameter of selected ball (impactor) in the case of impact-echo. In this paper the effect of repair material type and quality of concrete substrate on propagation of stress waves in repair system and their influence on the possibility of estimating the bond strength.

2. Effect of repair material

In the case of multilayer systems, the propagation of stress waves depends on the differences in acoustic impedance between a repair material and concrete substrate [15]. For two dissimilar materials, part of the energy of the vibration, A_i, is refracted into the new one, A_{tr}, while the other part is reflected back, A_r. The wave reflection is characterized by the reflection coefficient, R:

$$R = \frac{A_r}{A_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \tag{1}$$

where Z_1, Z_2 – acoustic impedances of material 1 and 2 in [kg/m^{2}s]; $Z = c_p \cdot d_v$, c_p – P wave velocity, m/s, d_v – volume density, kg/m^3.

The reflection coefficient for concrete/air interface is equals nearly to 1.0, which means there is almost total reflection at the interface. This is why NDT methods based on the stress wave propagation are useful for detection of "non-zero" volume defects containing air like voids, delaminations, etc.

Among various repair systems, polymer-cement composites (PCC) and polymer composites (PC) are commonly used [16]. Modified cement binder or its replacement with polymers improves technical properties of repair materials. To develop a procedure for non-destructive evaluation of these kinds of materials, it is necessary to determine how the presence of polymer influences a stress wave propagation and whether the assessment of a system: PCC (or PC) – concrete substrate might be performed using well-known NDT procedures for cement concrete.

Garbacz and Kwaśniewski [17] carried out comprehensive numerical time-domain studies by using Finite Element (FE) explicit code LS-Dyna, dedicated for transient dynamic problems. The FE model represents a segment of the cylinder with radius 260 mm, cut off about the vertical axis positioned along the impact direction (Fig. 2a). In the models two nodes are identified: node 1 – where the load was applied and node 7 – located 26.5 mm along x-axis corresponding to the vertical displacement detected by receiver. The developed model refers to an infinite plate with total thickness of 200 mm. The simulations were performed for three types of repair materials with different E modulus and constant density (Fig. 2b). Three different values of the R coefficient were determined from analysis. The clear frequency peak corresponding to reflection fromthe interface was observed only for R = +0.35.Similar results were obtained by Sansalone and Li [18, 19]. The FEM simulations and experimental investigations with IE method have shown that usually an interface is "visible", even in the case of high adhesion, if the absolute value of the R coefficient is higher than 0.24.

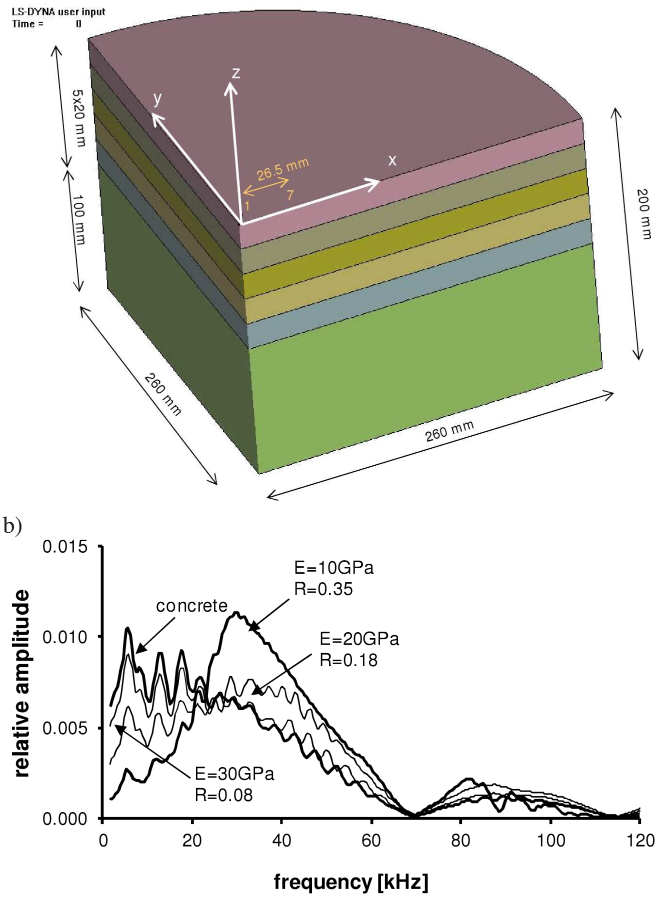


Fig. 2. a) FEM model of repair system and b) frequency spectra for repair materials with different reflection coefficient R (details in the text); adopted from Ref. 17

The effect of polymer content in PCC composites on a stress wave propagation in a repair system was analyzed by Garbacz [20]. The values of acoustic impedance for PCC were estimated, taking into account the measured volume densities and the pulse velocities. Addition of polymer increases the acoustic impedance about 5–15% in comparison to that for composites without polymer (Fig. 3a). These values are closed to the typical range [21] for cement concretes and mortars (dotted line in Fig. 3). The value of the reflection coefficient for this kind of interface can be estimated to be less than +0.15.

The similar analysis was performed for polymer mortars and concretes representing polymer repair materials (w/o Portland cement) taking into account acoustic impedance values that were calculated using pulse velocity and density data measured by Garbacz and Garboczi [22] for polymer mortars and concretes prepared using different polymer binder types (epoxy and vinylester), a fixed binder content (binder to aggregate ratio B/A: from 7 to 14 by mass), and various proportions coarse aggregate, sand and microfiller. In general, the values of acoustic impedances are higher than those of PCC composite, also close to typical range for cement concretes and mortars (Fig. 3b). The absolute value of reflection coefficient for the interface PC – concrete can be estimated to be less than +0.18.

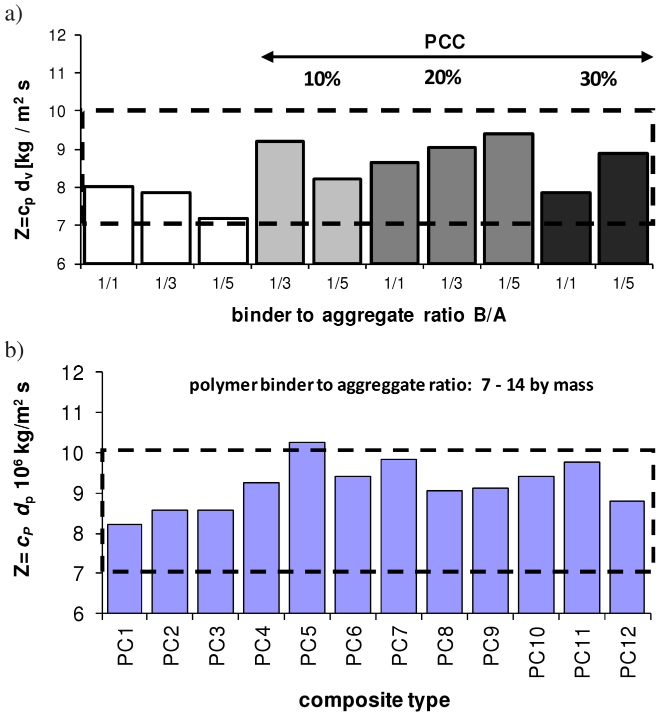


Fig. 3. Effect of polymer content on acoustic impedance of tested: a) polymer-cement and b) polymer (w/o Portland cement)mortars and concretes with different polymer content

The low values of reflection coefficient for both types of repair materials indicate that almost whole fraction of the stress wave energy will be transmitted through the interface PCC (or PC) composites – concrete substrate. The detection of flaws at the interface overlay – concrete substrate can be performed with procedures developed for “solid” concrete structures.

3. The effect of interface quality

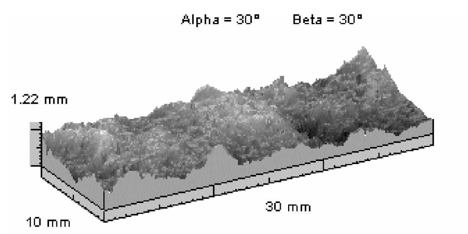
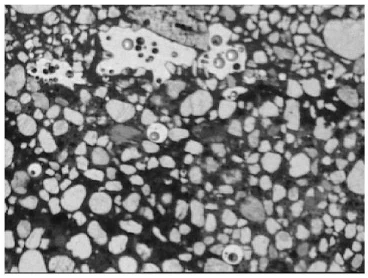
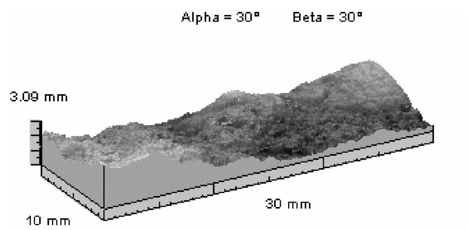
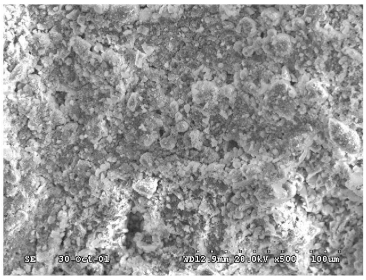
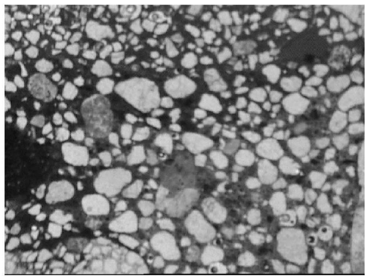
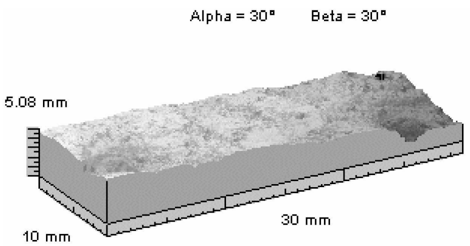
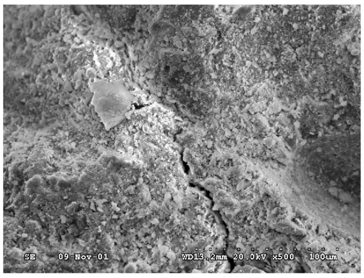
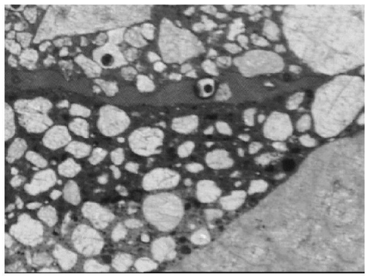
It has been widely demonstrated that a surface treatment of concrete substrate prior repair can influence significantly on the microcracking level and surface roughness, the substrate saturation level and, as a consequence, it may affect the bond strength between repair material and concrete substrate [2–27]. The positive effect of surface roughness was confirmed, e.g. by Courard et al., [27]. They have shown, using multiple regression approach, that roughness is a statistically significant variable influencing bond strength. Sadowski and Hoła [28] showed that substrate roughness is an important factor for the prediction of bond strength between the concrete layers in concrete floors using the nondestructive acoustic techniques together with artificial neural networks. However, results of other authors, e.g. [29, 30] have indicated that surface roughness is less important than microcracking in the near-to-surface layer. Moreover, presence of voids at the interface can decrease adhesion [30, 31].

Using stress waves based methods for evaluation of bond strength needs to find answers whether the interface quality affects the stress wave propagation and if is it possible to extract from the signal any information related to the bond strength. In the framework of several project conducted at Warsaw University of Technology in cooperation with the University of Liege various repair systems (Table 1), differing in concrete surface and interface quality, were tested. In the first stage, a commercial polymer-cement repair mortar containing glass microfibers was applied on relatively weak concrete substrate (C20/25) subjected, prior to repair, to surface treatments with different aggressiveness levels. According to the manufacturer's sheet, this mortar should be used with a polymer-cement bond coating because of its low workability (the details are given in [30]). The overlay (thickness 10 mm) was applied on the concrete substrate with and without a bond coat to obtain different air void contents and levels of compactions at the interface.

After 28 days of hardening, the IE and ultrasonic measurements were carried out. Afterwards, the adhesion between the repair material and the concrete substrate was determined with the pull-off test (acc. EN 1542]). Surface roughness was characterized by arithmetic mean of the deviation of the waviness profile (high frequency filtration of profile) from the mean line profile determined with a mechanical profilometer [30]. Additionally, the quality of interface was observed on the cross-sections with light microscope.

As the surface roughness increased, the pull-off strength for the systems without bond coat decreased and air voids at the interface zone were observed: an increasing of the roughness induces a high fraction of voids. The test results (Table 1) indicate that there is no correlation between the roughness of concrete surface (beneath repair mortar) and the P wave velocity (Fig. 4a) for the repair system with bond coat and without air voids. The statistically significant relationship was obtained for systems with air voids at the interface. For these systems, the P wave velocity increased as the roughness increased simultaneously, while for the system with the bond coat, such a relationship was not observed (Fig. 4b). In the latter case, the bond coat filled properly irregularities of concrete substrate. The results obtained indicates that for the IE method, the roughness of the concrete substrate does not affect significantly the P wave propagation through the repair system if the bond quality is sufficient (absence of large voids at the interface).

Table 1
Example of surface geometry, microcracking level and quality of interface of concrete substrate subjected to various surface treatment differ in their aggressiveness

Surface waviness profiles obtained by laser profilometry	Example of surface view SEM: magn. 500×	Example of interface without bond coat: magn. 63×
		
		
		

The same repair systems were tested further with ultrasonic pulse echo method using commercial digital ultrasonic flaw detector ULTRA CUD20 and a pair of transducers with nominal frequency of 500 kHz. This method is expected to be more sensitive to the presence of voids at interface because of shorter waves are generated. Each received A-scan consisted of characteristic peaks corresponding to the reflection from the interface. The following trend was found in studying the relationship between the amplitude of maximum frequency peak and the pull-off strength (Fig. 4c): as the pull-off strength increases, the amplitude value of peak decreases. Statistical significance of the relationship between the amplitude value of the highest peak and the mean waviness of surface profile (Fig. 4d) was found for this kind of repair systems without the bond coat, essentially because the fraction of air voids increased with the surface roughness.

The above relationship was investigated for stronger concrete (C40/50) [32]. Four types of surface preparation techniques were used: sandblasting, scabbling, water jetting (250 MPa of pomp pressure during 5 min) and polishing. The concrete slabs have been covered by a self-compacting commercial PCC mortars (3-cm thick). For the repair systems, two specific ranges of the frequency spectrums were analyzed: around the bottom peak frequency and around frequencies corresponding to the interface. The lowest mean values of bottom peak, A_{bmax}, were obtained for polishing and hydrodemolition. In the first case, it was probably due to delamination at the interface and parallel orientation of cracks to the interface surface. There could be different explanation for hydrodemolished samples. In the latter case, very rough surface (the biggest SRI) is not filled with the repair mortar, leaving air voids at the interface. The amplitude of interface peak, A_{imax}, was the highest for polished samples. Scabbled and hydrodemolished samples present similar values of interface peak. The relationships between amplitudes of either bottom or interface peaks and parameters describing quality of repair systems were not statistically significant for any of the tested repair systems (Fig. 4e,f).

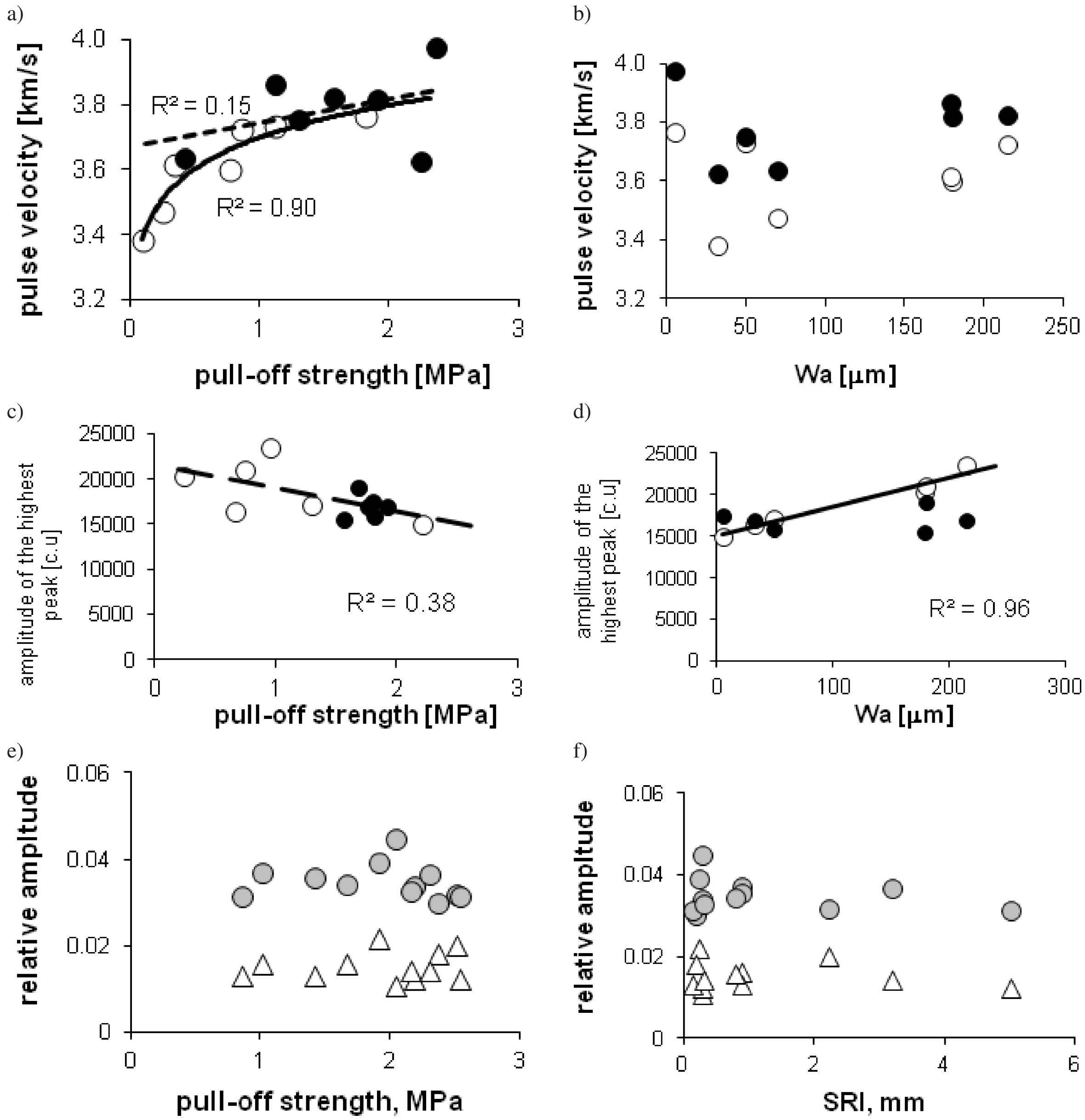


Fig. 4. Relationships between parameters describing stress wave propagation and parameters describing repair system quality: a) pulse velocity vs. pull-off strength, b) mean waviness of profile, Wa, vs. pulse velocity, c) amplitude of the highest peak of frequency spectrum of ultrasonic signal (c.u. – conventional unit) vs. pull-off strength, d) amplitude of the highest peak of frequency spectrum of ultrasonic signal vs. mean waviness of profile, Wa; (concrete substrate C20/25, overlays with (•) and without (o) the bond coat; adopted from Ref. 20. Amplitude of bottom (•) and interface (∆) frequency peaks versus: e) pull-off strength, f) surface roughness index, SRI (adopted from Ref. 32)

To investigate the effect of air voids at interface on stress wave propagation, the FEM model of repair system, presented in Sec. 3, was modified [33]. The meshes are built of regular hexagonal eight-node elements with typical xyz dimensions of 1×4×2 mm. The height of the elements in the interface was reduced to 1 mm to model substrate roughness and voids. Similarly to the first FE model, symmetry boundary conditions were defined on the vertical cross-sectional planes, where normal displacements were constrained. Two variants of the roughness patterns with air voids empty and filled by repair material were implemented in the FE models (Fig. 5a) with grooves oriented along the longer y direction.

The results of simulations indicate that the presence of larger air voids at the interface can significantly influence the stress wave propagation. This was observed in the both of experimental (Fig. 5b) and FEM (Fig. 5c) frequency spectra. If surface profile irregularities are filled, the surface roughness does not significantly influence the resulting frequency spectrum (Fig. 5d).

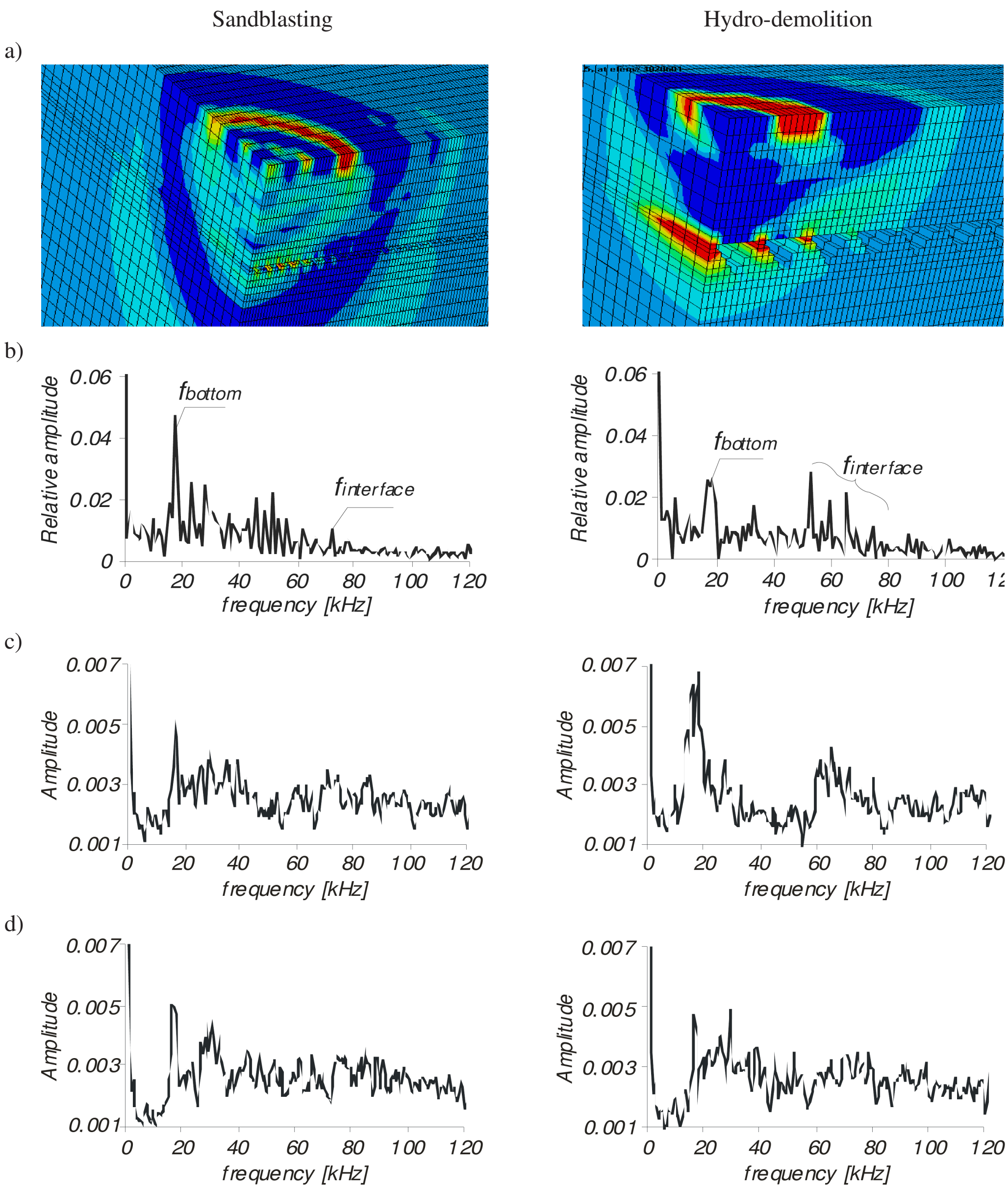


Fig. 5. Typical frequency spectra for repair systems with different roughness of concrete substrate obtained by using different treatments: sandblasting (left), hydrodemolition (right): a) examples of disturbance in wave propagation in the case of air voids presence at interface, b) experimental results for plate: 600×800×130 mm, c) FEM simulations for model concrete substrate irregularities unfilled – presence of air voids at the interface, d) FEM simulations for model with concrete substrate irregularities completely filled (adopted from Ref. 14)

Similar results were obtained by Santos et al. [34]. Their FEM simulations indicated also that the roughness of a concrete substrate had relatively low influence on the resulting signal amplitude. However, they observed that the pulse decreases in the presence of rough interfaces, due to a greater wave dispersion.

4. Effect of zero-volume discontinuities

The results presented in the previous section confirmed that the "non-zero volume" defects are relatively easy to detect if they are large enough. It is more complex to detect "zero-volume" defects, e.g dust or any other material on concrete substrate, which can decrease bond strength between repair material and concrete as well.

In order to carry out the research program, three concrete substrate slabs (600×800×80 mm) have been prepared with C20/25 concrete. Right after casting, samples have been covered with plastic sheet for twenty-four hours. Afterwards, samples have been demoulded and stored for the next twenty-eight days in standardised curing conditions (20°C, 90% relative humidity) in a humidity chamber. After 28 days of curing in standardised conditions, the surface of each slab has been treated by wet sandblasting method. This process resulted in low and regular roughness of surface. Two types of separating materials have been applied at the interface of the concrete slabs to simulate the air zero-volume defects: an area was impregnated with demoulding oil (approx. area: 55×35 cm), while another was cover with a plastic sheet (40×20 cm). One slab was left without any defect to serve as the reference. After the interfacial defects were applied, the repair material was placed. A commercial polymer-cement mortar has been used. For each type of interfacial defect, two series of test specimens were prepared with different repair thicknesses, 5 and 8 cm (Fig. 6).

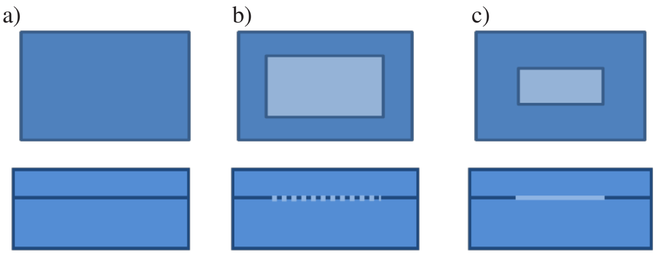


Fig. 6. Different types of defects at interface: a) no defect – reference slab, b) demoulding oil (55×35cm), c) rectangular plastic sheet (40×20 cm); in each case: concrete slab dimensions of 60×80×8 cm and repair material thicknesses of 5 or 8 cm

For the assessment of the defect detection efficiency,maps of interface peak amplitude were generated with use of Matlab environment. Usually, if the defect has sufficient influence on the bond strength, a frequency peak at interface zone should occur in the frequency spectrum. Thus, the peak amplitude maps should reveal areas, where the bond strength is weaker. Figure 7 presents the amplitude distributions of the bottom and interface peaks for tested repair systems. The peak amplitude maps for the specimens with oiled area are close to those of the reference. This indicates that this kind of imperfection of substrate preparation is difficult to detect with the IE method. In the case of the repair system with a plastic sheet inserted at the interface both types of peaks had low amplitudes and the low frequency peaks, characteristic of shallow delamination, were recorded.

The additional investigation with ground penetrating radar (GPR) using antenna 1.6 and 2.3 G did not exhibit ability to detect these kind of defects. Similar results [35] were obtained in investigations of monolithic slabs containing either a smooth or an air-bubble PVC foils (Fig. 8). The GPR was able to detect only the air-bubble foil. In contrast, both foils were detected by the IE method and most of the IE signals (90%) revealed the presence of shallow delamination.

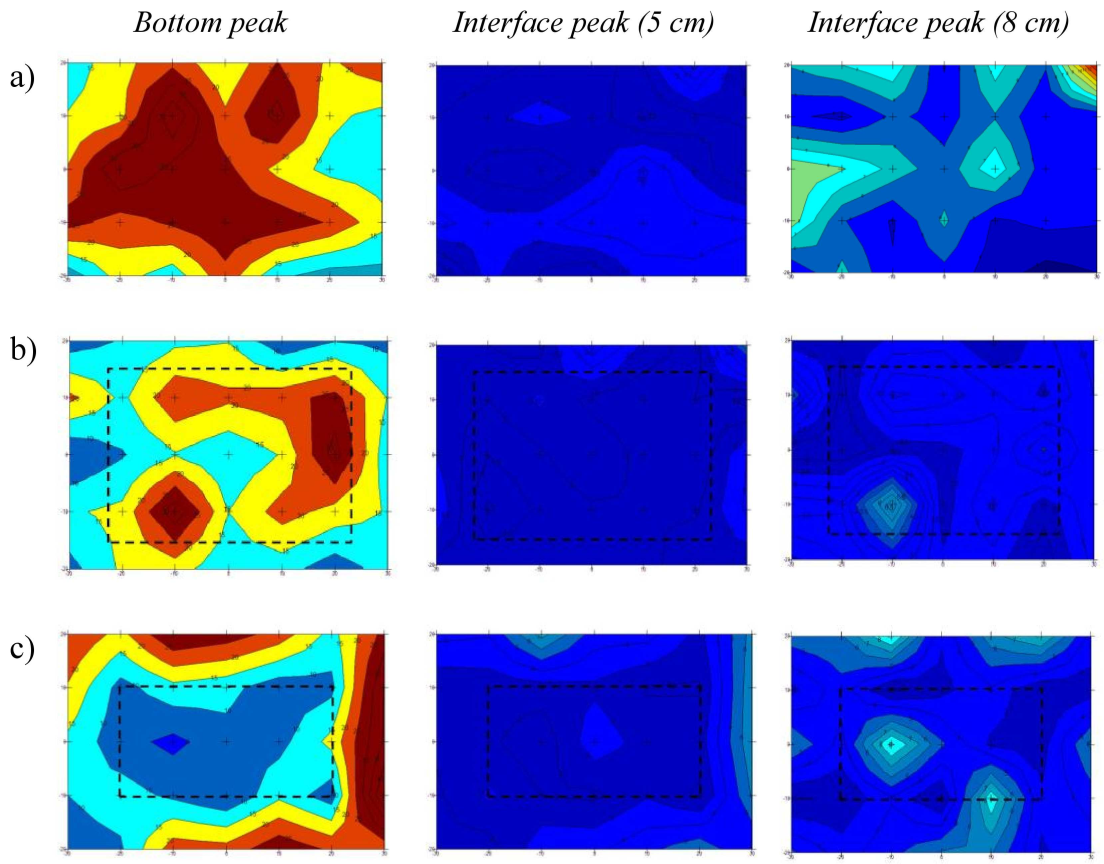


Fig. 7. Distributions of amplitude of the bottom and interface peaks (layer thickness 5 and 8 cm respectively): a) reference slab, b) substrate impregnated with demoulding oil (approx. area: 55×35 cm), c) plastic sheet at the interface (area: 40×20 cm)

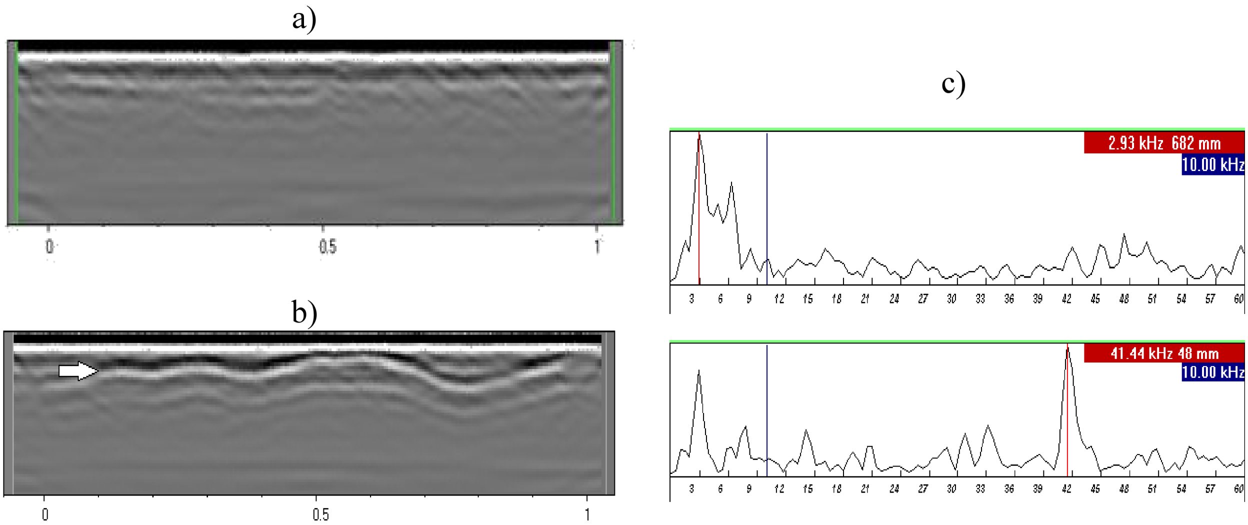


Fig. 8. GPR B-scan images (cross-section view) for monolithic slabs containing artificial defects: a) with smooth foil and b) air-bubble foil; c) typical IE frequency spectra for shallow delamination (top) and with interface peak (bottom) recorded for these slabs

5. Conclusions

On the basis of results obtained in complementary test programsthe following main conclusions can be formulated:

- the reflection coefficients, R, for the interface PCC-concrete and PC are relatively low (below 0.15 and 0.18 respectively). It justifies assumption that most the stress wave energy is transmitted throughan interface of good quality. Hence, for quality control of repair with PCC and PC composites,the procedure developed for the assessment of concrete structure can be adapted for the evaluation of interface quality;
- the roughness of concrete substrate does not affect significantly the P wave propagation through the repair system if the bond quality is sufficient, i.e. where no large voids are presented at the interface;
- the relationships between pull-off strength and values of bottom and interface peak amplitudes are not statistically significant – an amplitude of frequency peaks is not proper measure of a bond quality in repair systems;
- the results of investigation confirmed that stress wave based methods, especially impact-echo, exhibit great potential for nondestructive control of repair quality. However, the "zero-volume" disbonds, e.g. areas of discontinuity without significant voids such as those resulting from unclean substrate are difficult to detect with stress wavebased methods.

Acknowledgements. The author is thankful to professor L. Czarnecki, the scientific secretary of a Building Research Institute (ITB) for his valuable discussion and remarks.

This paper was elaborated within the framework of the research project which was granted by the National Centre for Research and Development – the grant number N R04 0024 10 (2010–2013). In the paper, the results of research projects carried out within the framework of the scientific cooperation programs between foreign agencies of Wallonia-Brussels International (Belgium) and (MNiSW) Poland were partially used.

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