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STRESS WAVE PROPAGATION THROUGHOUT AN INTERFACE: PCC COMPOSITES – CONCRETE SUBSTRATE IN REPAIR SYSTEM

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Abstract
Polymer-cement composites (PCC) are commonly considered as new and innovative building materials, especially useful for repair and surface protection of concrete structures. According to new European standard EN1504 and other technical guidelines, non-destructive methods, mainly based on a propagation of stress waves, are recommended for quality control of repair efficiency. The aim of this paper is the analysis of effect of PCC microstructure and quality of interface on a stress wave propagation in a repair system: PCC – concrete substrate tested with impact-echo and ultrasonic methods.

Streszczenie
Kompozyty polimerowo-cementowe (PCC) są uważane za nowe i innowacyjne materiały budowlane, szczególnie przydatne do napraw i ochrony powierzchniowej konstrukcji betonowych. Norma EN-1504, a także inne dokumenty techniczne zalecają stosowanie metod nieniszczących, w szczególności wykorzystujących fale sprężyste, do kontroli skuteczności napraw. Celem pracy jest analiza wpływu na propagację fali sprężystej mikrostruktury PCC oraz jakości zespolenia w układzie naprawczym: PCC – podłoże betonowe badanym metodami impact-echo i ultradźwiękowymi.

Keywords: **Concrete repair, Bond quality; Non-destructive evaluation; Polymer-cement composites; Stress wave propagation.**

1. INTRODUCTION

Recently, concrete structures deterioration has become one of the most important technical, economic and social problems in many countries. This implies necessity for their repair and strengthening [1] to ensure required ultimate and serviceability limit states. The determination of deterioration causes is necessary to ensure efficient and durable repair [2]. To correctly assess deterioration causes and, as consequences, building structure conditions the optimal in-situ testing methods should be applied [3].

The new EN 1504-10 standard "Products and systems for the protection and repair of concrete structures. Definitions. Requirements. Quality control and evaluation of conformity. Site application of products and systems and quality control of the works" gives some guidelines for structure evaluation at every stage of repair process: evaluation of substrate quality, control of conditions during material application and quality control of repair efficiency [4]. According to this standard a bond strength and quality of bond are main features of the repair system necessary to be assessed. The pull-off test is commonly used to evaluate both the bond strength and quality of interface. However, it is semidestructive and usually restricted to a few local points. That is why a growing interest in development of non-destructive techniques (NDT) for evaluation of repaired concrete structures is recently noted [5,6].

Majority of NDT methods for structures assessment, mentioned in EN 1504-10 (but also in other technical documents, e.g. Concrete Repair Manual [7]), are based on propagation of stress waves. Particularly, ultrasonic methods and impact echo (I-E) method are recommended (Fig. 1). Impact-echo method is very often used for quality control of various types of repair and concrete protection, eg. injection of cable ducts, interface quality in the case of overlays, patches, industrial floor, etc. [5-10].

As a result of repair, a system containing two or more layers is created. Two main groups of defects (Fig. 2) can occur in this system: adhesion type (non-zero volume disbands, weak adhesion areas, etc.) and cohesion type (porosity, cracks, honeycombing, partially non hardened resin in case of polymer composites). During selection of stress wave based method the following factors should be taken into account [11, 12]: type, size and location of defect, thickness of overlay, roughness of concrete substrate and type of repair material (potential effect of difference in acoustic properties). In case of multilayer system the propagation of stress waves depends on differences in acoustic impedances of both materials [12]. For two dissimilar materials, part of the energy of the vibration is refracted into the new one, Atr, while the other part is reflected back, A_r. The wave reflection is characterized by a reflection coefficient, R (Tab. 1):

$$R = \frac{A_r}{A_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (1)$$

where: Z_1, Z_2 – acoustic impedances of material 1 and 2; Z [kg/m^{2}s] = c_p [m/s] • d_v [kg/m^3]

Experimental investigations with I-E method [13], as well as FEM simulations [14], for concrete structures surrounded by soil and rocks have shown that an interface is "visible" if absolute value of R coefficient is higher than 0.24. FEM simulation by Garbacz and Kwaśniewski showed that the same relationship should exist in case of repair systems [15].

Polymer-cement composites (PCC) are commonly considered as new and innovative building materials [16], especially useful for repair and anticorrosion protection of concrete structures. To develop procedure for nondestructive evaluation of PCC it is necessary to determine how presence of polymer phase in microstructure influences both technical properties and stress wave propagation and whether assessment of system: PCC-concrete could be performed following well-known NDT procedures for cement concrete.

The aim of this paper is the analysis of effect of PCC microstructure and quality of interface on a stress wave propagation in a repair system: PCC – concrete substrate.

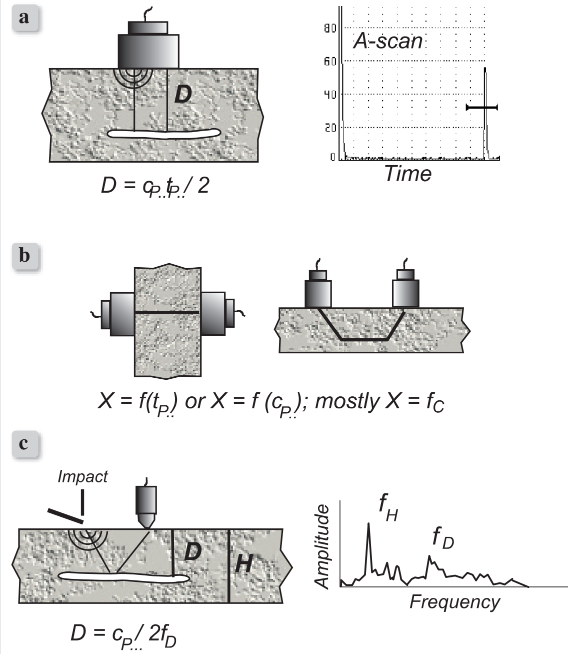

Figure 1.
Schematic representation of stress wave based NDT methods; t_p – travel time, c_p – P wave velocity, FD – frequency peak corresponded to reflection from voids
a) Ultrasonic Pulse Echo, UP-E,
b) Ultrasonic Pulse Velocity, UP-V
c) Impact-Echo, I-E

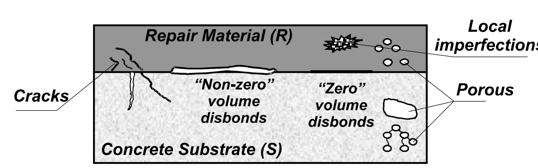

Figure 2.
Scheme of repair system with adhesion and cohesion defects (acc. to [5])

Table 1.
Reflection coefficient R for common "building interfaces"

Interface	Reflection coeff. R
Concrete / air	- 0.99
Concrete / water	- 0.71
Concrete / soil	- 0.63
Concrete / steel	+ 0.67
Bitumen/concrete	+ 0.80
Polymer/concrete	+ 0.39

2. EFFECT OF POLYMER CONTENT ON STRESS WAVE PROPAGATION IN POLYMER-CEMENT COMPOSITES

2.1. PCC microstructure model

Polymer-cement concrete and mortars (PCC) contain above 5% of polymer admixture (usually up to 20%). Polymer creates a separate phase in cement paste. According to the model of PCC structure formation [17], its final microstructure contains a complex binder which is combined inorganic and organic products participating in bulk properties, and aggregates and unhydrated cement particles are covered by polymer film (Fig. 3).

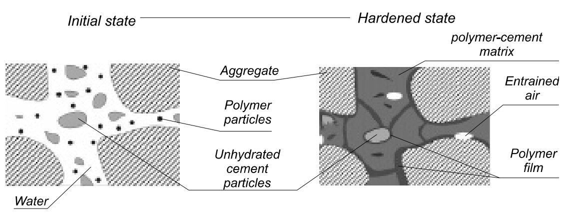

Figure 3.
Integrated model of PCC microstructure formulation (acc. to [17])

2.2. Materials and experimental procedure

Effect of polymer content on stress wave propagation was investigated for samples of PCC composites prepared from cement CEM32.5R and quartzite sand. Water dispersion of PAE was used as modifier. The investigation was performed for two groups of composites (Tab. 2, 3) that differed in content of polymer and filler as well as curing conditions. Compositions of the group B were determined using procedure of the statistical design of experiment. In case of all composites water to cement ratio was selected to obtain the same mix consistency. The composites of group A were conditioned 4 days in PVC foil and 24 days in laboratory conditions (25°C, 50%RH). The composites of group B were conditioned 2 days in PVC foil, 5 days in chamber (22°C, 99%RH) and 21 days in chamber (22°C, 60%RH).

The compressive strength, f_c, and the flexural strength, f_b, were tested for each beam-shaped samples (40mm×40mm×160mm) according to PN-85/B-04500. To determine tensile strength, f_t, "bone-shaped" samples were prepared and tested with the use of INSTRON 5567 machine. Additionally, volume density and porosity were determined for PCC of group A. Porosity, p, was calculated from the formula: $p = 1-(d_v/d_s)$, where volume density, d_v, and specific density (total mass divided by pore-free volume), d_s, were measured for each sample.

Table 2.
Average values of tested properties for composites of group A

Property	Composites of group A:									
	A1/0	A3/0	A5/0	A3/10	A5/10	A1/20	A3/20	A5/20	A1/30	A5/30
Polimer to cement ratio [%]	0	0	0	10	10	20	20	20	30	30
Binder to sand ratio (mass)	1:1	1:3	1:5	1:3	1:5	1:1	1:3	1:5	1:1	1:5
c_P [km/s]	3.89	3.69	3.30	4.21	3.81	4.16	4.20	4.31	3.78	4.14
f_c [MPa]	48.0	26.4	16.6	54.7	40.8	74.7	62.7	55.1	67.6	52.6
f_b [MPa]	5.9	5.5	4.3	11.6	9.3	15.6	13.3	11.2	11.3	3.2
f_t [MPa]	1.5	3.4	6.5	5.4	4.3	9.2	7.5	6.8	6.6	3.2
p [%]	21.7	18.1	17.1	14.8	16.6	11.1	11.2	11.7	10.3	12.6

Table 3.
Average values of tested properties for composites of group B (binder to sand ratio by mass 1:3)

Property	Composites of group B:							
	B1	B2	B3	B4	B5	B6	B7	B8
Polymer to cement ratio [%]	0	4.6	7.4	9.1	13.0	16.1	23.1	24.2
c_p [km/s]	3.63	3.91	3.91	4.01	4.03	3.99	3.87	3.91
f_c MPa	24.0	34.1	36.4	42.2	40.4	40.0	42.7	45.8
f_b [MPa]	4.6	5.6	5.5	6.8	5.7	7.8	6.7	8.2
f_t [MPa]	1.9	2.3	1.8	2.9	2.9	4.0	4.9	3.9

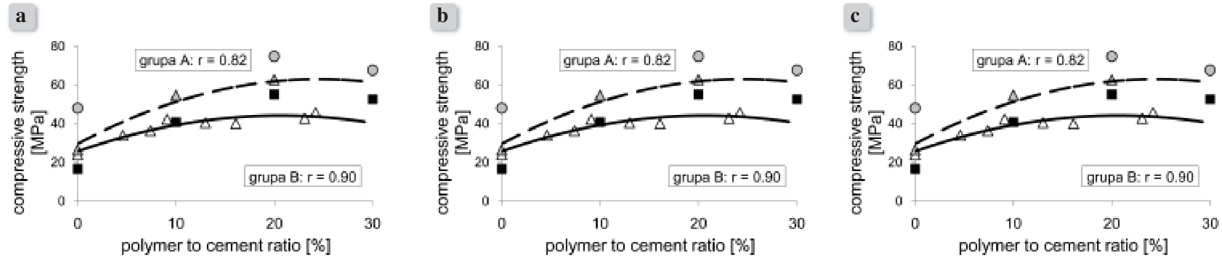

Figure 4.
Effect of polymer content in tested PCC composites on: a) compressive strength. b) flexural strength. c) tensile strength; binder to aggregate ratio: group A – 1:1. 1:3. 1:5 (○.△ ■. respectively); group B: 1:3 (△)

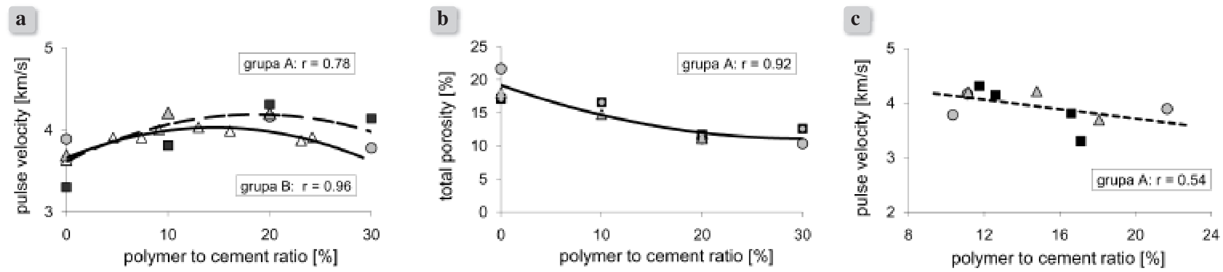

Figure 5.
Effect of polymer content in tested PCC composites on: a) pulse velocity and b) total porosity; c) non significant relationship between total porosity and pulse velocity; symbols like in Fig. 4

Ultrasonic pulse velocity was determined according to European Standard EN 12504-4 “Testing concrete in structures – Part 4: Determination of ultrasonic pulse velocity” using commercial digital ultrasonic flaw detector ULTRA CUD20 and pair of transducers with nominal frequency of 500kHz. The average values of tested properties are presented in table 2 and 3. Detailed results are presented in [18].

2.3. Results discussion

The obtained results showed significant effect of polymer content on technical properties of PCC composites and, in some extant, on stress wave propagation. Modification by polymer caused 2-3 times increase of the mechanical properties depending on the polymer and filler contents (Fig. 4). This effect was more visible for PCC composites curried in dryer conditions (group A). The values of pulse velocity ranged from 3.8 to 4.3 km/s and reached the maximum value at polymer content equal approx. 15-20% (Fig. 5a). As the polymer content increases the porosity decreases and the relationship between these parameters is characterized by relatively high regression coefficient – r = 0.92 (Fig. 5b). Different effects of the polymer content on pulse velocity and porosity cause low regression coefficient for the relationship: pulse velocity vs. porosity – r = 0.54 (Fig. 5c). This implies that pulse velocity in PCC composites depends mainly on a microstructure homogeneity of PCC. The obtained results show that for typical range of polymer content (5-20%) in PCC composites changes in the pulse velocity are relatively low – 100 m/s (2.5% of maximum value). On this basis it can be concluded that polymer phase in PCC microstructure does not affect significantly the velocity of stress waves.

The values of acoustic impedance for PCC composites of group A were estimated taking into account the values of volume density and pulse velocity. Addition of polymer increases the acoustic impedance about 5-15% in comparison to that for composites without polymer. However, its value is closed to typical range for cement concretes and mortars (dotted line in Fig. 6).

The value of reflection coefficient for this interface can be estimated below R = 0.12. Small effect of polymer content on the acoustic impedance is beneficial in case of quality control of repair with PCC composites. This indicates that almost „entire” energy of stress wave will be transmitted trough interface PCC

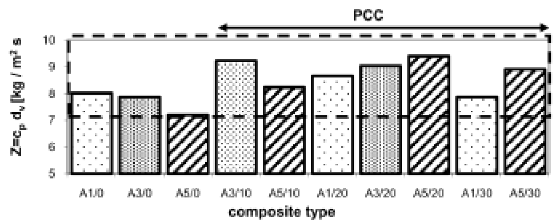

Figure 6.
Effect of polymer content on acoustic impedance of tested PCC composites

composites – concrete substrate. In opposite case the reflection of stress wave from the interface would be registered irrespective of bond quality.

Table 4.
Characteristics of the repair materials used (acc. Producer's Technical Data)

Property	bond coat (BC)	repair mortar (R)
Composition	Crack-bridging PCC mortar	PCC mortar containing glass microfibers
Max.grain size of aggregate. mm	0.5	2.0
Pull-off strength [MPa]	Without bond coat > 1.5 With bond coat > 2.0	
Requirements for concrete substrate preparation	Clean. sound with tensile strength higher than 1.5MPa; suggested way of substrate preparation: shotblasting. water-jet or thermal	

3. STRESS WAVE PROPAGATION THROUGHOUT INTERFACE: PCC – CONCRETE SUBSTRATE

3.1. Experimental procedure

The effect of the quality of interface: PCC - concrete on stress wave propagation was tested with impact echo and ultrasonic echo methods. Several repair systems differed in concrete surface and interface quality were tested [19]. Concrete substrates (300 × 300 × 50 mm) of C20/25 class were made from the concrete mix: CEM I 32.5, 2/8 limestone, 0/2 quartz sand. The following types of the mechanical treatments were used to prepare concrete substrates: grinding (GR), sandblasting (SB), shotblasting (SHB35 and SHB45, with treatment time of 35 and 45 s respectively), hand (HMIL) and mechanical (MMIL) milling. Additionally, concrete samples without treatment (NT) were tested as the reference ones.

Commercial polymer-cement mortar containing glass microfibers was used (Tab. 4) as repair material. According to the mortar producer's data it is recommended to use a suitable polymer-cement bond coat because of low workability of repair mortar. The overlay (thickness 10 mm) was applied on the concrete substrate with and without bond coat to obtain different quality of interface.

Surface roughness (Tab. 5) was characterized by arithmetic mean of the deviation of waviness profile from the profile mean line determined with mechanical profilometer [20]. The impact-echo and ultrasonic measurements were carried out after 28 days of hardening. Afterwards, adhesion between repair material and concrete substrate was characterized according to EN 1542 "Products and systems for the protection and repair of concrete structures. Test methods. Measurement of bond strength by pull-off" (see Tab. 5). Additionally, the quality of interface was observed on the cross-sections with light microscope.

Table 5.
Results of surface roughness characterization and pull-off measurements for repair systems with and without bond coat (acc. to [19])

Treatment type	Waviness parameters Wa [μm]	Mean pull-off strength (coefficient. of variation) [MPa]	
		No bond coat	Bond coat
NT	5	1.92 (23.4)	2.28 (17.1)
GR	32	1.82 (15.9)	1.16 (50.9)
SB	49	1.93 (11.4)	1.82 (32.4)
SHB35	180	1.68 (18.5)	0.78 (39.7)
SHB45	215	1.94 (11.3)	1.25 (28.8)
HMIL	70	1.42 (12.7)	1.01 (40.6)
MMIL	179	1.60 (24.4)	0.49 (57.1)

3.2. Results of bond quality evaluation

As the surface roughness increased, the pull-off strength for the systems without bond coat decreased. The repair material here tested had relatively low workability, partially due to the content of microfibers. It could not fill irregularities at the interface zone. Additionally, it was observed that the microfibers were blocked on the irregularities of profile. This caused the appearing of voids at the interface zone: the increase of surface roughness induces high fraction of voids. Flat surfaces resulting from "soft" treatments like sandblasting and grinding, as well as surfaces without treatment, were characterized by relatively low content of voids in the interface zone. For more "aggressive" treatments higher content of voids was observed (Fig. 7).

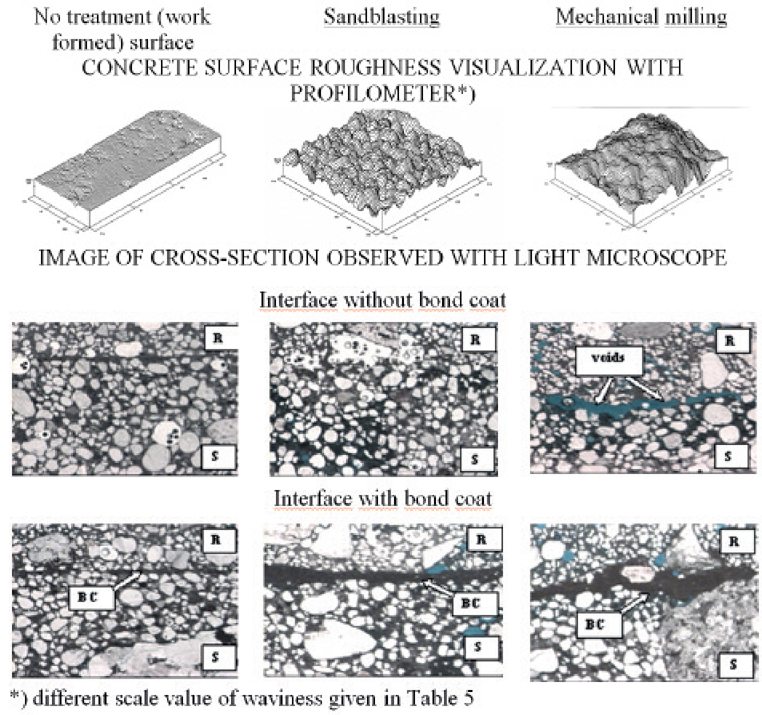

Figure 7.
View of the interface between concrete substrate and repair material without bond coat (upper) and with (bottom): (a) concrete substrate without treatment and after (b) sandblasting and (c) mechanical milling; S- concrete substrate. BC – bond coat. R – repair mortar; mag. 10x

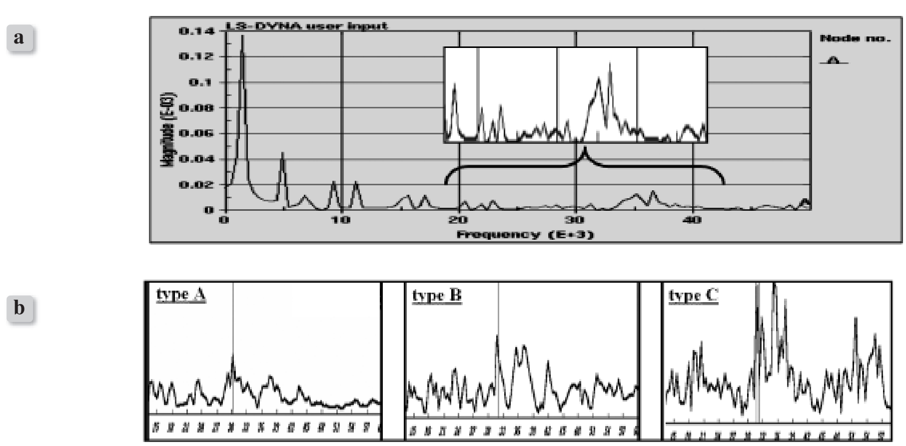

Figure 8.
Results of repair systems investigation with impact-echo method: a) FEM simulation of stress wave propagation in concrete with geometry corresponded to tested repair systems, b) three types of registered frequency spectrums

3.3. Nondestructive tests results vs. bond strength

In this work, due to the sample geometry, the impactor with diameter of 2 mm was used to generate stress waves. The spectrum consists of high amplitude frequency peak at low frequency (due to the sample geometry) and low amplitude frequency peak at approx. 30 kHz corresponded to the wave reflection from the bond interface. The representativeness of this spectrum pattern was confirmed by computer simulations (Fig. 8a) using FEM model described in [12]. Obtained registered frequency spectrums can be divided into three groups (Fig. 8b). The fractions of

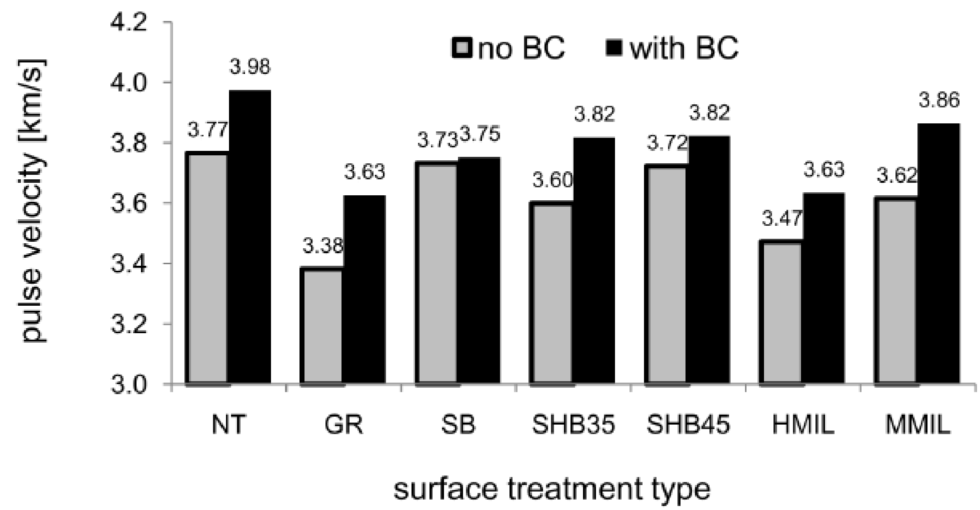

Figure 9.
Velocity of P-wave for rep air system with and without bond coat (BC)

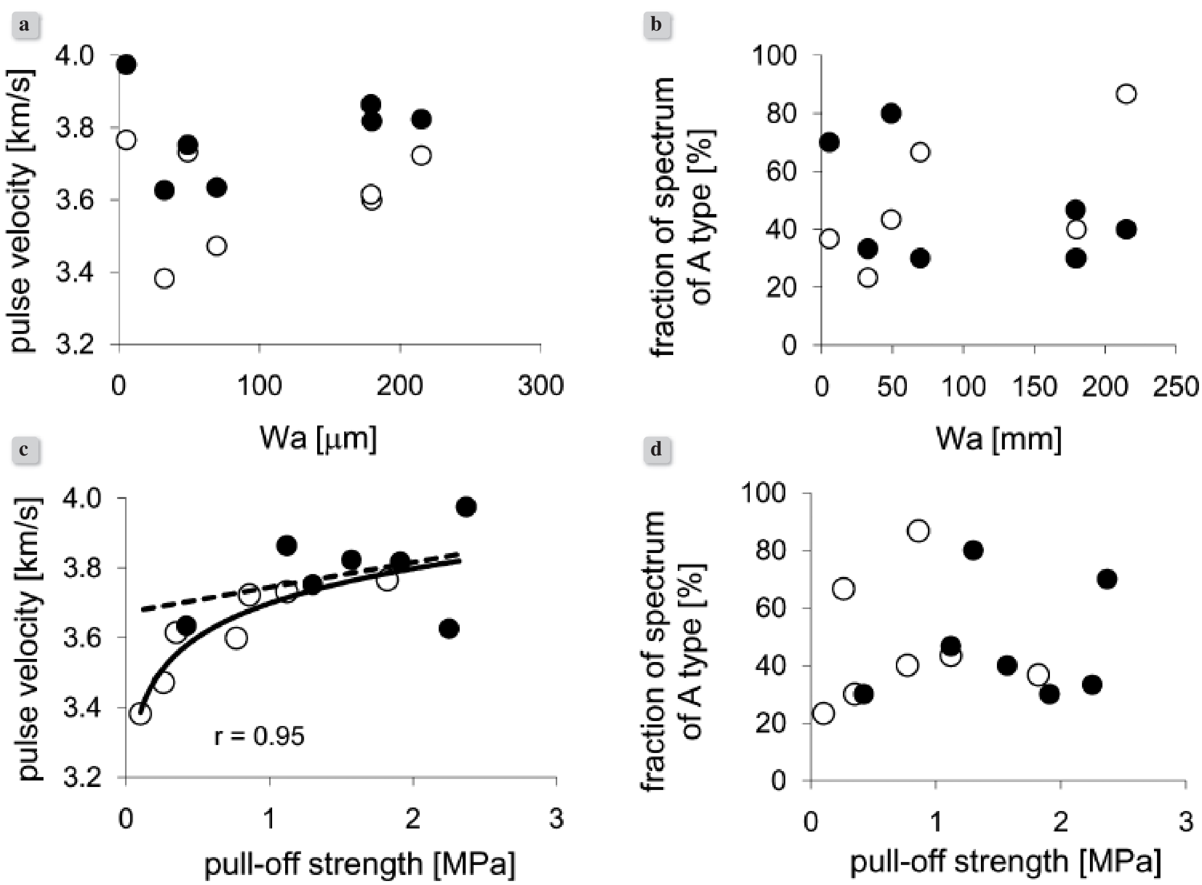

Figure 10.
Relationships pulse velocity and fraction of A type versus mean of the substrate profile waviness, Wa, and the pull-off strength respectively

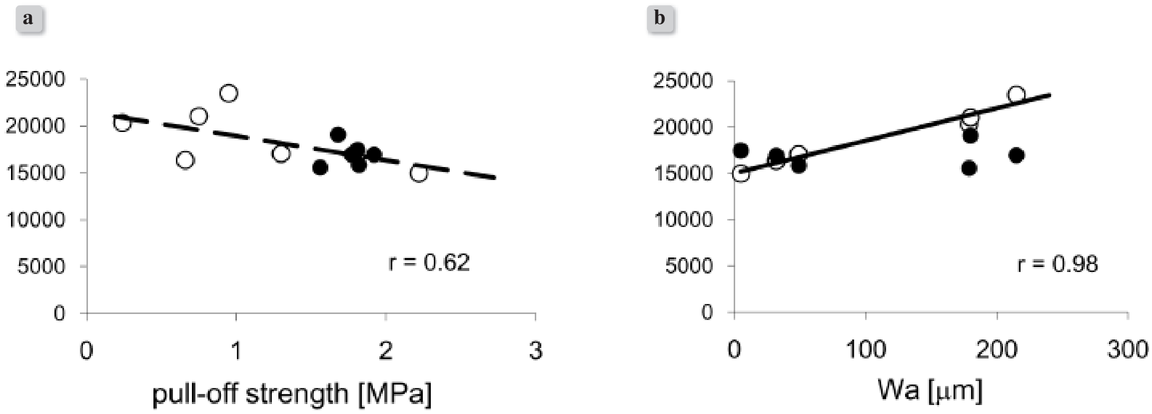

Figure 11.
Relationships between amplitude of the highest peak of frequency spectrum of ultrasonic signal and: a) pull-off strength. b) mean waviness of profile. Wa; overlays with (●) and without (o) the bond coat; c.u. – conventional unit

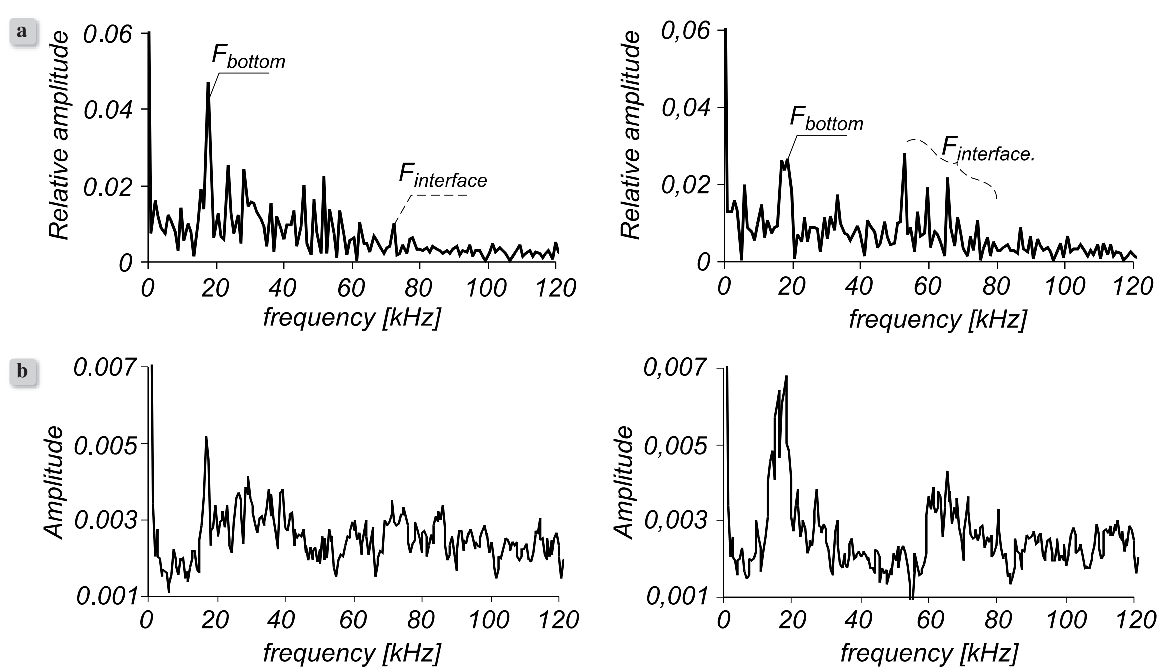

Figure 12.
Typical frequency spectra for repair systems with different roughness of concrete substrate obtained by using different treatments: sandblasting (left), hydrodemolition (right): a) experimental results for plate: 600 x 800 x 130 mm acc. to [21] and b) FEM simulations for corresponding model with concrete substrate irregularities not filled by repair mortar acc. to [22]

particular types do not correspond to surface treatment type and adhesion level. However, it was observed that type C appeared in case of two repair systems without bond coat only, i.e. the repair systems with concrete substrates prepared by sandblasting and mechanical milling. On the basis of the frequency value of dominant peak of type A, the P wave velocity for was calculated (Fig. 9).

Statistical analysis of the results obtained indicate that there is no correlation between the roughness of concrete surface (beneath repair mortar) and P wave velocity (Fig. 10a) as well as the fraction of type A spectrums (Fig. 10b) for the repair system with and without bond coat. Statistically significant relationship was obtained between the pulse velocity and pull-off strength for the repair systems without bond coat. In case of these repair systems the air voids at the interface were observed. For this system type, P wave velocity increased as the roughness increased, while for the systems with bond coat such type of relationship was not observed (Fig. 10c). In this case, the bond coat filled properly irregularities of concrete substrate after treatment. The relationship between the fraction of A type spectrums and the pull-off strength was not statistically significant (Fig. 10d). The results obtained indicate that for I-E methods the roughness of concrete substrate does not affect significantly P wave propagation through the repair system if the bond quality is good enough - no presence of large voids at the interface.

Above repair systems were tested additionally with ultrasonic pulse echo method using commercial digital ultrasonic flaw detector ULTRA CUD20 and pair of transducers with nominal frequency of 500 kHz. This method should be more sensitive to presence of voids at interface because shorter waves are generated. Each received A-scan consisted of characteristic peaks corresponded to the reflection from interface. The amplitude of peaks did not correspond to the pull-off strength and presence of air voids at the interface. The frequency spectrums obtained after signal transformation using Fast Fourier Transform for the systems with bond coat (without air-voids) had more regular character in comparison to those without bond coat (containing numbers of air voids at the interface). It was found also to be a significant trend for relationship: amplitude of maximum frequency peak vs. pull-off strength – as the pull-off strength increases the amplitude value of peak decreases (Fig. 11a). This can be explained taking into account quality of interface. As the fraction of air voids decreases less wave energy is reflected back. Statistical significance of relationship amplitude value of the highest peak vs. mean waviness of surface profile (Fig. 11b) was observed for this kind of repair system because the fraction of air voids was strictly connected with surface roughness.

The possible effect of voids presence at interface on character of waveform and frequency spectrum was confirmed experimentally (Fig. 12a) by Garbacz et al. [21] and using FEM computer simulations (Fig. 12b) by Kwaśniewski and Garbacz [22].

4. CONCLUSIONS

Based on the obtained results the following main conclusions can be formulated:

- polymer phase in PCC microstructure does not significantly affect the velocity of stress waves and the acoustic impedance,
- the roughness of concrete substrate does not significantly affect P wave propagation through the repair system if the bond quality is sufficient, i.e. no large voids are present at the interface.
- the reflection coefficient, R, for this interface PCC-concrete is relatively low (below R = 0.12). It can be assumed that almost „entire" energy of stress wave is transmitted trough interface of good bond quality. This is beneficial in case of quality control of repair with PCC composites and procedure developed for assessment of concrete structure can be applied for evaluation of interface quality,

The results of investigation confirmed that stress wave based methods, especially impact-echo, are useful for nondestructive efficiency control of repair with polymer-cement composites.

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