On the relation between bond quality and impact-echo frequency spectrum

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ABSTRACT: According to EN 1504-10 and ACI Concrete Repair Manual, bond strength and interface quality are the main features of repair system necessary to be assessed. Pull-off test is most commonly used for bond strength evaluation but growing interest in nondestructive techniques (NDT) is recently noted. Impact-echo (IE) is treated as the most promising one for this purpose. The aim of this paper is to analyze an effect of bond quality on stress wave propagation in repair systems. A group of samples has been prepared in order to obtain repair systems of different bond quality. Prior to repair, quality of concrete substrates has been characterized according different techniques: compressive strength, superficial cohesion, surface roughness index and cracking quantification. Than a polymer-modified repair mortar has been applied. After hardening, IE signals have been recorded and pull-off bond strength determined. The relationships between parameters characterizing surface quality, bond strength, IE frequency spectrum and results of wavelet analysis of IE signal have been analyzed.

1 INTRODUCTION

The general requirement for repair of concrete structures is efficiency and durability - Czarnecki and Emmons (2002). Following the compatibility rule formed by Czarnecki et al. (2004), it can be assured if a proper repair material selection is made but it is not the only condition to fulfil. There are many factors affecting on bond quality – Silfwerbrand et al. (2005). The basic operation during repair, that can increase (but also decrease) bond strength between repair material and concrete substrate, is surface treatment – Courard (2000). In this paper relation between bond quality and impact-echo frequency spectrum was analysed.

2 EXPERIMENTAL PROGRAM

2.1 Repair systems description

Several repair systems with deferent quality of concrete substrate surface were tested (Tab.1). The effect of the concrete surface treatment is mostly dependent upon the nature and the quality of concrete substrate. Two groups of three different types of concrete were designed in order to obtain classes of compressive strength from C25/30 to C50/60. The given classes were verified by compressive strength, f_{ck} evaluation. On each of group of concrete slabs, four types surface preparation methods were investigated. In order to obtain differences in profile development and level of microcracking in the near-to-surface layer, the surface preparation methods for Group A were: polishing (PL), dry sandblasting (SB-D), jack hammering (JH) and hydrodemolition (HD). For Group B surface preparation methods were suited as not to much aggressive ones to obtain similar profiles, low-level microcracking but differences in bond quality; they were: brushing (NT), waterjetting (LC), wet sandblasting (SB-W) and scarification (SC).

Table 1: Characteristic of tested repair systems

	Group A			Group B		
Concrete substrate	C30	C40	C45	C25	C35	C50
Compressive strength classes	C30/37	C40/50	C45/55	C25/30	C35/45	C50/60
Surface preparation	*PL, SB-D, JH, HD*			*NT, SB-W, SC, LC*		
Sample dimensions	80x60x10 cm			50x50x7cm		
Repair material	PCC (A), D_{max} = 2,0mm			PCC (B), D_{max} = 0,25mm		
Repair layer thickness	3cm			3cm		

2.2 Results of substrate characteristics

The quality of substrates was characterized from point of view of their roughness, microcracking and surface tensile strength. The roughness was measured by sand patch test according to EN 1766 resulting Surface Rough Index SRI (Fig.1a). Substrates of Group A can be ranked from polished smooth surface (PL), by dry sandblasted (SB-D) and jack hammered (JH) to very irregular hydrodemolitioned one (HD). In Group B low-pressure waterjetting (LC) has no big influence on profile in comparison to brushed surface (NT), while wet sandblasting (SB-W) and scarification (SC) increase roughness a little. Microcracking of samples of Group A was observed on the cross-section of the 8 cm cores on the near-to-surface layer in the area of 2 cm depth. Density of microcracks was calculated (Fig.1b). It can be concluded, that more aggressive surface preparation technique influence more on microcracking: it was observed two times higher density of microcracks after jack hammering (JH) and hydrodemolition (HD) than after dry sandblasting (SB-D) and polishing (PL). As the aggressiveness of surface treatment of samples of Group B was small, the microcracking was not observed here, although it can be expected a little higher level for scarification.

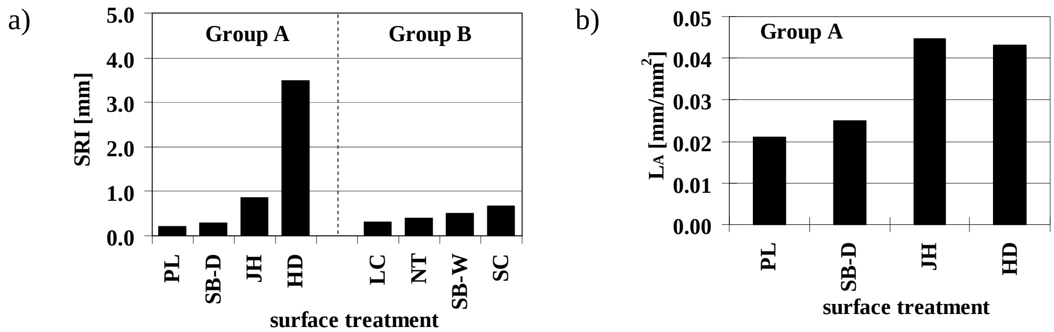


Figure 1: Surface Roughness Index, SRI (a) and density of microcracks, L_A (b) depending on the method of surface treatment

The pull-off test according EN 1542 and ASTM C 1583 04 commonly used for evaluation of bond strength (Fig.2b) was applied for surface tensile strength (f_{hs}) measurement (Fig.2a) including type of failure registration. In case of samples of Group A the concrete quality did not have a major influence on the surface tensile strength after surface treatment as it was for samples of Group B (Fig.3). It can be also observed (Fig.4) that for surfaces jack hammered (Group A) and scarified (Group B), more that 50 % of failures appeared near in the superficial zone (type A1, see Fig.2a). It is probably due to microcracking already mentioned.

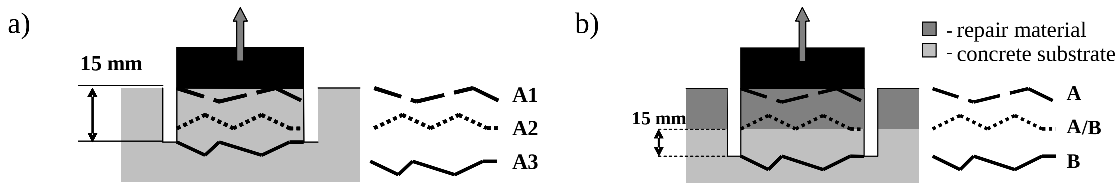


Figure 2: Pull-off for evaluation of surface tensile strength (a) and bond strength (b)

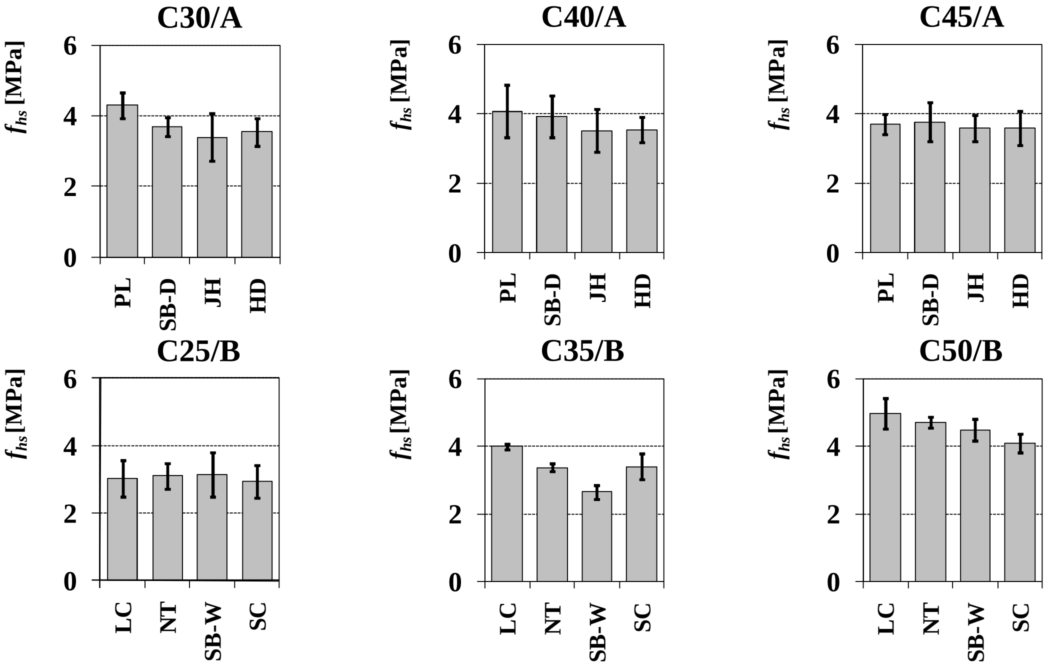


Figure 3: Surface tensile strength, f_{hs} of samples

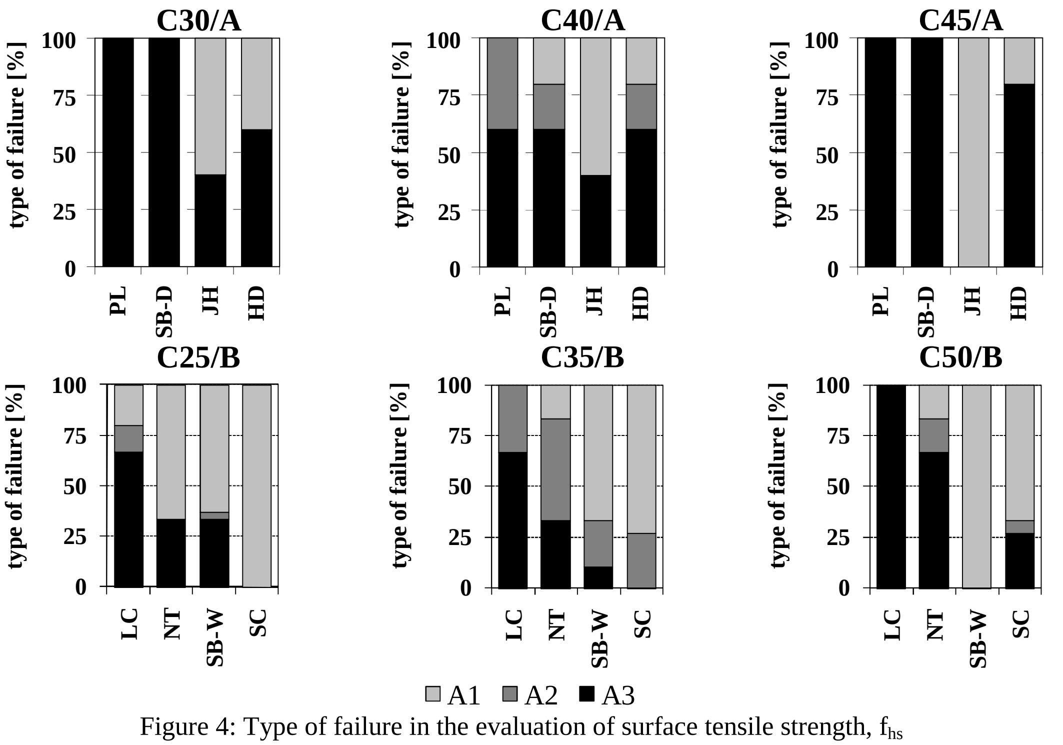


Figure 4: Type of failure in the evaluation of surface tensile strength, f_{hs}

2.3 Results of bond strength evaluation in repair systems

When repair was 28 days old, the pull-off tests were performed for evaluation of bond strength between concrete substrate and repair layer (Fig.5). Surface preparation effect on samples of Group A can be divided in two groups in regards to EN 1504-10: bond strength after hydrodemolition (HD) and sandblasting (SB-D) is greater than the threshold minimum values for laboratory performance both for structural repair (2.0MPa) and non structural (1.5MPa). The bond strength for polishing (PL) and jack hammering (JH) is close to or below this limit. For the Group B only the results on substrate C25 and C35 are at this level. In comparison to Group A, bond strength is much lower probably due to not sufficient development of surface profile.

Moreover, there was observed total delamination with substrate water jetted (LC) and brushed (NT) for samples C50. These methods seem to be not effective also for C35. Looking at the type of failure (Fig.6), an effect of microcracking is still visible for jack hammering (JH), where all failures were in the superficial zone of substrate (type A, see Fig.2b). For polishing (PL) all failures appeared at the interface (type A/B, see Fig.2b), because mechanical interlocking between substrate and repair layer was not sufficient. Situation is more unclear for dry sandblasting (SB-D) and hydrodemolition (HD) where cohesive B and interface A/B failures were observed. Analysing Group B samples, many failures in concrete (type A, see Fig.2b), appeared where concrete was weak (C25), especially when aggressive surface treatment like scarification (SC) was applied.

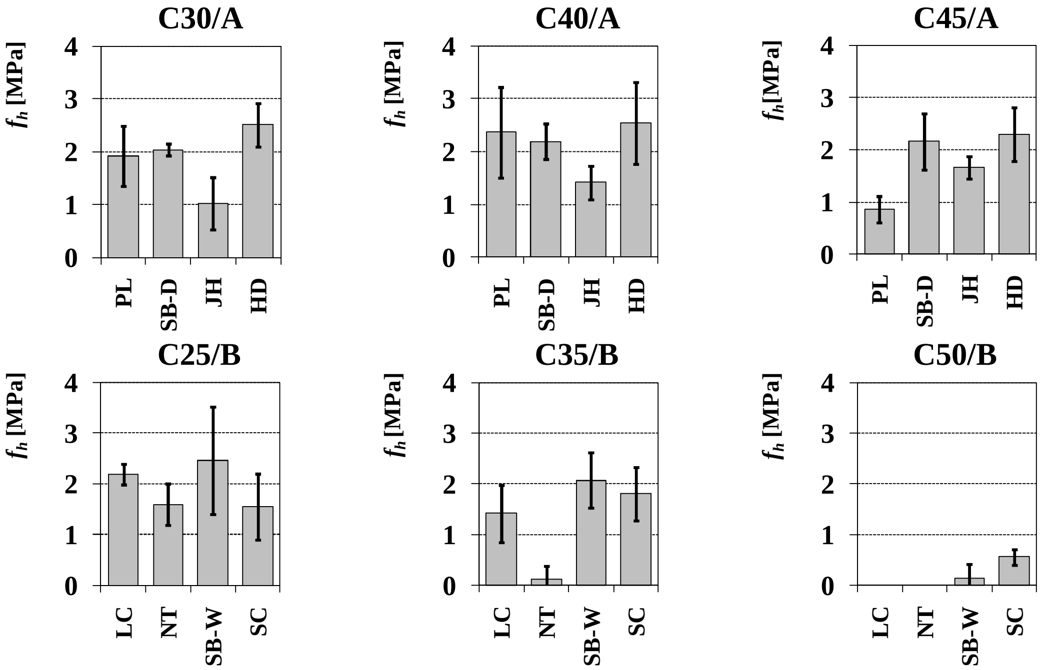


Figure 5: Bond strength, f_h between concrete substrate and repair layer

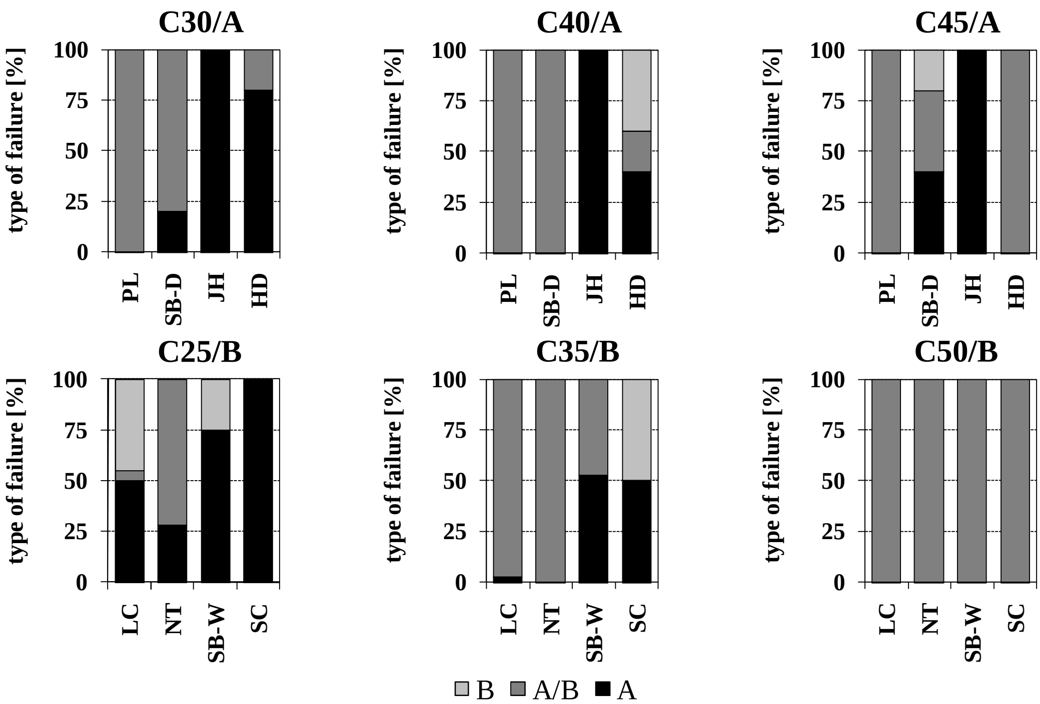


Figure 6: Type of failure in the evaluation of bond strength, f_h

2.4 *Influence of substrate characteristic on bond strength*

Multiply regression approach for evaluation of bond quality using calculated parameters of substrate characteristic (f_{ck},SRI,L_A,f_{hs}) as explanatory variables showed, that the biggest part in prediction of bond strength, f_h have f_{hs} and SRI. When using these parameters only the regression coefficient, R was 0.70 for Group A and 0.82 for Group B. Interesting is observation that while influence of SRI increase is in both cases positive, the influence of f_{hs} for Group A is positive and for Group B negative. This situation is clear visible on the graph of usability, defined as a value of high usability u= 1.0 for bond strength f_h= 2.5MPa, medium usability u= 0.5 for f_h= 1.5MPa and low usability u= 0.0 for f_h= 0.5 (Fig.7).

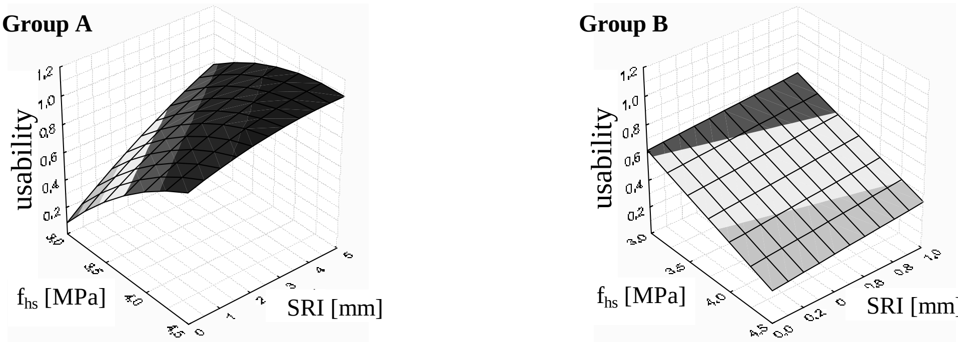


Figure 7: Usability graph for evaluation of bond strength using f_{hs} and SRI as explanatory variables

3 IMPACT-ECHO TESTS

3.1 *Impact-echo method description*

Impact-echo (IE) is a method for non-destructive evaluation of concrete, based on the use of an elastic, low energy impact of a steel ball on the surface generating low frequency stress waves (mainly below 60 kHz). These waves propagate through the structure and are reflected by interfaces within the material (internal flaws such as voids, honeycomb, cracks, delaminations) or external boundaries (Fig.8a). IE method is often used for quality control of various types of repair, e.g. injection of cable ducts, overlays etc.- Sansalone et al. (1997). As the stress waves generated in IE method have low frequencies (in comparison to e.g. ultrasonic), this method is less sensitive to heterogeneity of concrete. Additional feature of IE method is application besides a time-domain analysis (Fig.8b) a frequency analysis (Fig.8c). Based on frequency spectrum the depth of the reflecting interface (e.g. flaws) can be determined according to formula:

$$d = \frac{c_p}{2 \cdot f_d} \qquad (1)$$

where: d = depth of interface, c_p = wave velocity, f_d = frequency of dominant peak.

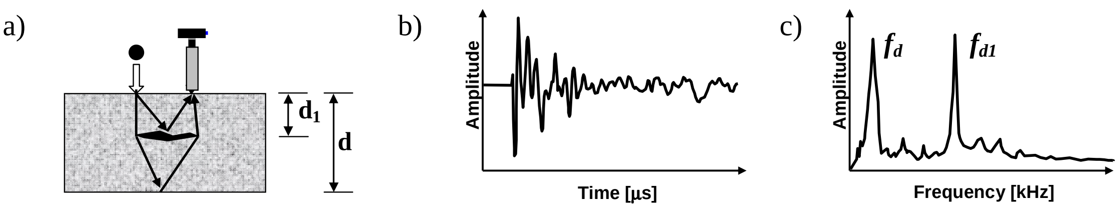


Figure 8: Scheme of impact-echo method (a), example of waveform (b) and corresponding frequency spectrum (c) when defect in concrete is observed

3.2 *Influence of substrate characteristic on impact-echo stress wave propagation*

First two specific ranges of the frequency spectrums were analyzed: first around of the bottom peak frequency and second one around frequencies corresponding to the interface. The relationships between amplitude of bottom and interface peaks and parameters describing quality of repair systems were not statistically significant - Piotrowski et al.(2007) and Garbacz et al.(2008). It means that amplitude of characteristic frequency peaks is not proper measure to estimate bond quality in repair systems. In next studies normalized frequency spectrums was spread on 3D amplitude - frequency distribution where the number of IE measurement (from 1 to 10 - Group A, and from 1 to 7 - Group B) was the third axe parameter. It can be observed (Fig.9) that for jack hammering (JH) and hydrodemolition (HD) in Group A, apart from the bottom peak at about 20 kHz, there are some high peaks in lower frequencies suggesting rough surface and microcracking. In case of C50 group B samples where total delamination and zero bonding in pull-off test was obtained (NT and LC) there are clear vibration peaks that have very low frequency and bottom peak is no visible (Fig.10) Obtained 3D amplitude - frequency distribution surfaces were characterized with RugoDS program using surface profile analysing approach – Garbacz et al. (2006). The statistical parameters for 3D amplitude – frequency distribution were calculated but still no statistically significant relationship between these parameters and pull-off strength was found.

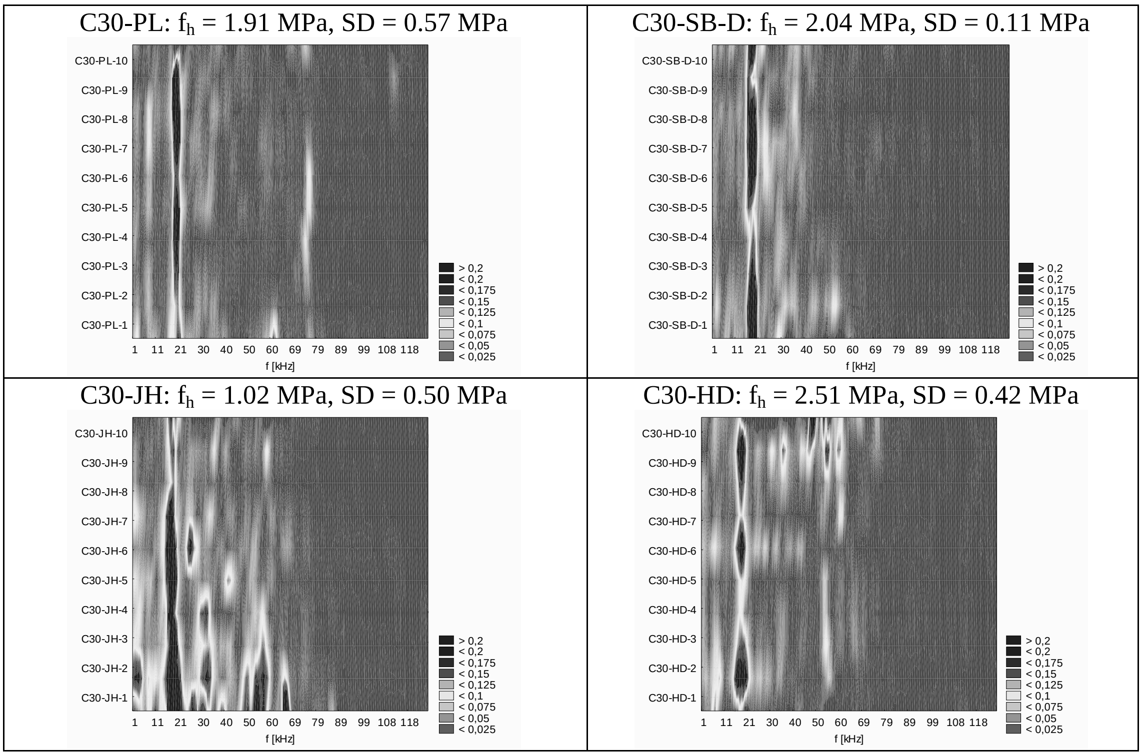


Figure 9: 3D amplitude - frequency distribution for C30 Group A

3.3 Evaluation of bond strength using wavelet approach

Wavelet analysis presents the next logic step in analysis of signals. It allows for use of long time sections, when analysis of low frequencies is made or short time – for high frequencies. This effect is a result of using, instead of sine function, a wavelet - "short" wave, well concentrated in both time and frequency. Wavelet analysis decomposes signal on a set of shifted and scaled versions of mother wavelet. Continuous Wavelet Transform - CWT results the C coefficients that are functions of scale and time position. Signal is then composed of a sum of shifted and scaled wavelet multiplied by C. If we use scaling parameters of powered 2 the Discrete Wavelet Transform - DWT is obtained. The result of DWT is a set of coefficient/time diagrams (details,D) on given scale levels 2,4,8,16 etc. Fundamental for wavelet analysis is relation between scale and sine frequency of wave phenomena. This relationship describes pseudo-frequency f_a equation:

$$f_a = \frac{f_c}{a \cdot \Delta} \tag{2}$$

where: f_c = wavelet centre frequency (dominant oscillation frequency), a = scale, Δ = sampling period in seconds.

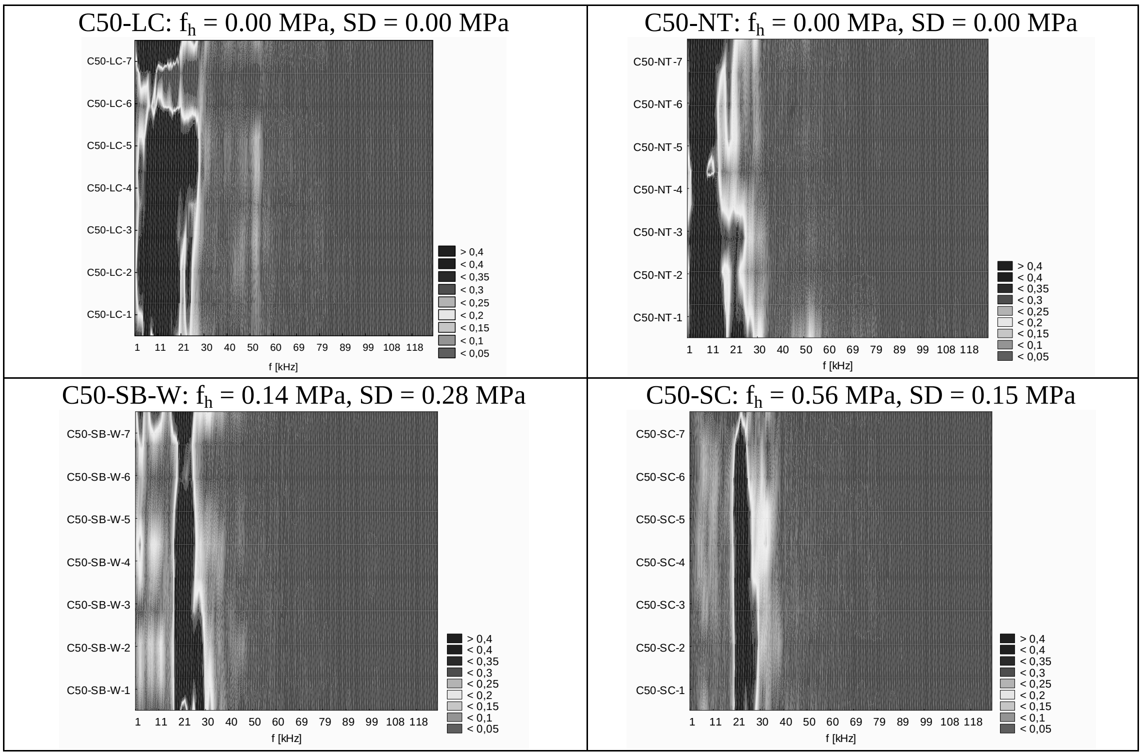
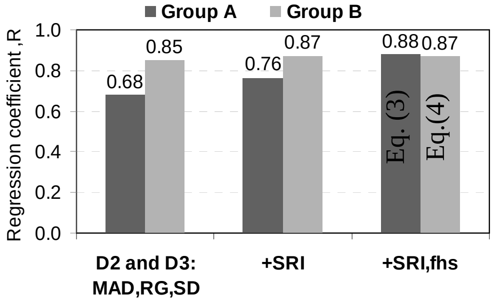


Figure 10: 3D amplitude - frequency distribution for C50 Group B

Analytical determination of scale and detail level for specific ranges of the frequency spectrums showed that the characteristic frequency ranges for interface echo are located at level D3-D2. Results of the DWT transform on IE signals – details D2 and D3 were statistically analysed using standard procedure of the MatLab by mean of absolute deviation (MAD), standard deviation (SD) and range of amplitude (RG). Than multiply regression approach for evaluation of bond quality using calculated parameters of detail distribution was performed. The regression coefficient, *R* was 0.68 for Group A and 0.85 for Group B (Fig.11), what is a similar level as it was in case when as explanatory variables f_{hs} and SRI were used. If we add to the explanatory variables parameters from characterisation of concrete substrate (f_{hs},SRI) and wavelet analysis of IE signal (MAD,SD,RG for D2 and D3) the regression coefficient, R increase to 0.88 for Group A and 0.87 for Group B. A result of multiply regression approach was the regression equations (Fig.11b) which allows for calculation of estimated bond strength on the base of explanatory parameters.

a)



b)

Group A - Eq.(3):

$f_{h,IE}$ = -5.9 + 1.7 f_{hs} + 0.3 SRI +
- 166.6 D2_MAD + 150.8 D2_SD - 13.1 D2_RG +
- 32.6 D3_MAD + 79.7 D3_SD - 4.2 D3_SD

Group B - Eq.(4):

$f_{h,IE}$ = 1.6 + 0.3 f_{hs} + 1.1 SRI +
+ 128.0 D2_MAD + 100.8 D2_SD + 5.5 D2_RG +
- 188.5 D3_MAD + 139.6 D3_SD – 3.8 D3_SD

Figure 11: Multiply regression coefficients in evaluation of bond strength using different explanatory variables (a) and equations for calculation of estimated bond strength, $f_{h,IE}$ (b)

If we plot measured bond strength vs. estimated bond strength the points are localised quite close to basic regression line of $f_h = f_{h,IE}$, (Fig.12). To calculate minimal evaluated bond strength, we need to corrected regression line (solid line) by shifting the basic regression line (dot line), as it is recommended in EN 13791, on value:

$$\Delta f_h = -1.48 \cdot s \tag{5}$$

where: s = standard deviation of distance between points and basic regression line.

Points located in the grey area on the left form corrected regression line have big probability for low bond strength or even delamination.

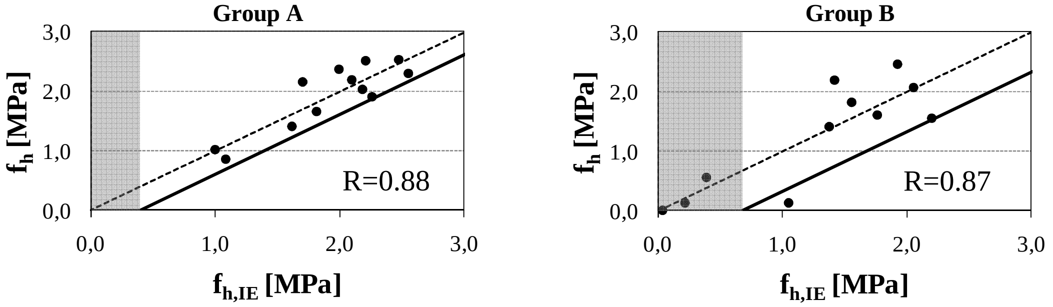


Figure 12: Bond strength measured, f_h vs. bond strength estimated, $f_{h,IE}$ with multiple regression using as explanatory variables D2 and D2 MAD,RG,SD together with SRI and f_{hs}

4 CONCLUSIONS

Results presented in this paper and obtained in earlier research lead to a statement that bond strength estimation in repair systems can be made by impact-echo signal analysis, especially using wavelet approach. Including into analysis the parameters characterizing concrete substrate quality, like Surface Roughness Index and surface tensile strength, significantly improves this estimation. Method of bond strength estimation in repair systems using impact-echo could be based on the procedure of assessment of in-situ compressive strength given in EN 13791.

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