Combined Non-Destructive Testing Approach to Waste Fine Aggregate Cement Composites

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ABSTRACT

The research programme presented in this paper covers the estimation of fine aggregate cement composites strength by combined methods of non-destructive testing. Waste fine aggregate and CEM I 32.5 were used to prepare cement composites characterized by workability class V1 and V2 (according to EN 206-1) and compressive strength ranging from 12 to 33MPa. There were composed eight mixes characterized by cement/water ratio ranging from 1.09 to 2.36. Specimens were tested in three saturation states: "dry", "moist" and "wet". Both commonly used rebound hammer and ultrasonic pulse velocity tests were conducted. Various charts showing the results are presented. The aim of the research programme was to deliver characteristic of rebound number versus ultrasonic pulse velocity, specific for the waste fine aggregate cement composite similar to such composites cast 30 years ago. It would enable to assess strength of waste fine aggregate cement composites used to erect structures in 1980's. This characteristic with 95% prediction intervals is presented at the end of the paper.

Keywords: non-destructive testing, cement composite, fine aggregate, waste aggregate, compressive strength

INTRODUCTION

The production of ordinary concrete usually consumes coarse aggregate (e.g. gravel) and fine aggregate (e.g. sand) in weight proportion approximately equal to 3:1 (Neville 1997). Unfortunately, in majority of cases, natural resources of coarse and fine aggregates can be found in very different weight proportions. For example, natural aggregates in Pomerania region in Poland are of glacial origin and they occur in a form of sands and all-in-aggregates. Production of ordinary concrete based on such, locally available fine aggregate is hindered. High transport costs of coarse aggregate from distant pit deposits (often over 200km) to the precast elements production facility, force producers to use the process of hydroclassification of natural all-in-aggregate in order to receive coarse aggregate. Approximately half of documented deposits of aggregate in the Pomerania region is constituted by deposits hydroclassified during the exploitation. Process of hydroclassification allows to divide all-in-aggregate into coarse aggregate and fine aggregate. Waste fine aggregate (WFA) is a by-product of hydroclassification process. Natural all-in-aggregate constitutes from 70% to 90% (by weight) of sand. Because of a huge deficit of coarse aggregate in the region, coarse aggregate obtained

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during hydroclassification of all-in-aggregate is constantly being sold and always on demand. Fine aggregate received during the hydroclassification process, due to excessive amount of natural sand in the region, is called WFA.

For the last 30 years there have been numerous attempts to produce different precast elements (including large scale elements) from cement composites based on WFA as the only or main aggregate. Various civil engineering applications of waste fine aggregate cement composites have proved that meticulously made fine aggregate cement composite is characterized by satisfactory strength and durability in order to be applied in civil engineering as a standard construction material (Katzer & Kobaka 2006). Attempts to produce precast units based on WFA covered a wide range of elements, starting from small size pavement elements, through full size wall units, floor slabs and finishing with sewage pipes. Using fine aggregate as a main component of cement composite affects properties of a fresh mix (Wang & Chung 1998) as well as mechanical behaviour of hardened composite (Katzer & Kobaka 2009). The large surface area of the fine aggregate increases the amount of water necessary to wet all the solids. More water is thus needed (comparing to ordinary concrete) to maintain the same workability of the fresh cement composite mix.

Due to concerns about durability of WFA cement composites cast 20-30 years ago there is growing demand to evaluate the state of structures and building erected using such cement composites. The most desirable methods of structure safety checks are these based on non-destructive testing (NDT). In case of concrete structures long-established NDT methods are rebound hammer test (also known as a Schmidt hammer or a Swiss hammer) and ultrasonic pulse velocity test.

The hammer measures the rebound of a spring loaded mass impacting against the surface of the specimen and is measured with the help of arbitrary scale ranging from 10 to 100. Using this method of testing is classed as indirect as it does not give a direct measurement of the strength of the material. It simply gives an indication based on surface properties and it is only suitable for making comparisons between concrete specimens and real concrete structure. There are some calibration diagrams provided by hammer manufacturer. Other diagrams are suggested by different national codes and instructions (Komlos et al. 1996). Because the stiffness of concrete is influenced by the type of aggregate used, the use of "global" diagrams relating the hardness number and strength is inadvisable (Neville 1997). The most accurate procedure is to establish experimentally the relation between the rebound number measured on specimens and their actual strength.

From the other hand, there is no direct physical relation between velocity of ultrasonic pulse and strength of cement composite. For a given aggregate and a given richness of the mix the ultrasonic pulse velocity is affected by the C/W ratio, which affects the modulus of elasticity of the hardened cement composite. It is only within these limitations that the ultrasonic pulse velocity test can be used to assess the strength of cement composite, preferably by making comparisons between samples (Komlos et al. 1996). Further on, both discussed methods are sensitive to water content of the specimen and saturated material will give different results from a dry one. Despite all these limitations and technological problems, both methods are commonly used all over the world to assess concrete strength (Bilgin et al. 2002, Hassen et al. 1995, Hobbs & Kebir 2007). Therefore authors decided to conduct a research programme focusing on possible application of ultrasound velocity tester and Schmidt hammer to assess the strength of cement composites based on WFA and cast 20-30 years ago. Successful correlation of the real strength of specimens and results of NDT tests would allow evaluation of the state of the existing (20-30 years old) WFA cement composite structures.

MATERIALS AND MIXES

All results reported in this paper were obtained on specimens prepared using ordinary Portland cement (CEM I 32.5), waste fine aggregate and gap-graded gravel. Setting time, soundness and strength properties of the cement were tested before approving it for the research programme. Setting time of the cement was determined using Vicat apparatus and was equal to 130 minutes and 390 minutes for an initial set and final set respectively. Soundness of the cement was tested using Le Chatelier apparatus and it was equal to 5mm (expansion of Portland cement is limited to 10mm by EN 196-3) Tested strength properties of used cement are presented in the Figure 1.

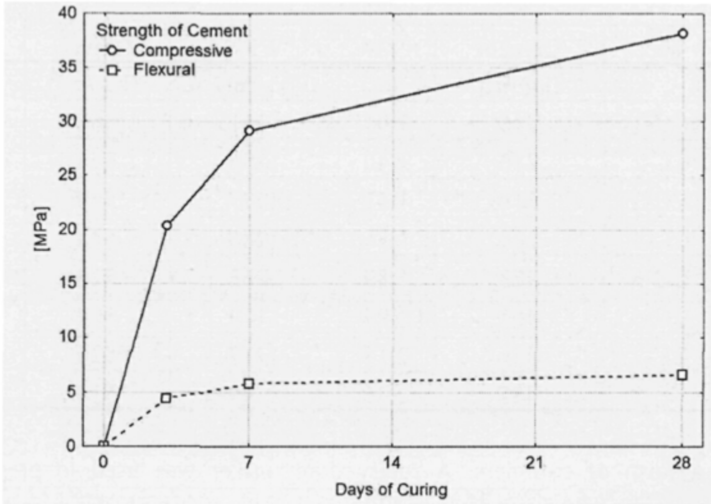

Fig. 1: Strength properties of used Portland cement

Aggregate was composed from waste fine aggregate and two fractions of gravel. Used waste fine aggregate (WFA) is a by-product of hydroclassification process of all-in-aggregate. Properties of this type of WFA were thoroughly described in previous publication (Katzer & Kobaka 2006). Grain-size distribution of used WFA is presented in the Figure 2. WFA was enriched by addition of two fractions (2-4mm and 4-10mm) of natural gravel. Obtained aggregate mix constituted 70% of WFA, 15% of 2mm-4mm gravel fraction and 15% of 4mm-10mm gravel fraction. Loose bulk density and compacted bulk density of aggregate mix was equal to 1516 kg/m^3 and 1878 kg/m^3 respectively. Tap water was used for mixing and curing. There were designed eight mixes characterized by cement/water ratio ranging from 1.09 to 2.36. The mixes were codified as CC-1, ... , CC-8. Workability of the mixes tested according to the Vebe procedure was ranging from t_{Vebe}=12s to t_{Vebe}=30s (workability class V1 and V2 according to EN 206-1). Proportions of all cast mixes are summarized in Table 1. No additives or admixtures were applied in order to maintain the traditional way of concrete production. The quality of cast specimens was comparable to the quality of WFA cement composites cast 20-30 years ago.

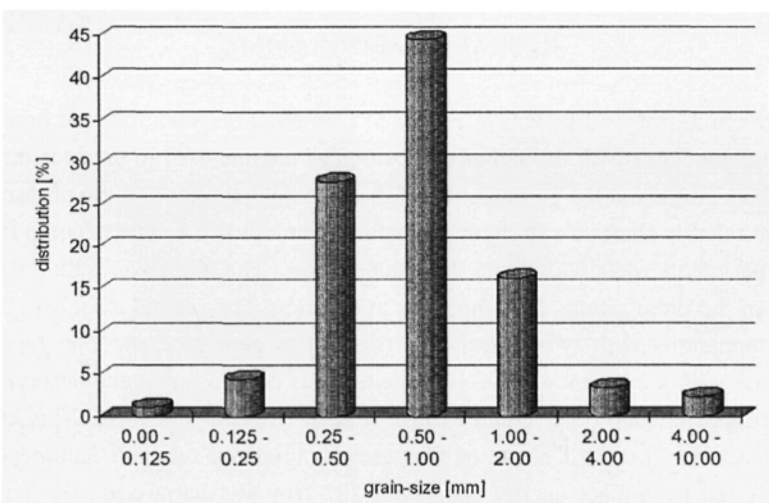

Fig. 2: Grain-size distribution of WFA

Table 1

Mix proportions

Mix	Cement [kg/m^3]	C/W	WFA [kg/m^3]	Gravel [kg/m^3]
CC-1	246	1.09	1311	562
CC-2	283	1.40	1296	554
CC-3	319	1.53	1277	546
CC-4	360	1.76	1280	548
CC-5	383	1.89	1266	524
CC-6	405	1.99	1179	504
CC-7	456	2.18	1217	520
CC-8	487	2.36	1199	514

All specimens were in a form of cylinders. A rotary drum mixer was used to prepare composite mixtures. Compaction of fresh concrete mix was performed externally using a vibrating table. Each specimen was vibrated in two layers, with each layer filling half of the thickness. Each layer was vibrated for 20s (until a thin film of bleed water appeared on the surface). The specimens were cast in steel moulds to maintain the same material as the formwork material used while casting the structure. The material of the formwork influences the quality of cement composite surface what have direct impact on a results of rebound hammer test (Hobbs & Kebir 2007).

The first step of curing was to keep the specimens in their moulds covered with polyethylene sheets for 24h. The specimens were then removed from their moulds and cured by storing them in laboratory conditions (Temp: +22°C, Rh: 100%), where they were applied moisture curing as described by Toutanji & Bayasi. The second step of curing was to divide specimens into three groups and cure them for further 7 days in three different ways. Group of specimens number 1 was placed in a water tank (Temp: +21°C), group number 2 was stored in ordinary conditions (Temp: +21°C, Rh: 45%) and group number 3 was placed in an oven (Temp: +105°C, Rh: 0%). At the end of the curing process specimens were in full saturation state ("wet"), ordinary saturation state ("moist") and "dry" state from group 1, 2 and 3 respectively. All specimens were tested at the age of 35 days.

RESEARCH PROGRAMME

The main aim of the research programme was to establish correlation between rebound number and ultrasonic pulse velocity for WFA cement composites with the same composition as the one used to produce different pre-cast elements 20-30 years ago. The authors employed the combination of the rebound hammer and the ultrasonic pulse velocity tester in order to get suitable and reliable charts for strength evaluation of an old WFA cement composites, easy to use on site.

The programme of experiments was divided into three main stages. The objective of the first stage was to determine the compressive strength of the three groups of composites in question. The second stage was to conduct the ultrasonic pulse velocity tests. An apparatus with two transducers (one pulse generator and one receiver) was employed to generate an ultrasound pulse with a frequency of 54kHz. The test was carried out at one observation point at a time. The transducers were located opposite each other creating direct transmission of the wave. This kind of transmission was employed as the most sensitive. The third phase of the research involved rebound hammer tests. Original Schmidt hammer type N, characterized by impact energy equal to 2.207 Nm was harnessed. The hammer was in a vertical position during all tests and no correction of the results was required.

The examination results were statistically processed and values bearing the gross error were assessed on the basis of Grubbs criterion. The objectivity of the experiments was assured by the choice of the sequence of the realization of specific experiments from a table of random numbers. Fitted functions were characterized by the coefficient of determination R^2 greater than 0.55. All calculations connected with specifying and graphic interpretation of the received mathematic model were carried out with the help of Statistica 8.0 computer programme (Hill & Lewicki 2007). Results of the first stage of the research programme are presented in the Figure 3. Equations (1), (2) and (3) describe fitted functions. In case of dry and wet specimens the best fitting was achieved by linear function. The moist specimens required polynomial fitting to get similar values of coefficient of determination. Compressive strength was ranging from 12MPa to 33MPa depending on C/W and curing conditions.

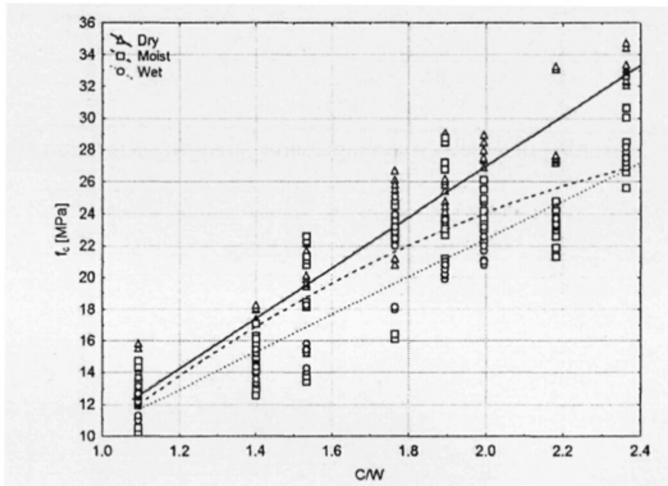

Fig. 3: Compressive strength of cement composites depending on C/W

$$f_{c,dry} = -4.85 + 15.91(C/W) \qquad R^2=0.8964 \tag{1}$$
$$f_{c,moist} = -12.31 + 27.10(C/W) - 4.46(C/W)^2 \qquad R^2=0.7783 \tag{2}$$
$$f_{c,wet} = -1.32 + 11.88(C/W) \qquad R^2=0.8817 \tag{3}$$

Results of an ultrasonic pulse velocity test are presented in the Figure 4. Equations (4), (5) and (6) describe fitted functions. The best fitting correlations were achieved using exponential functions. The authors feel that striving for traditional linearity of the formulae for the sake of simplicity has lost its significance in the era of commonly available personal computers allowing comprehensive data analysis. Exponential formula of mathematical form of regression for ultrasonic method is also recommended by some national standards including Russian Standard GOST 17624. Once the velocity is determined, an idea about quality, uniformity, condition, and strength of the tested cement composite can be attained. Velocity of ultrasonic pulse classifies the quality of tested concrete (Qasrawi 2000, Whitehurst 1951). Velocity range V>4.5km/s, 4.5km/s>V>3.5km/s and 3.5km/s>V>3.0km/s defines quality of concrete as excellent, good and medium respectively. Using this classification examined cement composite mixes are characterized by good and excellent quality.

$$f_{c,dry} = 0.2867e^{1\,1903V} \qquad R^2=0.7001 \tag{4}$$
$$f_{c,moist} = 0.0136e^{1\,6746V} \qquad R^2=0.7642 \tag{5}$$
$$f_{c,wet} = 0.0083e^{1\,7465V} \qquad R^2=0.8391 \tag{6}$$

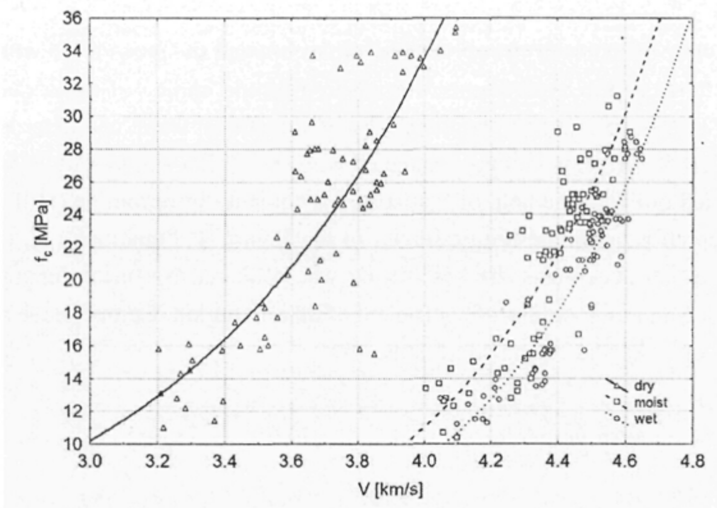

Fig. 4: Ultrasonic pulse velocity/compressive strength calibration curves

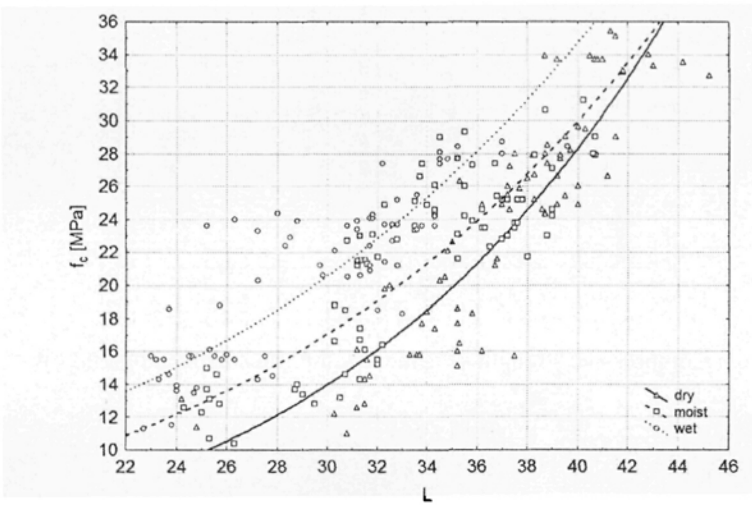

Fig. 5: Rebound number/compressive strength calibration curves

$f_{c,dry} = 1.6866e^{0.0705L}$ $R^2=0.7733$ (7)

$f_{c,moist} = 3.1568e^{0.0562L}$ $R^2=0.7133$ (8)

$f_{c,wet} = 4.2993e^{0.0522L}$ $R^2=0.7822$ (9)

Results of a rebound hammer test are presented in the Figure 5. Equations (7), (8) and (9) describe fitted functions. The best fitting correlations were achieved using exponential functions.

DISCUSSION

The increase in moisture content of cement composites increases the ultrasonic pulse velocity but decreases the rebound number. When the specimens are dry, ultrasonic readings are vulnerable to influence of cracks, voids and other defects of composite texture. These defects are practically undetectable if they are filled with fluid. Relations presented in the Figure 4 illustrate this phenomenon. Dry cement composites are characterized by lower pulse velocity value than moist and wet composites. On average the difference is equal to 1.0km/s and 1.1km/s comparing to pulse velocity values of moist and dry composites respectively. It means that dry cement composite with compressive strength equal to 35MPa and moist cement composite with compressive strength equal to 12MPa are both characterized by the same pulse velocity value. Moreover, pulse velocity readings are less scattered when dealing with moist and wet composites, than the results with lower values of the coefficient of determination of fitted functions.

Rebound hammer test is sensitive to local variations in the cement composite internal structure, for instance, the presence of a large piece of aggregate immediately underneath the plunger would result in an abnormally high rebound number; conversely, the presence of a void in a similar position would lead to a low result. It must be also remembered that the rebound hammer test measures the properties of only the surface zone of concrete, the depth of this zone is about 30mm. In case of tested cement composites these limitations of rebound hammer method are not very important because of the specific character of the fine aggregate cement matrix. There are no large aggregate grains which could influence the hammer reading when located under the plunger or a void of relatively large diameter. Curves describing wet and moist composites are nearly parallel with average difference in strength prediction (for the same rebound number) is approximately equal to 3.5MPa. Dry composites are described by slightly different fitted function what results in difference in strength prediction equal to 3MPa for low strength composites (10MPa-12MPa). Further on readings are getting closer and closer to the moist composites characteristics. In case of composites characterized by compressive strength equal to 35MPa, the rebound number of dry and moist characteristics predicts the same compressive strength.

Relationships between the measured ultrasonic pulse velocity and the corresponding rebound number for the tested specimens are presented in the Figure 6. The best fitting was achieved by linear formulae. Equations (10), (11) and (12) describe fitted functions. The general trend for the velocity to increase with the increase in rebound number is noticed in case of all three saturation states. The 95% prediction intervals are equal to $V_{dry} \pm 0.30$ km/s, $V_{moist} \pm 0.15$ km/s and $V_{wet} \pm 0.13$ km/s. The prediction interval is significantly wider in case of dry specimens than prediction interval of moist and wet specimens.

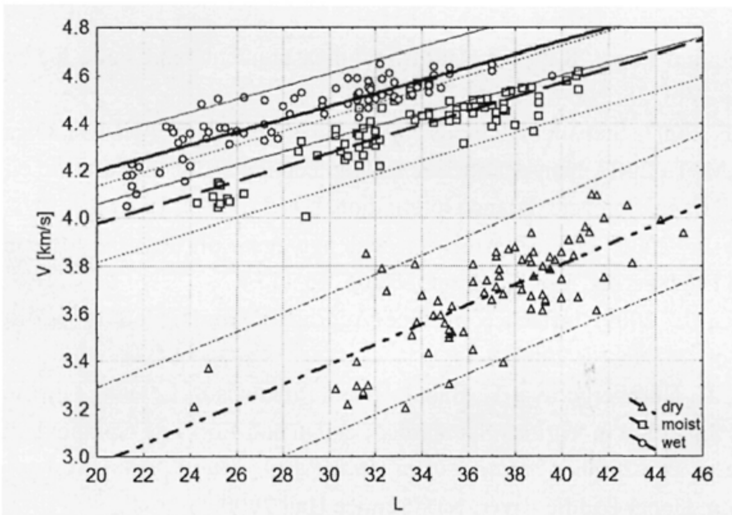

Fig. 6: Rebound number versus ultrasonic pulse velocity.

$$V_{dry} = 2.1279 + 0.0419L \qquad R^2 = 0.5650 \tag{10}$$

$$V_{moist} = 3.3808 + 0.0297L \qquad R^2 = 0.7388 \tag{11}$$

$$V_{wet} = 3.6529 + 0.0273L \qquad R^2 = 0.7687 \tag{12}$$

Similar relationship for concretes produced in Middle East countries was presented by Qasrawi (2000) and described by following equation:

$$V = 3.166 + 0.0329L \qquad R^2 = 0.7358 \qquad (13)$$

The 95% prediction interval achieved by Qasrawi (2000) was equal approximately to V ± 0.25 km/s and tested specimens were in moist/wet state.

CONCLUSIONS

Real cement composite structures in Central Europe due to moderate climate, which can be classified as *Dfb* according to the Köppen climate classification (McKnight et al. 2000) are usually in moist or wet saturation state. This means that tests conducted in-situ would assess WFA cement composite compressive strength with the help of "moist" or "wet" characteristics. These characteristics are more precise and reliable. Combined characteristics of rebound number versus ultrasonic pulse velocity presented in the Figure 6 allow using both non-destructive methods together and reduce the errors created by using one method alone to evaluate WFA cement composites.

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