Proceedings of the 7th Asian Symposium on Polymers in Concrete, Publisher Istanbul Tech. University
Ed. M.H. ÖZKUL, M.N. ATAHAN, U.A. DOGAN, B.Y. PEKMECZI, O. SENGUL ISBN 978-975-561-427-9

Fly ash polymer concrete quality assessment using ultrasonic method

Andrzej Garbacz, Joanna Sokołowska
Department of Building Materials Engineering (DBME) at Warsaw University of Technology, Warsaw, Poland
E-Mail(s): a.garbacz@il.pw.edu.pl, j.sokolowska@il.pw.edu.pl

Arkadiusz Lutomirski, Luc Courard

Department of Building Materials Engineering (DBME) at Warsaw University of Technology, Warsaw, Poland
ArGEnCO Department at University of Liege, Liege, Belgium
E-Mail: alumirski@o2.pl, luc.courard@ulg.ac.be

Abstract

Polymer concretes appear as useful materials for manufacturing precast elements as well as for repair and protection of building structures. In both cases, there is a need for quality control and diagnosis during service life as well. Therefore the development of nondestructive assessment methods is an important issue. Ultrasonic methods are among the most common nondestructive techniques used in material science and industry.

The aim of the paper was to analyze the usability of ultrasonic methods for assessing properties of polymer concretes modified with fly ashes. In the paper the effects of substitution of microfiller with fly ash in polyester and vinyl ester concretes on ultrasonic wave propagation are presented. Compositions of tested fly ash polymer concretes were determined using material optimization approach. Propagation of ultrasonic wave was characterized using wave velocity and a frequency spectrum characteristic. As a result, regression functions for ultrasonic evaluation of fly ash polymer concrete are proposed. Those functions can be used to develop reference curves for calibration procedures for this kind of composites.

Keywords: *Sustainable development, Polymer concrete, Nondestructive quality control, Ultrasonic method, Fly ash.*

Introduction

Polymer concretes appear as useful materials for manufacturing precast elements as well as for repair and protection of building structures. In case of pre-cast elements, as well as repair materials, the usefulness and durability of polymer composites depend on the materials selection for obtaining the composite with controllable properties. This task is a material design and optimization issue. In both cases there is a need for quality control (verification tests) and diagnosis procedures during service life as well. Therefore the development of nondestructive assessment methods is an important issue. Ultrasonic methods are among the most common nondestructive techniques used in material science and industry.

The aim of the paper was to analyze the usability of ultrasonic methods for assessing properties of polymer concretes, in particular polymer concretes modified with selected fly ash of fluidized bed combustion (FBC). Composition, microstructure and specimens geometry are considered as the most important factors affecting the ultrasonic wave propagation. In this paper the effect of substitution of microfiller with fly ash in polyester and vinyl ester concretes on ultrasonic wave propagation is discussed.

PC as the Subject of NDT Testing

The use of fly ash, technically the lower quality component in PC technology, required quality control of composite modified in such modified way. The usefulness of ultrasonic methods in non-destructive testing of polymer composites has been demonstrated in the work of Czarnecki, Garbacz, Krystosiak (2006), Garbacz, Garboczi (2003) and Garbacz (2005, 2007), who developed the appropriate scaling curves used for assessment of the quality of PC. They found that one of the most important factors influencing the properties PC (affecting ultrasonic wave propagation) is the volume content of the aggregate and microfiller (Figure 1). In these works it was pointed out that a higher filler content would induce a lower porosity and a higher modulus of elasticity of the composite. Moreover, the ultrasonic wave velocity increased, while the aggregate increase in surface area reduced the wave velocity.

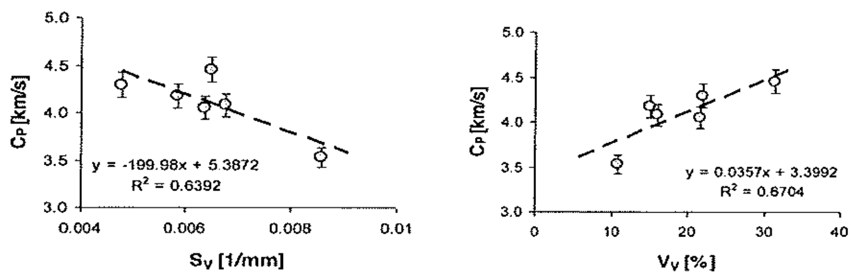

Figure 1. Statistically significant correlations between technical characteristics of PC and stereological parameters of aggregate (left) and microfiller (right); c_p - wave velocity, S_v - surface area of the aggregate; V_v - microfiller volume fraction (Garbacz, 2007)

Tested Materials and Methodology

Substituting quartzite microfiller by fluidized fly ash can significantly affect the propagation of ultrasonic wave in the composite. Two types of concretes were tested: concretes of vinyl ester (VE) and unsaturated orthophthalic polyester (UP) binder. The particular concretes were designed and produced according to the 2nd Degree Box experimental design (15 compositions with additional 5-hold repetition of central point – 20 compositions altogether, the compositions differed with 3 material variables - relative ratios of contents by weight: aggregate/binder, binder/microfiller and fly ash/microfiller). Each composite contained the standard sand as fine aggregate and river gravel of fraction 4/8 mm (washed and dried) as coarse aggregate; the microfiller fraction contained quartzite meal and fluidized fly ash of various proportions. 40 compositions of fly ash polymer concretes were designed and tested (detailed explanation of components selection and designing procedure according to the Box design authors presented in previous publications – e.g. Czarnecki, Garbacz, Sokołowska, 2010, Garbacz, Sokołowska, 2010, Czarnecki, Sokołowska, 2011).

The test was carried out on the halves of standard specimens of dimensions of 40 x 40 x 160 mm remaining after the bending test. Ultrasonic testing has been done by direct method using a digital ultrasonic flaw detector EPOCH4 Parametrics (Figure 2). The signals were recorded using a specialized program EpochData 1.1. To ensure adequate acoustic coupling between the concrete and the transducers as the coupling agent the commercial Parametrics Soundsafe® Couplant G gel was used. The study was conducted with a piezoelectric transducer of 100 kHz frequency. Additionally, signals of the ultrasonic wave passing through the selected specimens of fly ash polymer concrete were recorded using transducers of 500 kHz. The measurement consisted in measuring the velocity of ultrasonic waves passing through the concrete of known thickness. Among other parameters, the influence the degree of substitution of microfiller with fluidized fly ash on the propagation of ultrasonic wave, as well as the relation between PC strength and speed characteristics of ultrasonic wave, were analyzed.

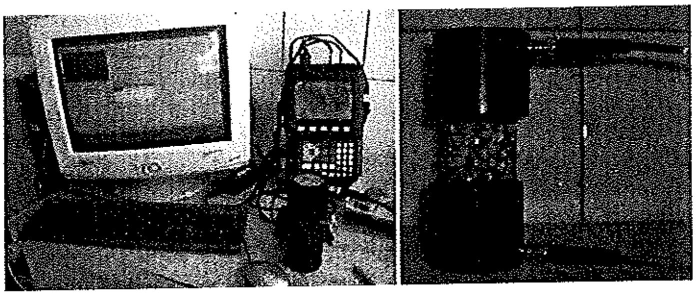

Figure 2. Testing equipment for ultrasonic waves propagation in fly ash PC

Ultrasonic Tests Results

The study included the determination of transit time of ultrasonic wave through the specimen of fly ash polymer concrete of known thickness (40 mm) and then the calculation of the wave velocity in accordance with EN 12504-4. Results were obtained for 120 polyester concrete specimens and 120 vinyl ester concrete specimens. Table 1 summarizes the average results of six ultrasonic wave velocity measurements for each composition. Wave velocity is varying with regard to the content of fly ash in microfiller, FA/M (relative contents by weight) and the aggregate/binder ratio, A/B (relative contents by weight). The lowest value - 1105.28 m/s - was obtained for vinyl ester concrete of composition No 6 (see Table 1) and the highest - 4249.28 m/s - for polyester concrete No 13. In most cases, relatively high repeatability of results was obtained – the coefficient of variance CV < 10%; however, much higher CV values were obtained in case of low-strength concretes characterized by high ash content.

Table 1. Average values of ultrasonic wave velocity (c_p), standard deviation (SD) and coefficient of variance (CV) of polyester and vinyl ester fly ash concretes (compositions adequate to points of statistical Box design)

No	FA/M [-]	A/B [-]	Polyester Fly Ash Concrete			Vinyl Ester Fly Ash Concrete		
			c_p [m/s]	SD [m/s]	CV [-]	c_p [m/s]	SD [m/s]	CV [-]
1	0.210	6.050	3963.27	237.64	0.060	3618.95	343.32	0.095
2	0.210	8.950	4158.38	197.47	0.047	3409.10	146.16	0.043
3	0.210	6.050	3958.27	169.57	0.043	3382.28	178.87	0.053
4	0.790	6.050	2658.25	968.68	0.364	1298.78	253.78	0.195
5	0.210	8.950	4125.57	149.11	0.036	3697.90	37.79	0.01
6	0.790	8.950	1646.92	135.41	0.082	1105.28	192.23	0.174
7	0.790	6.050	3819.88	363.12	0.095	3406.55	142.71	0.042
8	0.790	8.950	3256.02	291.82	0.090	2823.45	121.57	0.043
9	0.500	5.075	3847.93	199.56	0.052	3351.60	176.64	0.053
10	0.500	9.925	3356.47	248.17	0.074	3437.38	79.93	0.023
11	0.500	7.500	2881.28	196.72	0.068	2937.27	96.24	0.033
12	0.500	7.500	4071.57	187.67	0.046	3395.15	243.62	0.072
13	0.015	7.500	4249.28	256.26	0.060	3642.78	139.69	0.038
14	0.985	7.500	2926.60	764.37	0.261	1270.73	227.39	0.179
15	0.500	7.500	3910.35	177.86	0.045	3460.32	215.21	0.062
16	0.500	7.500	3911.22	303.59	0.078	3166.40	81.05	0.026
17	0.500	7.500	3783.45	263.24	0.070	3384.70	188.62	0.056
18	0.500	7.500	3760.45	302.14	0.080	3383.42	224.95	0.066
19	0.500	7.500	3971.02	206.49	0.052	3457.17	175.19	0.051
20	0.500	7.500	3522.75	199.17	0.057	3426.67	239.53	0.07

In total, 240 values of velocity, average frequency and bandwidth of polymer concretes of different fly ash contents were recorded using 500 kHz transducers. As shown in Figure 3 for the polymer concretes and up to 50% fly ash content, the signal is characterized by a relatively large amplitude and repeatability. Figure 4 shows that ultrasonic wave signal recorded for high fly ash content (79% substitution) concretes are characterized by low amplitude, providing a strong attenuation of the wave.

Based on the results of ultrasonic testing (Table 1), the impact of fly ash content in microfiller, FA/M, and the impact of A/B on wave velocity was observed. Particularly low values of velocity were obtained for compositions No 4 (A/B = 6.05, FA/M = 0.79) and 14 (A/B = 7.5, FA/M = 0.985) which were also characterized by low mechanical strength (Czarnecki, Garbacz, Sokolowska, 2010, Garbacz, Sokołowska, 2010). Figure 5 presents the velocity as a function of c_p values, A/B and FA/M. It is noticeable that when A/B is low and the FA/M increases, the ultrasonic wave velocity also increases.

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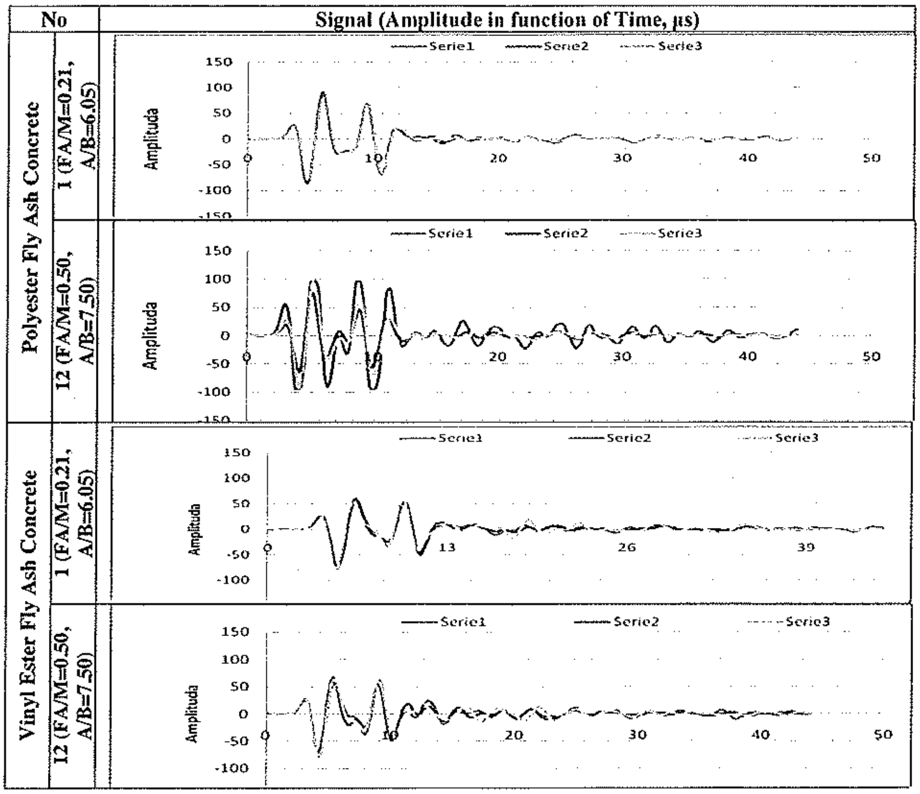


Figure 3. Signals of the ultrasonic wave revorded for polyester and vinyl ester concretes compositions of 21% and 50% fly ash content respectively (head 500kHz)

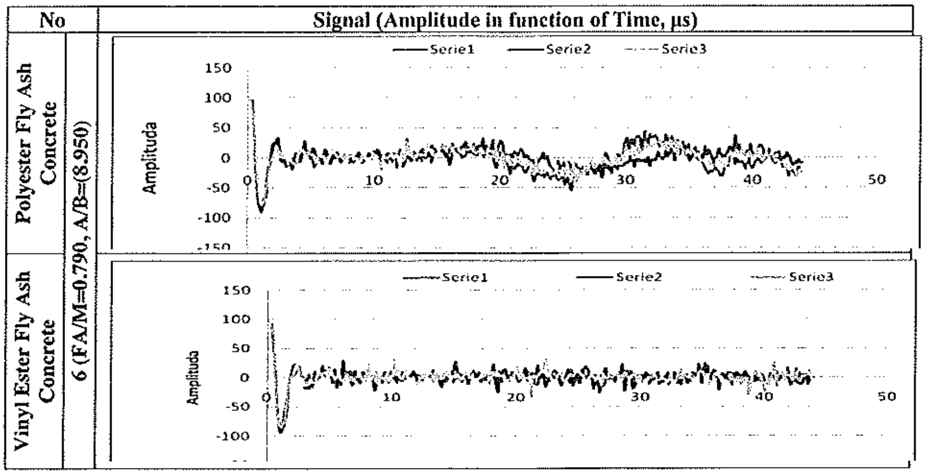
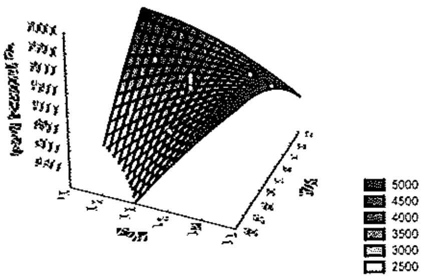


Figure 4. Signals of the ultrasonic wave revorded for polyester and vinyl ester concretes compositions of 79% fly ash content (head 500kHz)

Table 2 presents the regression functions of the velocity of ultrasonic wave versus A/B and FA/M relative ratios for polyester and vinyl ester fly ash concretes. The relations between A/B and the velocity of ultrasonic wave c_p [km/s] for polyester and vinyl ester concretes are describe by the functions of a similar type but a low correlation coefficient ($R \leq 0.37$). In contrast, the regression functions describing the relationship between FA/M and the velocity of ultrasonic waves are giving higher correlation coefficients, particularly for vinyl ester concrete $R > 0.64$.
1



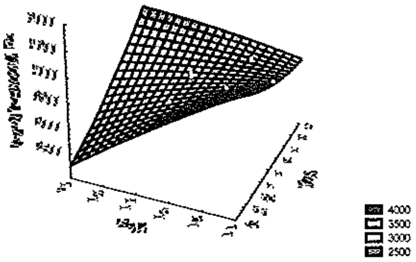


Figure 5. Ultrasonic wave velocity (c_p) in function of A/B and FA/M detected with head of 100 kHz: polyester fly ash concrete (left) and vinyl ester fly ash concrete (right)

Table 2. Regression function of the velocity of ultrasonic wave depending on the A/B and FA/M relative ratios of polyester and vinyl ester fly ash concretes

Variable	Velocity of ultrasonic wave (regression function)	Correlation coefficient, R
Polyester Fly Ash Concrete		
x = A/B	$c_p = -39.7\,x^2 + 429.3\,x + 2763.4$	0.36
x = FA/M	$c_p = -0.21\,x^2 + 0.97\,x + 4168.9$	0.64
Vinyl Ester Fly Ash Concrete		
x = A/B	$c_p = -21.8\,x^2 + 153.8\,x + 3330.3$	0.37
x = FA/M	$c_p = -0.41\,x^2 + 17.44\,x + 3452.1$	0.81

Discussion of Results

Figure 6 presents the regression functions describing the relation between wave velocity and flexural strength, compressive strength and tensile strength of polymer fly ash concretes (results of earlier mechanical tests were used for calculation – Czarnecki, Garbacz, Sokołowska, 2010 and Garbacz, Sokołowska, 2010). Regression functions are statistically significant as correlation coefficient is not lower than 0.89.

During ultrasonic testing, it was observed that some specimens yield irregular low-amplitude signals. That's probably due to the composition of those polymer concretes, characterized with high content of ash in microfiller – over 79% and insufficient homogenization of polymer concrete mix. These specimens considerably differed from the observed trend. For this reason, the relation between the ultrasonic wave velocity and mechanical properties does not include the results of concretes of the compositions refered with numbers 4, 14 (according to the adopted Box design – see Tab. 1) in case of polyester concrete, and 4, 6 and 14 for vinyl ester concrete. It can be concluded that the fly ash polymer concrete quality should be evaluated not only on the base of velocity of ultrasonic waves but also on the ultrasonic wave signal analysis (including uniformity and amplitude). Registration of low-amplitude signal in case of polymer concretes with lower contents of fly ash may be evidence of heterogeneity in the distribution of fly ash.

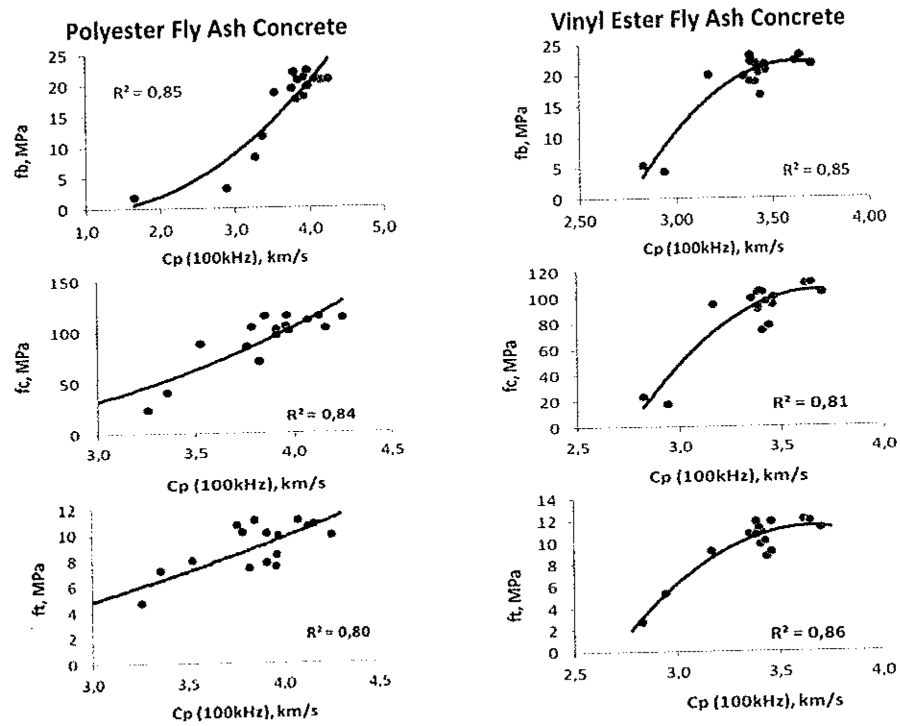


Figure 6. Ultrasonic wave velocity in function of: flexural strength (f_b), compressive strength (f_c) and tensile strength (f_t) of tested polyester (left) and vinyl ester (right) fly ash concretes

Table 3. Ultrasonic wave velocity in function of: flexural strength (f_b), compressive strength (f_c) and tensile strength (f_t) of polyester and vinyl ester fly ash concretes

No	Relation	Regression funcion for c_p	Correlation coefficient, R
		Polyester Fly Ash Concrete	
1	$f_b = f(c_P)$	$f_b = 2.32\ c_P^2 - 4.69\ c_P + 2.11$	0.92
2	$f_c = f(c_P)$	$f_c = 21.91\ c_P^2 - 81.17\ c_P + 78.32$	0.92
3	$f_t = f(c_P)$	$f_t = 0.63\ c_P^2 + 0.48\ c_P - 2.3$	0.89
		Vinzl Ester Fly Ash Concrete	
1	$f_b = f(c_P)$	$f_b = -30.23\ c_P^2 + 218.23\ c_P - 371.7$	0.92
2	$f_c = f(c_P)$	$f_c = -120.4\ c_P^2 + 888.87\ c_P - 1531.7$	0.90
3	$f_t = f(c_P)$	$f_t = -12.06\ c_P^2 + 88.19\ c_P - 149.8$	0.93

Table 3 (above) lists the set of regression functions. The relation between flexural strength of polyester concrete and ultrasonic wave velocity offers the best correlation ($R = 0.92$). The same relation for vinyl ester concrete is described by different regression function (although the same correlation coefficient $R > 0.92$). In case of relation between wave velocity and compressive strength, higher correlation (R = 0.92) was obtained for the polyester concrete. In the case of relation between wave velocity and the tensile strength, similar high correlation (R = 0.93) was obtained for vinyl ester concrete.

Conclusions

On the basis of the obtained results, the following conclusions concerning ultrasonic assessment of fly ash polymer concrete may be formulated: the regression functions justify the possibility of applying ultrasonic methods for nondestructive evaluation of properties of fly ash polyester and vinyl ester concretes; in engineering practice, a reference curve should be made for the given type of polymer concrete, taking into account the type of resin binder and the type of aggregate; when developing the reference curve for calibration procedures one has to take into account the following parameters: the aggregate to resin binder ratio, the sand fraction, in a limited range, the microfiller content and, if necessary, the aggregate moisture content; the material optimization approach gives the possibility for developing a reference curve for a given polymer concrete type with high accuracy and uniform distribution of data points in the tested range of mechanical properties and pulse velocity.

Acknowledgements This paper has been realized in the framework of the Warsaw University of Technology grant: 504 P 1088 1207. This research was financially supported by the cooperation project (2011-2012) "Non destructive methods for the quality control of eco-materials used in repair works" between the Government of Poland and the Regional Government of Wallonia (Wallonia-Brussels International), Belgium.

References

Czarnecki L., Garbacz A., Krystosiak M. (2006) On the ultrasonic assessment of adhesion between polymer coating and concrete substrate, *Cement Concrete Composites*, 28, 2006, s. 360-369.

Czarnecki L., Garbacz A., Sokołowska J. (2010) Fly Ash Polymer Concretes, *Proc. of Second International Conference on Sustainable Construction Materials And Technologies*, Ancona, Italy, p. 127-137.

Czarnecki L., Sokołowska J. (2011) Optimization of polymer-cement coating composition using material model, *Key Engineering Materials*, 466, 191-199.

Garbacz A. (2007) Non-destructive investigations of polymer-concrete composites with stress waves – repair efficiency evaluation, *Zeszyty Naukowe, Budownictwo z. nr 147*, Oficyna Wydawnicza Politechniki Warszawskiej [in Polish].

Garbacz A. (2005) Application of ultrasonic methods for assessment of polymer concrete properties in tanks for chemically aggressive liquid, *CD Proc. of 34 National Conference on Nondestructive testing* [in Polish].

Garbacz A., Garboczi E.J. (2003) Ultrasonic evaluation methods applicable to polymer concrete composites, *NIST Report nr NISTIR 6975*, National Institute of Standards and Technology, Gaithersburg.

Garbacz, Sokołowska (2010) Effect of calcium Ely Ash on PC properties, *Proc. of 13th International Congress on Polymers in Concrete*, ICPIC 2010, Funchal-Madeira, p. 281-288.