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Ultra-high performance concrete – properties and technology

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Abstract. The paper deals with information concerning properties and technology of a new generation cementitious composite i.e. Ultra-High Performance Concrete. High performance here means both high strength and high durability under the influence of environmental factors. This group of composites is mainly represented by Reactive Powder Concretes (RPC), which show both outstanding durability and mechanical properties. Characteristic features of RPC are mainly due to the very low water-cement ratio, which involves application of superplasticizer, significant reduction of aggregate grains size as well as hydrothermal treatment. In the first part of the paper selected properties of RPC are compared to ordinary concrete and to other groups of new generation concrete. Moreover, fundamental technological factors influencing properties of RPC are described as well. The second part deals with the RPC developed at Cracow University of Technology. The presented test results are mainly focused on the influence of steel fibres content on mechanical properties of reactive powder concrete and hydrothermal treatment on composites microstructure. The quantitative and qualitative evaluation of this relationship expand the knowledge of the UHPC technology. Finally, the third part presents the most significant and newest structures which have been erected with the use of RPC.

Key words: Ultra-High Performance Concrete, Reactive Powder Concrete, technology, mechanical properties, microstructure, steaming, autoclaving, steel fibres.

1. Introduction

One of the most advanced cementitious composites is the reactive powder concrete (RPC), belonging to a group of UHPC (Ultra High Performance Concrete). This material is often classified as so called low-temperature ceramics. The production of such composites has been made possible, first and foremost, thanks to the progress in mineral binder technology, increased availability of highly effective superplasticizers and wide recognition of influence of mineral additives on the microstructure and general properties of cementitious composites.

The compressive strength of this multi-component material ranges from 150 to 300 MPa, depending on the composition and curing conditions. According to Czarnecki [1], its place in a series of cement-based composites is illustrated by the following diagram (see Fig. 1).

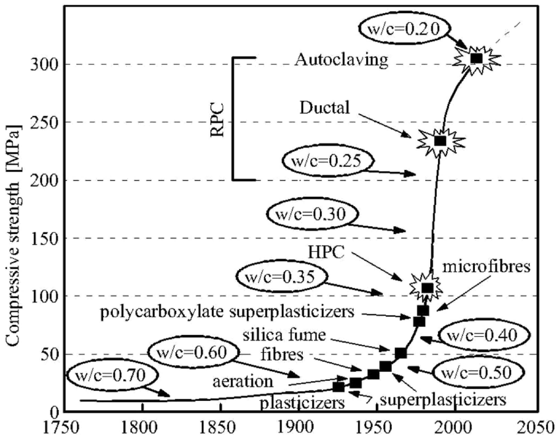

Fig. 1. Generalized curve of concrete development

A general description of RPC, which can be also treated as a universal definition of this material, was proposed by Collepardi [2]. According to this author, RPC is characterized by very low w/c ratio, contains dispersed reinforcement, superplasticizer and a high volume of silica fume. Moreover, the coarse aggregate is replaced with quartz sand with maximum grain diameter less than 500 μm.

2. Basic information on RPC technology

In simple terms one can say that the group of RPC materials are the result of successive reduction or elimination of disadvantages of traditional concrete. The validity of this approach to RPC, apart from the similarity of the basic ingredients (cement, aggregate, water), may be shown by the picture (Fig. 2). The image presents a comparison of ordinary concrete macrostructure and RPC microstructure.

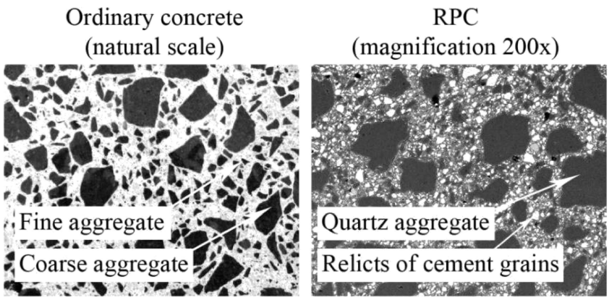

Fig. 2. Comparison of ordinary concrete macrostructure (a) and RPC microstructure (b)

The technological factors listed and described below allow obtaining very high strength and durability of RPC compos-

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ites. The following could be recognized the most important issues:

1. minimization of composite porosity by:
    - application of granular components with suitable grain size distribution, providing the maximum packing density,
    - reduction of water to binder ratio, which obviously involves addition of highly effective superplasticizers,
    - optional application of the vacuum process or press moulding of the RPC mixture in the initial stage of binder setting,
2. modification of the matrix microstructure by application of an appropriate heat treatment, which brings about the increase in mechanical properties,
3. increasing the physical homogeneity of material by incorporation of a filler (aggregate) with very fine grains.

Minimization of porosity. One of the primary factors in the RPC porosity reduction is obtaining the maximum possible packing density of the granular components. According to Fuller and Thompson [3], the best packing density for aggregate in conventional concrete is obtained when the cumulative grain size distribution is similar to the curve expressed with the equation:

$$y = \left(\frac{D_i^n}{D_{\text{Max}}^n}\right) \cdot 100\%,$$

where y_i – cumulative % of the i-th fraction, D_i – diameter of the i-th fraction [mm], D_{Max} – diameter of the maximum grain [mm], n – a constant equal to 0.5.

However, the research program presented in Chapter 4, was based on the grain size distribution given by Funk [4], who adapted the Fuller's curve to composites with any minimum and maximum grains size. This equation has the following form:

$$y = \left(\frac{D_i^n - D_{\text{Min}}^n}{D_{\text{Max}}^n - D_{\text{Min}}^n}\right) \cdot 100\%$$

where y_i –cumulative % of the i-th fraction, D_i – diameter of the i-th fraction [μm], D_{Max} – diameter of the maximum grain [μm], D_{Min} – diameter of the minimum grain [μm], n – a constant equal to 0.37.

However, another important factor influencing the reduction of porosity is the decrease in water-binder ratio. This is possible due to application of new generation superplasticizers, which enables, in comparison to ordinary concrete, significant reduction of the amount of mixing water in RPC. The average value of water to binder ratio can be reduced to about 0.20 or even lower. Such a small amount of water, especially at higher temperatures, is completely used up in the reaction with cement during setting. This limits the possibility of formation of capillary pores which is the result of the evaporation of the excess unreacted water.

Another way to reduce the porosity is the removal of air from a mixture of RPC by subjecting it to compression. According to Richard [5], this method significantly reduces the porosity of the hardened material and also allows the removal of excess water from the sample. Moreover, long time pressing (24 hours) causes the stress compensation resulting from contraction.

Modification of the matrix microstructure. Setting of reactive powder concrete in the environment of water vapour and at elevated temperature, as in the case of traditional cementitious materials, brings about changes in its microstructure. In most reported studies two types of hydrothermal treatment are used. In the first one, low pressure steam curing at about 90°C, accelerates the processes of cement hydration and enhances the pozzolanic activity of the other ingredients. Elevated temperature causes increase in SiO_2 solubility, regardless of its form (amorphous – silica fume or crystalline – ground quartz). The positive effect of this treatment is related to the appearance of additional quantities of C-S-H phase, which directly entails reduction of the composite porosity. Moreover, according to Staquet [6], the rise of temperature during cement hydration is beneficial from the standpoint of the shrinkage reduction, especially if it contains a huge amount of binder.

The second type of heat treatment applied to RPC materials is autoclaving process, which is often conducted at 250°C. These conditions, in addition to the changes also taking place at lower temperatures, cause the appearance of crystalline forms of hydrated calcium silicates. The phases which are usually encountered in materials subjected to such treatment, are tobermorite $C_5S_6H_5$ and xonotlite C_6S_6H. There are some contradictory reports concerning the impact of crystalline phases on the mechanical properties of the material. However, some researchers observe a clear increase in both compressive and tensile strengths [5]. Moreover, the crystallization of calcium silicate hydrates in the free spaces of the material (pores and microcracks) reduce the porosity and thereby heal its structure [7].

Inappropriate conduction of steam curing and autoclaving can lead to decrease of the mechanical properties and durability of the composite. The following should be listed among the adverse phenomena that can be ascribed to heat treatment of cementitious materials: formation of microcracks as a result of improperly chosen initial period of setting, delayed ettringite formation, and decreased specific surface area of hydrated calcium silicates, leading to a deterioration in their adhesion to the inclusion.

Extensive research completed by the author concerning the impact of initial curing conditions on the mechanical properties of matured RPC composites allowed establishing the best parameters both for low-pressure steam curing and for autoclaving. The research was focused on: the time of initial setting as well as the temperature and time of isothermal heating. The test results showed that the best mechanical properties of the steam cured materials were obtained when the initial setting period lasted for 6 hours and the temperature was 90°C. The influence of time of isothermal heating, verified in temperatures ranging from12 to 48 hours, was negligible from the standpoint of mechanical properties. In the case of autoclaving the best temperature for isothermal heating was 250°C.

Both the initial setting time, studied within the range 0 to 24h, and time of isothermal heating (12 to 48 h) were the factors which did not bring about significant changes in mechanical properties of the material. According to the author's test results the best curves for hydrothermal treatment, in terms of manufacturing technology and the subsequent mechanical properties of RPC composites, are shown in Fig. 3.

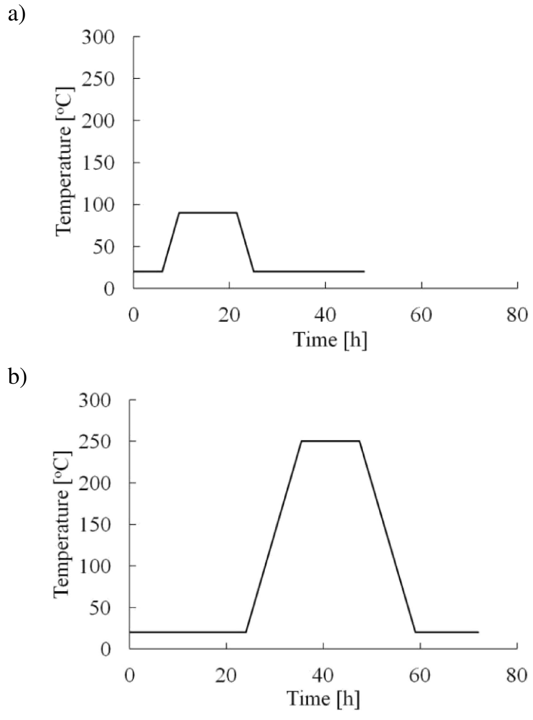

Fig. 3. Optimal curves for a) steam curing and b) autoclaving of reactive powder concretes

Increasing the homogeneity of the material. Among other things, designing the composition of the RPC consists in reducing the size of the maximum grain. Definitely the most common ingredients of micro-aggregate are quartz sand, whose maximum grain size does not exceed 600 μm, and quartz powder with grain size distribution similar to cement [8–10]. This results in obtaining high homogeneity of the composite, which is directly reflected in the actual distribution of stress in the transition zone between cement paste and aggregate in the loaded material. Besides the reduction of the inclusion size, there is also incorporated a large amount of binder, which causes increase of distance between grains of the aggregate. The diagram of the actual stress distribution in the granular composite depending on the grain size of aggregates and their distance is shown in Fig. 4 [11].

It should be added that in the case of RPC composites, the role of aggregate and binder is not clear. In conventional concretes each component plays its characteristic role, e.g. a filler or a matrix. A finer part of RPC's aggregate due to its reactivity plays the role of an active ingredient of the matrix. Moreover, cement, which so far had been treated only as a binder, due to the very small amount of mixing water in the mixture, leaves a significant number of unhydrated relicts of its grains in the hardened material. These grains play the role of inclusion with excellent physical characteristics. In addition, matrix adhesion, (i.e. the C-S-H phase) to the cement grains is very good (see Fig. 12).

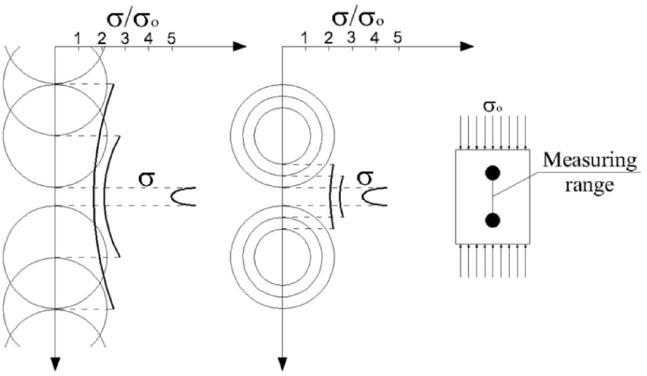

Fig. 4. State of stress in hardened cement paste between two grains of aggregate

Volumetric proportions of the binder and aggregate as well as grains sizes of RPC, related to ordinary concretes are shown in Fig. 5.

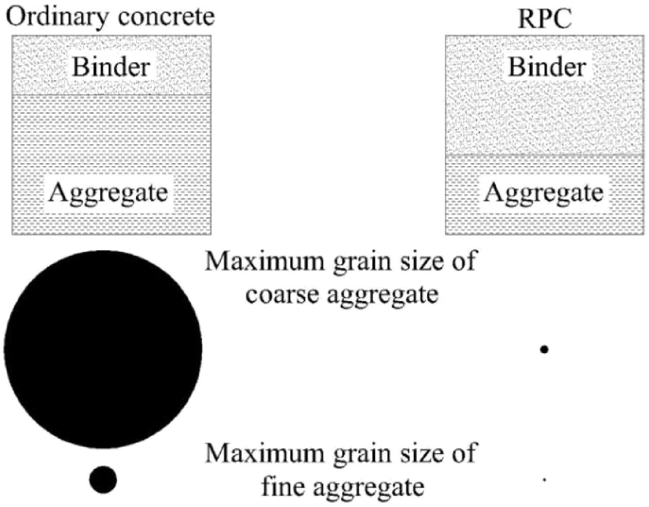

Fig. 5. Comparison of the composition and grains sizes in ordinary concrete and in RPC

All aforementioned issues, such as incorporation of fine and reactive aggregate, changes of microstructure by hydrothermal treatment and incorporation of silica fume, indicate that RPC should be treated as a nano-composite. This is consistent with the graph presented in [1] (see Fig. 6). However, it should be emphasized that on the one hand usage of fine components brings about many beneficial changes, on the other hand water demand of concrete mixture is significantly higher. The specific surface of all dry components of RPC is about 40 times higher in comparison to ordinary concrete (see Table 1). This involves the use of highly effective new generation superplasticizers.

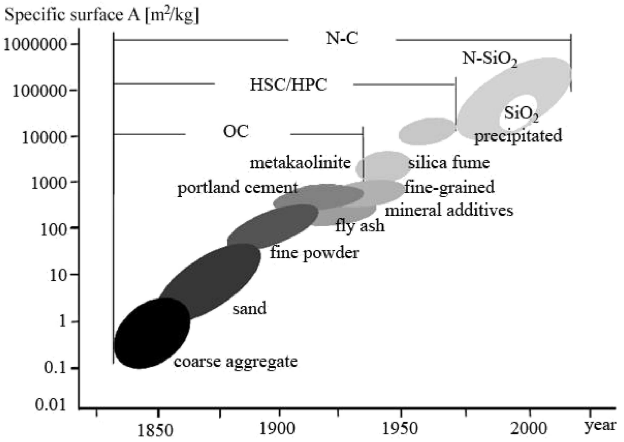

Fig. 6. Change in specific surface of cement-based composites components

Table 1
Comparison of grainy components specific surface in the ordinary concrete and the RPC

Grainy component	Specific surface [m^2/kg]	OC	RPC
		Content [kg/m^3]	Content [kg/m^3]
Cement	30 to 40	300	930
Silica fume	22500	–	180
Ground quartz	800	–	310
Sand	40	650	730
Coarse aggregate	5	1400	–
Total value of grainy components specific surface expressed in [m^2] by 1 m^3 of the composite	–	116	4699

3. Requirements for basic components of the RPC

Obtaining the adequate composition of the RPC composite is a complex problem, which consists not only in determining the relative proportions between the components characterized by different sizes of grains, but also on their appropriate selection in terms of their physical and chemical properties. Currently the author's research is focused on a very precise analysis of selected characteristics of the components and their effect on composite features.

The basic ingredient of RPC composite is cement, which accounts for almost 30% of its volume. So from the standpoint of the rheological properties of the mixture and subsequent mechanical properties of the hardened material, it is very important to make the right decision. One of the basic features of cement is C_3A phase content. In the case of high concentration of C_3A a significant reduction in superplasticizer effectiveness is observed. Moreover, other features, such as alkali concentration, silica modulus and finally specific surface also play an important role in the production of UHPC materials. Various papers on the subject suggest that the best results can be obtained if the cement is characterized by the following contents: $C_3A<4\%$, $Na_2O_e<0.4\%$ and the specific surface, according to Blaine, should be about 3400 cm^2/g [5, 12, 13].

The binder used for production of ultra-high performance concretes is always multi-componential. Actually, all RPC materials contain a large amount of pozzolanic additives, usually silica fume. It modifies the properties of reactive powder concrete in a similar manner as in the case of high performance concretes (HPC). Its primary function, associated with its grains size, is to fill the empty spaces between the much larger grains of cement and aggregate. In order to achieve the maximum packing density of dry ingredients, a much larger fraction of silica fume is used in comparison to HPC (about 20 to 25% of cement weigh). This amount of additive can theoretically react with $Ca(OH)_2$ derived from clinker in the cement. Apart from the quantitative reduction of portlandite in the cement paste, silica fume with its nucleation abilities causes the precipitation of very fine and scattered crystals of calcium hydroxide. This has beneficial effect on durability and mechanical properties of the material. A similar effect of silica fume addition can be observed in the contact zone between cement paste and aggregate. This weakest part of cementitious composite is very beneficially modified by hindrance of precipitation of large and oriented portlandite crystals on the surface of aggregate. Furthermore, addition of silica fume to the concrete cured in natural conditions changes the average C/S ratio in C-S-H phase from about 1.7 to 1.2. In consequence, the phase characterized by a low C/S ratio is close to 1.4 nm tobermorite structure, which limits the progress of corrosion, especially in the presence of alkaline ions such as Na^+ or K^+ [14]. In many publications the requirements for silica fume as a component of RPC were formulated clearly. According to Richard [5], the best results are obtained when the silica fume is characterized by specific surface about 14 m^2/g. This type of silica fume can be obtained as a by-product during manufacture of zirconium oxide. The next important factor ascribed to this pozzolanic additive is the amount of impurities, i.e. the total alkali content and loss on ignition. Generally, the lower concentration of these pollutants, the higher superplasticizer efficiency is observed [13, 15].

The materials used as the micro-aggregate of RPC are quartz sand and quartz powder, characterized by polymorphic modification of β-quartz. These ingredients, recognized as an inert part of RPC, show a significant increase in pozzolanic activity when the particle size is below 5 μm [16, 17]. Due to the often used hydrothermal treatment at temperatures above 100°C, crystalline forms of hydrated calcium silicates are detected. Therefore, the amount of active SiO_2 incorporated by the amorphous silica fume, quartz powder and quartz sand should be such that the C/S ratio in C-S-H phase would vary from 0.83 to 1.0. Hence, if a suitable hydrothermal treatment is completed, crystals of tobermorite and xonotlite can appear, which positively affects the mechanical properties of RPC [5, 18]. In practice, the total amount of micro-aggregate (quartz powder and quartz sand) ranges from 1000 to 1200 kg/m^3, which is 38 to 45% of total volume of the composite. The essential requirements for RPC micro-aggregate are mainly ascribed to its grain size distribution due to the homogenous nature of the composite and its packing density.

4. Characteristics of the RPC composite developed at the Cracow University of Technology

The main aim of this study was to develop a technology of RPC materials characterized by the highest possible mechanical properties, with the assumption that, except for the superplasticizer, only domestic ingredients can be used.

The primary criterion for selection of the cement was the highest actual compressive strength of the binder. The chemical and mineral composition as well as water demand were also taken into consideration. The analysis of available cements and the requirements described in Sec. 3 revealed that the most suitable one would be CEM I 52.5R NA from the cement plant in Rejowiec. Detailed information of its chemical and phase composition is given in Table 2.

Table 2
Chemical and phase composition of CEM I 52.5R NA, Rejowiec

SiO_2	22.98
CaO	65.58
MgO	1.06
Al_2O_3	4.41
Fe_2O_3	2.10
SO_3	3.32
Na_2O_e	0.51
Cl^-	0.009
C_3S	59.09
C_2S	17.97
C_3A	8.12
C_4AF	6.38

From among the available pozzolanic additives, we have selected the silica fume named Silimic from the Silesian plant Łaziska. This additive was obtained as a by-product in the production of iron-silicon alloys and was characterized by the following basic features: the amount of amorphous SiO_2 – 94%, loss on ignition – 0.74%, specific surface 22.4 m^2/g, density – 2.23 g/cm^3.

Micro-aggregate i.e. ground quartz and silica sand were taken from Kopalnia i Zakład Przeróbczy Piasków Szklarskich OSIECZNICA Sp. z o.o. Both ingredients are characterized by polymorphic modification of β-quartz and SiO_2 content over 98.5 %.

4.1. Determining the RPC composition allowing for obtaining maximum compressive strength. The main aim of the adopted research program was to obtain the best possible composition of the RPC material. The program consisted of three stages. In the first one the proportion of quartz powder and quartz sand was determined in order to obtain the maximum grain packing density. For this purpose, the packing of the components of micro-aggregate consisting of a mixture of sand and quartz powder was analyzed. The proportions of ingredients were changing in the range from 0 to 100% with variability of 10%. Particle size distribution of both components is shown in Fig. 7.

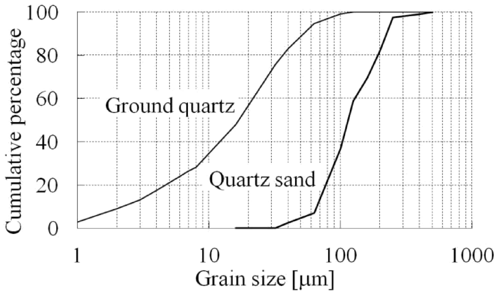

Fig. 7. Grain size distribution of components of RPC micro-aggregate

The test results confirm that the maximum packing density was obtained after mixing sand and silica powder in the proportion of 60/40% by mass. This result was consistent with the calculations resulting from the adjusting the actual grain size distribution to the adopted Funk's curve [4]. However, due to the problem of concrete mixture workability, at the previously established binder to aggregate ratio, ground quartz content was reduced to 30%. Due to this operation, the packing density was not reduced significantly and reached approximately 70%. Moreover, the missing fine fractions were supplemented by grains of cement because of its similar grain size distribution.

In the second stage of the research program the best proportions of binder, consisting of cement, silica fume and water, were found. At the constant volume fractions of micro-aggregate and the binder (40/60%, respectively) and the proportions of quartz powder to quartz sand (30/70%), the impact of the quantity of mixing water and silica fume on mechanical properties of RPC was determined. The samples were cured in three different conditions: water at 20°C, low-pressure steam curing at 90°C and autoclaving at 250°C. The analyzed compositions of the material were different in terms of water to binder ratio (in the range 0.20 to 0.35 with variability of 0.05) and the same time silica fume to cement ratio (in the range 0 to 30% with variability of 10%). The research program established in this manner involved testing of 16 RPC compositions cured in 3 different hydrothermal conditions. Therefore 48 different composites were actually tested.

The most important conclusion drawn from the second stage of the research program was that, regardless of the curing conditions, the best mechanical properties were obtained for the composition characterized by the W/S=0.20 and SF/CEM = 20%. Tables 3 and 4 show the composition of the developed RPC and its basic mechanical properties depending on the applied hydrothermal curing conditions.

Table 3
Composition of the developed RPC with the best mechanical properties

Component	Content [kg/m^3]
Cement	1.00
Silica fume	0.20
Ground quartz	0.34
Quartz sand	0.81
Water	0.24
Superplasticizer	0.02

Table 4
Summary of the basic features of the RPC with the composition as described above

Curing conditions	f_{cm} [MPa]	f_{fm} [MPa]	Density [g/cm^3]
Water at 20°C	194	10.6	2.33
Steam curing at 90°C	212	14.3	2.32
Autoclaving at 250°C	268	18.6	2.30

The final, third stage of the research program consisted in incorporation of steel fibers with a diameter of 0.175mm and length of 6 mm to the previously established RPC mineral matrix. Fibres were characterized by tensile strength 2200MPa and modulus of elasticity 210GPa. The maximum volume fraction of dispersed reinforcement (V_{fmax} = 4% vol.) was defined by obtaining proper workability of concrete mix without changing its composition and the assumption that inclusion is to be homogeneously dispersed in the whole composite. The following fractions of steel fibres were applied: V_f = 0.5; 1.0; 2.0; 3.0 and 4.0 % vol. (i.e. 39, 78, 155, 233 and 310 kg/m^3).

4.2. Mechanical properties of the developed RPC. Strength and deformability at compression. The compressive strength of each material, in both stages II and III, was obtained by testing 12 cubes (40×40×40 mm^3). The specimens were cut from beams with dimensions 40×40×160 mm^3. The cross section of all samples confirmed quasi-homogeneous fibres dispersion. Figure 8 presents average values of compressive strengths with linear regression. In the case of curing in water (W), specimens were examined after 28 days of setting. Steam cured (S) and autoclaved (A) specimens were tested after heat treatment was completed and the specimens were cooled down.

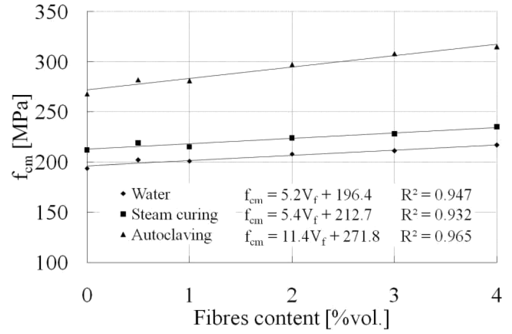

Fig. 8. Influence of fibres content on compressive strength of RPC, cured in three different conditions

Deformability of each composite was determined on three cylindrical specimens with dimensions 50x100mm. Six electric resistance wire strain gauges with the length of measurement equal to 15mm were stuck on the specimens. Three of them were placed in order to measure transverse deformation ε_x and the other three for longitudinal deformation ε_y. Modulus of elasticity was determined in compliance with the procedure characterized in PN-EN 14580.

The test of deformability during compression was developed for the following materials: without steel fibres addition and cured in water (W), steam-cured (S), autoclaved (A) and a composite with the maximum amount of fibres (4% vol.) cured in autoclave (ASt). The aforementioned choice of composites was made in order to obtain information on the influence of curing conditions and presence of steel fibres on RPC deformability. The test results (i.e. relationship between stress and strain, Poisson's ratio as well as modulus of elasticity) are presented in Fig. 9 and in Table 5.

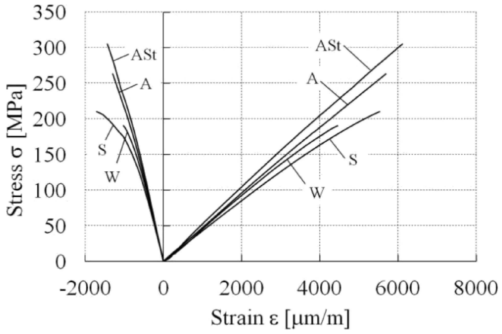

Fig. 9. Relationship between stress and strain in dfferent types of RPCs

Table 5
Average values of modulus of elasticity and Poisson ratio for selected RPC variants

Composite	Modulus of elasticity [GPa]	Poisson ratio [–]
Without fibres – water 20°C (W)	47	0.20
Without fibres – steam-curing 90°C (S)	44	
Without fibres – autoclaving 250°C (A)	50	
Steel fibres V_f = 4% vol. – autoclaving 250°C (ASt)	50	

The higher the fibres fraction, the more the compressive strength increases, but the progression is rather slight. In the case of materials containing 4% of fibres, cured in water and steam cured, the compressive strength increased by about 10% in relation to materials without fibres. The higher progression, about 20%, can be observed when materials were subjected to autoclaving. The highest value, 315 MPa, was obtained after addition of 4% of fibres and autoclaving process.

On the basis of the test results presented in Table 5, it may be concluded that neither curing conditions nor the presence of steel fibres influence the parameters characterizing deformability of RPC during compression. Modulus of elasticity vary from 44 to 50 GPa, which corresponds to the values obtained by Fehling et al. [19], however Poisson ratio remain stable at the level of 0.20. The smallest value of modulus of elasticity was observed in the case of steam–cured composite.

Strength and deformability at bending. The tensile strength at bending in stages II and III was determined by testing 6 prisms (160×40×40 mm^3). A three-point bending test was applied while the distance between supports was equal to 100 mm. Figure 10 includes the average values of tensile strengths at bending with linear regression. Curing conditions were exactly the same as described above in the case of compressive strength.

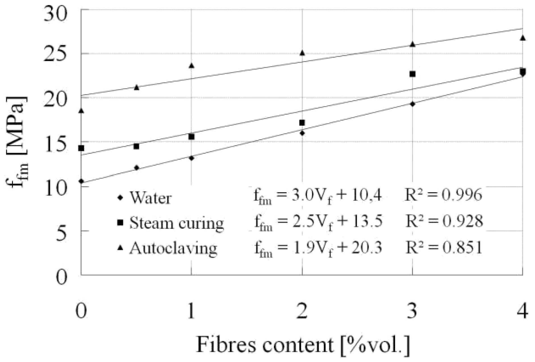

Fig. 10. Influence of fibres content on the tensile strength of RPC cured in three different conditions

Deformability of the specimens was registered during determination of flexural strength. Dimensions of the specimens and the rate of loading were not consistent with ASTM C1018-97. Therefore, the following analysis of the calculated parameters has only comparative character. On the basis of the registered curves, which represent the relationship between force and deflection for all considered curing conditions (see Fig. 11), the following parameters were calculated: flexural strength, work of fracture and toughness indices I_5, I_{10} and I_{20} (see Table 6).

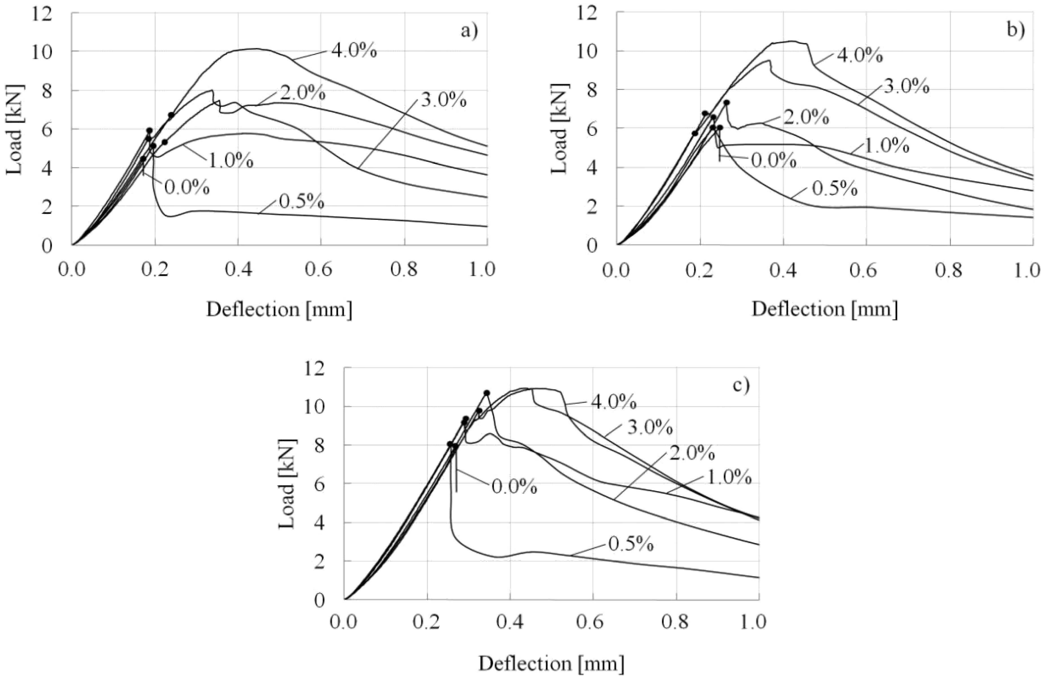

Fig. 11. Representative load-deflection curves registered during bending test of RPC with variable steel fibres content; a) setting in water, b) steam curing, c) autoclaving

Table 6
Average values of toughness indices I_5, I_{10}, I_{20} and work of fracture WF

Curing conditions	Features	Without fibres	Volume fraction of fibres [%]				
			0.5	1.0	2.0	3.0	4.0
W	I_5 [–]	–	3.0	4.9	5.5	6.2	5.6
	I_{10} [–]	–	5.0	8.3	8.8	9.9	7.9
	I_{20} [–]	–	6.9	10.4	10.7	12.5	9.9
	WF [kNmm]	0.3	3.0	6.1	7.4	7.1	10.3
S	I_5 [–]	–	3.0	5.0	5.1	6.6	5.5
	I_{10} [–]	–	4.7	8.0	8.4	10.3	7.7
	I_{20} [–]	–	6.3	10.4	10.5	12.9	9.1
	WF [kNmm]	0.7	3.0	5.9	6.0	8.7	9.2
A	I_5 [–]	–	2.2	2.5	4.1	4.5	6.7
	I_{10} [–]	–	2.7	3.1	6.0	7.4	8.6
	I_{20} [–]	–	2.9	3.4	5.8	7.0	9.3
	WF [kNmm]	0.9	3.4	6.1	9.2	9.4	10.8

The flexural strength of RPC with variable amounts of fibres vary from 12 MPa ($V_f = 0.5\%$ vol. setting in water) to 27 MPa ($V_f = 4.0\%$ vol. autoclaving). The influence of fibres content on the discussed strength is greater than in the case of compressive strength. Higher than double increase of flexural strength was observed for RPC cured in water and containing 4% vol. of fibres. In the case of steam cured and autoclaved materials with the same amount of fibres the increase of flexural strength was equal to 60 and 45%, respectively. Like in the case of compressive strength, the flexural strength for all curing conditions increases in linear rate versus volume fraction of fibres.

Materials that were steamed and cured in water show nearly identical values of fracture toughness indices for the whole range of fibres dosage. The maximum value of indices I_5, I_{10} and I_{20} can be observed in composites containing 3% vol. of fibres. Further increase of fibres volume (V_f = 4% vol.) leads to decrease of all the determined toughness indices. This effect is ascribed to materials steamed and cured in water, while the autoclaved composites do not reveal such tendency. This may be attributed to the increase of strength of mineral matrix [7].

4.3. Microstructure and durability. Positive changes in compressive and flexural strength as well as deformability during bending caused by hydrothermal treatment and steel fibres addition are confirmed by observation of RPC's microstructure. All previously discussed technological and material factors which allow obtaining ultra-high performance concrete are reflected in the microstructure of the studied materials. In the presented pictures, taken with the use of SEM, the following features can be observed:

- adequate grain size distribution of all dry components (Fig. 2b),
- very compacted microstructure of C-S-H phase caused by very low water/cement ratio and using a large amount of silica fume (Figs. 12, 14b and 15b),
- very good adhesion of C-S-H phase to mineral inclusions (grains of grounded quartz and quartz sand) and also to steel fibres, mainly due to appropriately selected parameters of hydrothermal treatment and production of IV type of C-S-H phase, according to the Diamond's division, characterized by highly developed specific surface area, (Figs. 12 and 14),
- filling empty spaces in RPC microstructure caused by crystallization with xonotlite and tobermorite during autoclaving (Fig. 15).

Figure 12 shows the microstructure formation of the composites cured in water and subjected to autoclaving process. Regardless of the curing conditions, very compacted microstructure of C-S-H phase and its excellent adhesion to the grains of cement (light inclusion) as well as to the quartz grains (dark inclusion) can be observed. Moreover, linear EDS analysis of transition zones: steel fibre/C-S-H phase and quartz grain/C-S-H phase, proves that there is no increase of Ca^{2+} concentration (see Fig. 13). Steel fibres with tightly sheathed products of cement hydration are presented in Fig. 14. In addition, all voids of the autoclaved RPC (pores, micro-cracking etc.) are completely or partly filled with crystals of xonotlite and tobermorite (see Fig. 15) [20].

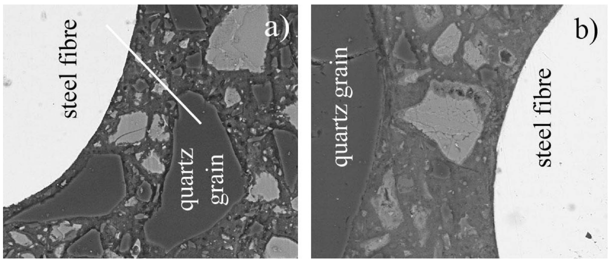

Fig. 12. Transition zone between steel fibre and C-S-H phase as well as quartz grain and C-S-H phase in RPC, a) curing in water, b) autoclaving, magnification 2000x

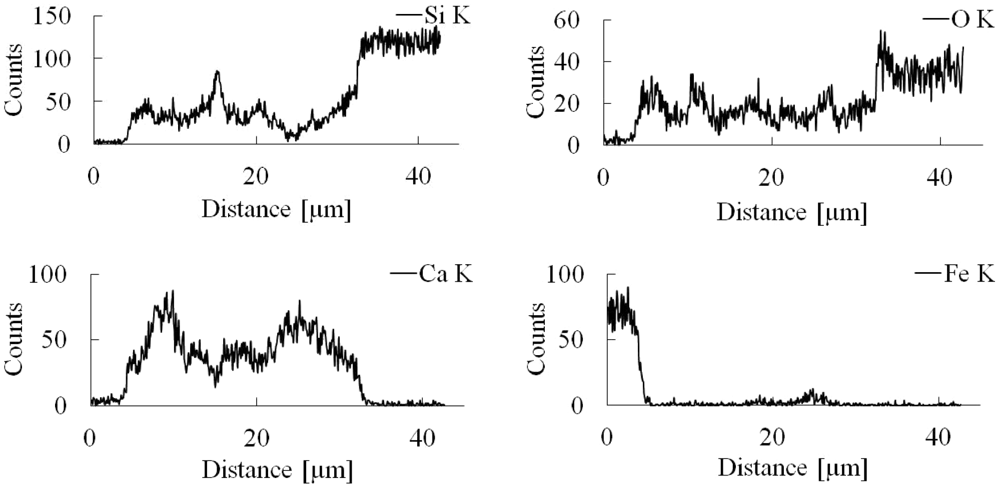

Fig. 13. EDS linear analysis of the area marked in Fig. 12a

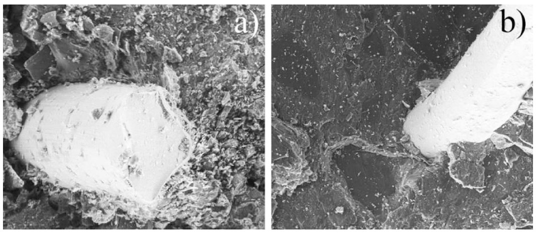

Fig. 14. Steel fibre in RPC, (a) curing in water, (b) autoclaving, magnification 500x

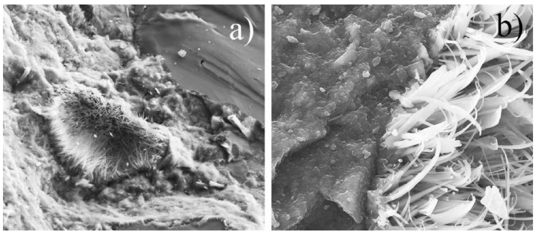

Fig. 15. A micropore partly filled with xonotlite and tobermorite crystals, a) magnification 2 000x, b) magnification 10 000x

An attempt to characterize durability of the tested materials by their water absorption proved that all composites have water tight structure. Regardless of the curing conditions the water absorption was less than 0.5%, which reinforces the belief in the material's high resistance to chemical corrosion. Additionally, analysis of microporosity was done with the use of mercury porosimetry. For this test once again the same material, characterized by the best mechanical properties was selected. Three different curing conditions described above were applied. The test results are shown in Fig. 16.

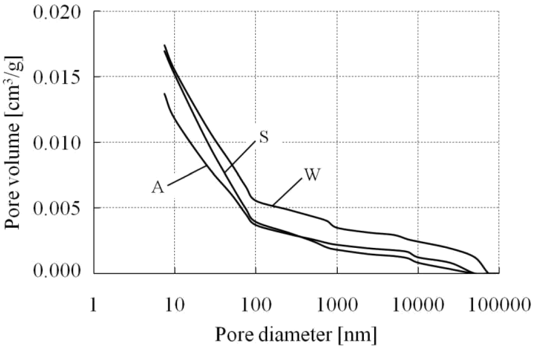

Fig. 16. Effect of different curing conditions on RPC microporosity

During low-pressure steam curing the total porosity of composites does not actually change in relation to the porosity of the RPC cured in water. However, a noticeable reduction of pores above 100 nm can be observed. In steamed concretes, in comparison to the ones cured in water, a trend of increasing number of capillary pores in the range 100 – 3.7 nm was detected. Moreover, it can also be observed that autoclaving causes reduction of porosity in the whole analyzed range. This fact is probably caused by both increased pozzolanic activity of the components and also crystallization of xonotlite and tobermorite in the empty spaces of the composite. Occurrence of these crystals brings about healing of the structure (see Fig. 14). The total porosity of autoclaved material in relation to the one cured in natural conditions was reduced by approximately 20% [18].

The aforementioned test results confirm the high potential of RPC durability. Regardless of the applied curing conditions, total porosity is lower than 0.017 cm^3/g. Assuming RPC's density at 2.3 $\mathrm{g/cm}^3$, one can say that the total porosity is less than 4%.

Therefore two items of evidence weigh in favour of using RPC. The first is the already mentioned potential durability, and the second are significantly elevated mechanical properties which can bring about reduction of the cross-section size of bearing elements and thereby reduction of the structure weight. Moreover, according to Schachinger [21], the RPC materials setting under natural conditions and subjected to steam curing show steady increase in compressive strength, even after eight years.

5. Applications

The first structure that was built using the RPC technology should be considered, a footbridge built in Sherbrooke (Canada) in 1997 [22]. This structure has a span of 60 meters and a width of 3.3 m. It is composed of six precast segments, 10 m long each, and joined together by twelve prestressing tendons. After connecting the precast elements, the bridge construction consisted of positioning the upper and lower beams, connected by a truss. The upper beam is 30 mm thick. The two main beams of the bridge were made of RPC, prepared in a conventional manner and compacted by vibrators. The material was subjected to low-pressure steam curing for 48 hours at 90°C. This procedure allowed obtaining the compressive and flexural strength of 200 and 25 MPa, respectively. The total weight of the structure was about 50 tons, and since it was based on the previously prepared six elements, the erection of the structure took only four days. Figure 17 shows the image and cross-section of the footbridge.

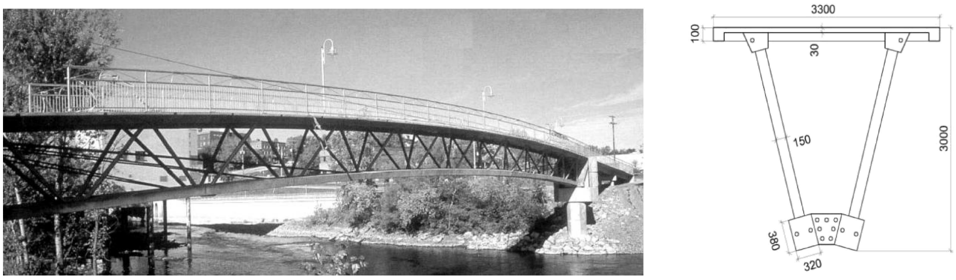

Fig. 17. Pedestrian bridge – the world's first reactive powder concrete structure, erected in 1997 in Sherbrooke, Canada

The newest facility where RPC technology is planned to be applied is the building of the Fondation Louis Vuitton pour la Créationin Paris. The erection is expected to begin in 2012. The project involves building of the object as a steel structure covered with glass. The inner part of the building is going to be made of 16,000 prefabricated panels of RPC, with dimensions of about 1.5 × 0.4 m and a thickness of just 25 mm. It should also be noted that each panel will have a different shape. A novelty introduced by Lafarge company in Ductal technology is going to be the application of vacuum filling of moulds during the manufacture of prefabricated elements. The model of the structure is shown in Fig. 18 [23].

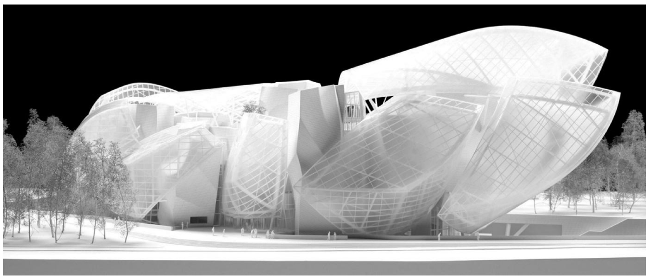

Fig. 18. Visualization of the building of Fondation Louis Vuitton pour la Création in Paris

6. Conclusions

General conclusions. At present reactive powder concrete is one of the most modern technologies of the cement matrix composites. Its development can be attributed to the observed general tendency to interfere into the nanostructure of all materials, including cement-based composites. The application of components with a colloidal particle size (superplasticizer or, silica fume) influence directly the structure and properties of C-S-H phase, which is one of the main factors leading to obtaining such outstanding RPC's mechanical properties.

The presented RPC composite, designed at the Cracow University of Technology, remains an important contribution to the extension of knowledge in the field of building materials in Poland and abroad. It is worth noticing that while the research program was carried out, only Polish ingredients were used, except the superplasticizer. Moreover, the created RPC shows higher mechanical properties than the others reported in the world literature on the subject.

Completing the research program allowed solving and detailed description of such technological issues as:

- the influence of basic parameters of RPCs composition (i.e. water/binder ratio and silica fume content) on the compressive and tensile strengths at bending,
- the influence of hydrothermal treatment on RPC's mechanical properties,
- influence of steel fibres content on RPC's mechanical properties,
- verification of Funk and Dinger optimal grain size distribution in the aspect of its suitability in micro-aggregate used in the RPC technology.

Detailed conclusions. The presented test results are the grounds for drawing more detailed conclusions:

It is possible to receive ultra-high performance concrete using regular ingredients and generally traditional curing conditions. In the case of material without fibres content and cured in natural conditions, its obtained compressive strength is about 200 MPa and flexural strength – 11 MPa. Application of steam curing allows the increase of both strengths up to 212 and 14 MPa, respectively, while autoclaving even to 268 MPa and 18 MPa.

Steel fibres addition allows a further increase of both compressive and flexural strengths. The highest value of compressive strength was 315 MPa and 27 MPa for flexural strength. These parameters were obtained for autoclaved composite, containing 4% vol. (310 kg/m^3) of steel fibres.

Regardless of curing conditions and steel fibres content, the modulus of elasticity and Poisson ratio remain stable and equal 47 GPa and 0.20, respectively.

Regarding the compressive and flexural strengths, the volume fraction of the examined steel fibres ($l = 6$ mm, $\varphi = 0.16$ mm) should not exceed 3%. Further increase of fibres dosage does not bring significant advantages.

Steel fibres content and curing conditions strongly influence deformability of reactive powder concrete in a bending test. In order to obtain optimum ductility of the tested composites, the addition of steel fibres should not exceed 3% of volume.

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