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COMPOSITES THEORY AND PRACTICE

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SURFACE FREE ENERGY OF HIGH PERFORMANCE CONCRETE WITH ADDITION OF POLYPROPYLENE FIBERS

The study of the physical and mechanical properties of high performance concrete with polypropylene fiber was presented in the paper. Its basic characteristics and physical strength were defined, i.e.: absorbability, density, open porosity, compressive strength, splitting tensile strength, flexural tensile strength and modulus of elasticity. The use of polypropylene fibers results in different wetting and adhesion properties of high performance concrete. The wetting properties of the concretes were determined by measuring the contact angle of their surfaces using two measuring liquids: water and glycerin. Measurements were carried out three times: at the time of application of drops after 0, 5 and 40 minutes. On this basis, the total surface free energy (SFE) was determined. The SFE polar and dispersion components were defined using the Owens--Wendt method. By analyzing the examination results, it can be noticed that the contact angle values depend on the type of concrete. The results of contact angle measurements proved that all the glycerine contact angles (θ_g) were higher than the water contact angles (θ_w), and they decreased in the course of time. The highest contact angle was shown for concrete without fibers both at the beginning of the tests and after 40 minutes. The smallest contact angle with water was obtained by the concrete with the smallest addition of fibers. The biggest SFE difference was observed for the lowest fiber content of 0.5%. This is due to the physical characteristics of this concrete. The concrete with the 0.5% addition of fibers is characterized by the highest porosity, absorptivity, and the lowest density among the tested concretes. This indicates increased wettability and increased adhesion properties. Based on the SEM study, the microstructure and distribution of cracks and pores in high performance fiber reinforced concretes were shown.

Keywords: surface free energy (SFE), contact angle, high performance concrete, polypropylene fibers

SWOBODNA ENERGIA POWIERZCHNIOWA BETONU WYSOKOWARTOŚCIOWEGO Z DODATKIEM WŁÓKIEN POLIPROPYLENOWYCH

Przedstawiono badania właściwości fizycznych i mechanicznych betonu wysokowartościowego z włóknem polipropylenowym. Określono jego podstawowe charakterystyki wytrzymałościowe i fizyczne, tj.: nasiąkliwość, gęstość objętościową, porowatość otwartą, wytrzymałości na ściskanie, na rozciąganie przez rozłupywanie, na rozciąganie przy zginaniu oraz moduł sprężystości. Zastosowanie włókien polipropylenowych prowadzi do uzyskania odmiennych właściwości zwilżania oraz właściwości adhezyjnych betonu wysokowartościowego. Właściwości zwilżania betonów określono przez pomiar kąta zwilżania ich powierzchni przy użyciu dwóch cieczy pomiarowych: wody i gliceryny. Pomiary wykonano 3-krotnie: w momencie naniesienia kropli oraz po upływie 5 i 40 minut. Na tej podstawie obliczono całkowitą swobodną energię powierzchniową (SEP). Polarne i dyspersyjne składowe SEP wyznaczono z użyciem metody Owensa-Wendta. Analizując wyniki badań, można zauważyć, że wartości kątów zwilżania zależą od rodzaju betonu. Uzyskane wyniki pomiarów kątów zwilżania wykazały, że we wszystkich przypadkach kąt zwilżania gliceryną (θ_g) jest większy niż w przypadku zwilżania wodą (θ_w) oraz maleje wraz z upływem czasu. Najwyższy kąt zwilżania odnotowano w przypadku betonów bez włókien zarówno na początku badania, jak i po 40 minutach. Najmniejszy kąt zwilżania wodą uzyskał beton z najmniejszym procentowym dodatkiem włókien. Największą różnicę SEP zaobserwowano dla najmniejszej zawartości włókien 0,5%. Związane jest to z parametrami fizycznymi tego betonu. Beton z 0,5% dodatkiem włókien charakteryzował się największą porowatością, nasiąkliwością oraz najmniejszą gęstością spośród badanych betonów. Świadczy to o zwiększonej zwilżalności i większych właściwościach adhezyjnych. Na podstawie badania SEM przedstawiono mikrostrukturę oraz rozkład rys i porów w fibrobetonach wysokowartościowych.

Słowa kluczowe: swobodna energia powierzchniowa (SEP), kąt zwilżania, beton wysokowartościowy, włókna polipropylenowe

INTRODUCTION

High performance concretes (HPC) are construction materials that are increasingly common in the construction industry [1]. Fiber reinforced high performance concrete (FRHPC) is a cementitious material with the addition of fibers with a high cement content and low water/cement ratio. Consequently, the mechanical properties of FRHPC are considerably enhanced compared to those of ordinary concretes [2]. The material is char-

acterized by its high strength, low absorbability, low water permeability and high freeze resistance, which results in high durability [3]. Fibers are added to the matrix as reinforcement to control cracking and to improve general ductility of the material [4]. Some properties of concrete can be improved by polypropylene fibers. Usually, in order to improve mechanical and physical properties, especially tensile and flexural strength and long-term concrete shrinkage, polypropylene fibers are used [5].

High performance concretes are often exposed to aggressive impacts of the environment and therefore they must have a high resistance to chemical corrosion, frost corrosion, the impact of aggressive water and many other corrosive agents. The research on concretes, including their wettability and surface free energy (SFE), are considered to be important elements in assessing adhesion properties. They are particularly useful in analysing the effects of modifying the HPC surface by means of various protective coatings.

According to the reference data [6], the contact angle of materials is an indicator of their wettability properties and resistance to corrosion. The contact angle can be used to determine the surface tension and to define surface free energy and adhesion [7]. High hydrophilicity occurs at a low contact angle < 90°. A very popular method to measure the contact angle is direct measurement using a contact angle analyzer or a goniometer [8].

Surface free energy is an important parameter while evaluating the physicochemical characteristics of solid surfaces. The surface may be of a dispersive (dispersion component) or polar (polar component) nature. Depending on the properties of concrete surfaces, one can have an impact on decreasing or increasing the SFE, and therefore the surface tension of materials, causing their unwettability, which among other things, is related to chemical corrosion and frost resistance. SFE represents the state of imbalance of intermolecular interactions present at the phase boundary of two different agents. There are numerous methods for directly determining the SFE of liquids. Owing to the fact that there are no direct methods for determining the SFE of solids, some indirect methods are used, which include for example, the contact angle measurement method and calculating the SFE on the basis thereon [8]. The main methods for determining the SFE were formulated by Neumann, Wu, Owens and Wendt, Zisman and Fox, Fowkes, Van-Oss-Chaudhury-Good [6, 9]. The Owens-Wendt method is commonly used for determining the SFE of materials [6]. This method consists in determining the SFE dispersion and polar components. The polar component (γ_s^p), which is a measure of surface polarity, is associated with, among other things, the bond strength between the materials.

The analysis of the nature of HPC surfaces with polypropylene fibers in terms of wettability presented in the article allowed us to evaluate the behavior of the material in the presence of water and corrosive compounds. In cases where significant resistance of the concrete surface layer to the impact of a corrosive environment is required, it is desirable to use concretes of the lowest SFE value.

MATERIALS AND TEST PROGRAM

Concrete mixtures

In the laboratory, five concrete mixtures were prepared using: Portland cement (CEM I 52.5 N-HSR/NA) 670.5 kg/m^3, coarse aggregate 2÷16 mm 990 kg/m^3, sand 500 kg/m^3, water 178 l/m^3, microsilica 74.5 kg/m^3, superplasticizer 20 l/m^3 and quantities of polypropylene fibers which varied in percentage. The polypropylene fibers were 12 mm in length and they had a modulus of elasticity of 3.5 GPa. In order to obtain the same workability in all the concrete mixtures, an efficient superplasticizer was used based on polycarboxylate ethers with a density of 1.065 g/cm^3 at 20°C, added in the amount of 1.5% in relation to the weight of cement and microsilica. The admixture met the requirements of superplasticizers specified in EN 934-2. CEM I 52.5 N-HSR/NA tests were conducted in accordance with the Polish standards PN-EN 197-1:2012 and PN-B-19707:2013. Determination of the particle size distribution for basalt and quartz sand aggregate was done according to standard EN 933-1:1997. The abbreviated names of the concretes and quantities of polypropylene fibers for various batches are shown in Table 1.

TABLE 1. **Percentage and weight content of fibers in various concretes**
TABELA 1. **Procentowa i wagowa zawartość włókien w betonach**

Concrete type	Percentage [%] polypropylene fibers	Mass [kg/m^3] polypropylene fibers
C0	-	-
C0.5	0.5	4.5
C1	1.0	9.0
C1.5	1.5	13.5
C2	2.0	18.0

After mixing the components thoroughly, the fibers were added gradually in order to obtain homogeneous and workable mixtures. After placing the concrete in molds, it was compacted on a vibrating table. The cubical and rectangular samples were compacted in one layer, while the cylindrical samples in two layers. Over a period of 24÷72 hours the samples were left in molds and protected against water loss. After removing the samples from the molds, they were taken to tubs filled with water, where they were kept for a period of 14 days. Over the next few days, until the time of test completion - after 28 and 56 days, the samples remained in air-dry conditions.

Concrete properties

Physical properties

Tests of porosity and bulk density were performed in accordance with EN 12390-7: 2001. Three cubic samples of 100x100x100 mm from each batch were used for the study. The wettability test was carried out according to standard PN-88/B-06250 on three 100x100x100 mm cubic specimens from each batch.

Compressive strength and splitting tensile strength

Cubic concrete samples with the following dimensions 100x100x100 mm were used. The research was conducted according to EN 12390-3:2002 normative-compressive strength and EN 12390-6:2001 normative-splitting tensile strength (Fig. 1a). Evaluation of the concrete grade was carried out using a Walter-Baj AG and Controls compression tester within 3 MN after 28 and 56 days of maturation, when the average compressive strength was obtained by the samples.

a)

b)

Fig. 1. Tests of high performance concretes with fibers: a) splitting tensile strength, b) modulus of elasticity

Rys. 1. Badania betonów wysokowartościowych z włóknami: a) rozciąganie przy rozłupywaniu, b) moduł sprężystości

Flexural strength

The test of fiber reinforced concretes was performed on samples with diameters of 50x50x250 mm, while the test of concrete without the addition of fibers was carried out on samples with diameters of 50x63x350 mm. The research was conducted according to EN 12390-5:2009 normative-flexural strength. Testing was performed after 28 days of sample curing. Samples of the first type were loaded with a centrally placed force (3-point bending) and samples of the second type were loaded with a pair of forces (4-point bending).

Modulus of elasticity

Determination of the modulus of elasticity was carried out on three cylinders having a diameter of 150 mm and a height of 300 mm by measuring the deformation of the sample within the stress range from 0.5 MPa to 30% of the concrete compressive strength. The examination was conducted by means of the Walter-Baj AG press and using a modulus measuring device with an extensometer (Fig. 1).

Contact angle and surface free energy

In order to calculate surface free energy, contact angle measurements of the analyzed concretes were conducted. The method of direct measurement of the angle formed by a drop of measuring liquid with the measured surface was used, using a computer program for image analysis. The measurement of the contact angle of the measuring liquid drop was carried out on a research stand consisting of a goniometer integrated with a camera for taking photos of a drop put onto the surface of the sample. The stand construction was described in the [10].

In order to examine the contact angle, two measuring were liquids used - distilled water and glycerine according to the Owens-Wendt model used in analyses. Measuring liquid drops of 2 mm^3 were placed by means of a micropipette [5]. Due to the heterogeneity of the material, six drops were put on each sample. Measurements were carried out three times: at the time of application of the drops after 0, 5 and 40 minutes. The FRHPC surfaces during examining the contact angle of a drop of glycerine and water are shown in Figures 2 and 3.

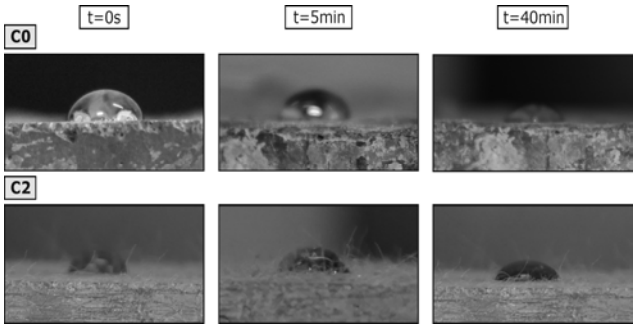

Fig. 2. Concrete surfaces during examining contact angle with drop of glycerine: standard sample C0 and sample C2

Rys. 2. Powierzchnie betonów podczas badania kąta zwilżania kroplą gliceryny: próbka wzorcowa C0 i próbka C2

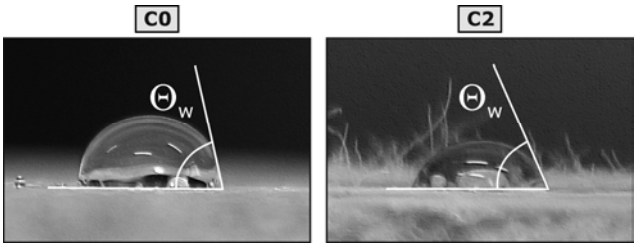

Fig. 3. Measuring contact angle of concrete with water after $t_2 = 5$ minutes: standard sample C0 and sample C2

Rys. 3. Pomiar kąta zwilżania betonu wodą po czasie $t_2 = 5$ minut: próbka wzorcowa C0 i próbka C2

To calculate the wettability of the concrete surface, the measuring liquid SFE values (γ_L), and their dispersion (γ_L^d), and polar components (γ_L^p), were adopted as follows [6]: distilled water - γ_w^d = 21.8 mJ/m^2, γ_w^p = 51.0 mJ/m^2, glycerine - γ_g^d = 21.2 mJ/m^2, γ_g^p = 41.5 mJ/m^2.

In the Owens-Wendt model, the following equations were used for the dispersion component and the polar component [5]:

$$\gamma_S^d = \frac{\gamma_g\left(\cos\theta_g + 1\right) - \gamma_w\left(\cos\theta_w + 1\right)\sqrt{\frac{\gamma_g^p}{\gamma_w^p}}}{2\left(\sqrt{\gamma_g^d} - \sqrt{\frac{\gamma_g^p\gamma_w^d}{\gamma_w^p}}\right)} \quad (1)$$

$$\left(\gamma_S^p\right)^{1/2} = \frac{\gamma_w\left(\cos\theta_w + 1\right) - 2\sqrt{\gamma_S^d\gamma_w^d}}{2\sqrt{\gamma_w^p}} \quad (2)$$

where:
γ_w - water surface free energy, γ_w^d - water SFE dispersion component, γ_w^p - water SFE polar component, γ_g - glycerine SFE, γ_g^d - glycerine SFE dispersion component, γ_g^p - glycerine SFE polar component, γ_S^p - SFE polar component of the examined material, γ_S^d - SFE dispersion component of the examined material, θ_g - glycerine contact angle, θ_w - water contact angle.

The total value of SFE (γ_S) was determined as a sum of the polar and dispersion components:

$$\gamma_S = \gamma_S^p + \gamma_S^d \quad (3)$$

Scanning electron microscopy of the concrete

The qualitative analysis of the chemical composition within the main mineral components of concrete, morphology and microtopography were determined using a scanning electron microscope FEI Quanta 250 FEG equipped with a chemical composition analysis system based on energy dispersion spectroscopy (EDS). The samples were prepared in the form of thin-layer plates, on which X-ray microanalyses were performed in the field mode and the composition of elements was determined for the seven batches of concrete. The sample preparation methodology excludes the formation of microdefects associated with cracking of the concrete surface. In order to avoid the formation of other surface defects, low vacuum and beam energy were used during the SEM analysis.

RESULTS AND ANALYSIS

Physical properties

The physical properties of the concretes adopted for the examination are shown in Table 2.

The results show that the quantity of polypropylene fibers affects the increase in concrete absorptivity and the decrease in concrete density. The decrease in density is from 6 to 11% and increases accordingly with the quantity of fiber added from 0.5 to 2%, compared to samples without any addition. On the basis of the study conducted, it was shown that the concrete produced had a density of 2270÷2560 kg/m^3. The open porosity of the concrete was within the range of 3.8÷4.3% and corresponded to high performance concretes. The addition of fibers in the quantity of 0.5% caused an increase in porosity of 9%, however, with a further increase in fiber content, the porosity decreased and is for the C2 concrete 11.6% lower than the standard concrete - C0.

TABLE 2. **Physical properties of concretes**
TABELA 2. **Właściwości fizyczne betonów**

Concrete type	Absorptivity n_p [kg/m^2]	Apparent density ρ_b [g/cm^3]	Open porosity ρ_o [%]
C0	0.6	2.56	4.3
C0.5	0.9	2.41	4.7
C1	0.9	2.37	4.0
C1.5	0.8	2.30	3.9
C2	0.7	2.27	3.8

Sample absorptivity is very low and ranges from 0.6 to 0.9%. The addition of 0.5 and 1% fibers causes the highest increase in absorptivity by more than 33%, while the addition of 2%, an increase by 14.3% compared to the samples without any addition - C0. It was found that with an increasing quantity of polypropylene fibers above 0.5%, they cause a gradual decrease in absorptivity, density and open porosity.

Due to the poor transition zone, weaker adhesion of the polypropylene fibers to the matrix caused by the high hydrophobicity of the fibers, the pore volume increased and more micro-defects in the cement matrix are formed. Adding small quantities of PP fibers resulted in worse water absorption characteristics, however, more fibers caused greater tightness of the composites.

Strength properties

The strength properties of the concretes adopted for the examination are shown in Figures 4-7.

Based on the results obtained in Figure 4, an adverse effect of the addition of polypropylene fibers on concrete compressive strength can be found. The addition of fibers ranging from 0.5 to 2% resulted in lowering the strength from 6 to 18% respectively, compared to the strength of concrete without fibers after 28 days and likewise from 6.2 to 18.8% after 56 days. The increase in strength of concrete without fibers after 56 days was only 2% compared to the strength after 28 days. In the case of fiber reinforced concretes - C0.5-C2 after 56 days, there was a slight increase in strength which was lower as the quantity of fibers was increased and ranged from 1.5% for C0.5 to 0.8% for C2.

The results of the average splitting tensile strength (Fig. 5) after 28 days showed that this strength was slightly increased by a maximum of 10.5% at the lowest fiber content.

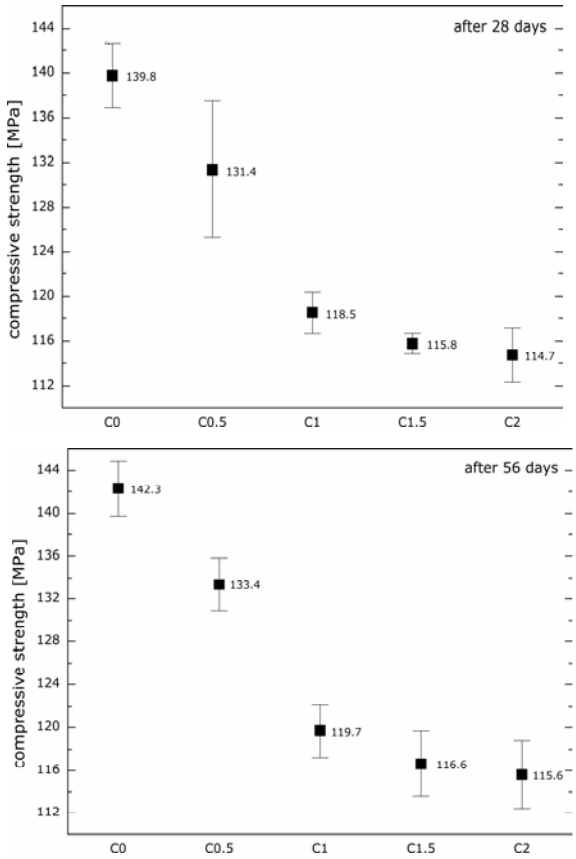

Fig. 4. Average compressive strength after 28 and 56 days

Rys. 4. Średnia wytrzymałość na ściskanie po 28 i 56 dniach

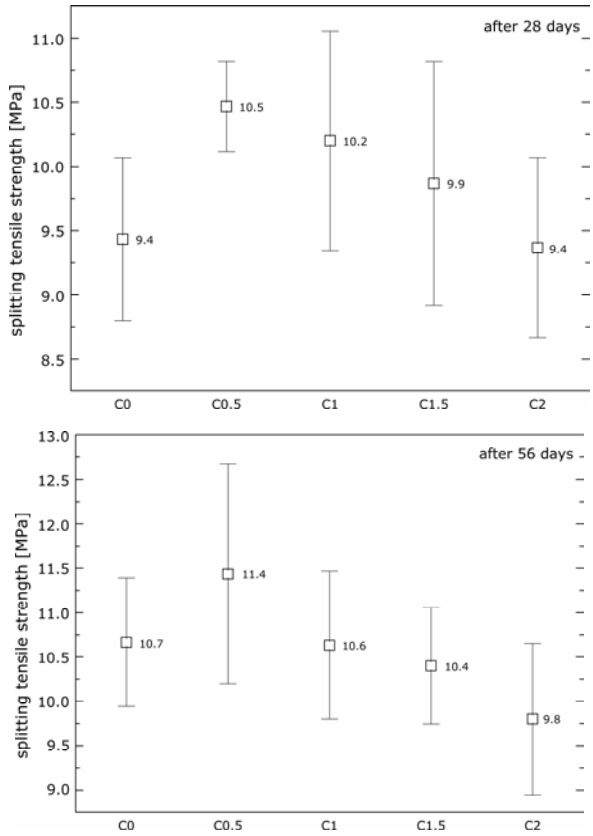

Fig. 5. Average splitting tensile strength after 28 and 56 days

Rys. 5. Średnia wytrzymałość na rozciąganie przy rozłupywaniu po 28 i 56 dniach

For the highest fiber content of 2%, the strength is the same as for the standard concrete. After 56 days, the concrete without fibers obtained a tensile strength which was 12% higher than after 28 days. For fiber reinforced concretes, this strength increased by 8% for C0.5 and 4% for C2, compared to the tests prior to this 28-day-period. With regard to the results of the standard concrete C0 after 56 days, we observed a gradual loss of strength from 1 to 8% for the quantity of fibers from 1 to 2% and an increase in strength for the batch of concrete which contained the lowest quantity of fibers. The increase in strength was 6.1%.

Figure 6 shows the adverse effect of the addition of polypropylene fibers on the concrete bending tensile strength and static modulus of elasticity. With an increasing addition of fibers from 0.5 to 2%, the strength gradually decreased from 2.7 to 24%. The modulus of elasticity dropped from 10 to 17.8% also with an increasing addition of polypropylene fibers.

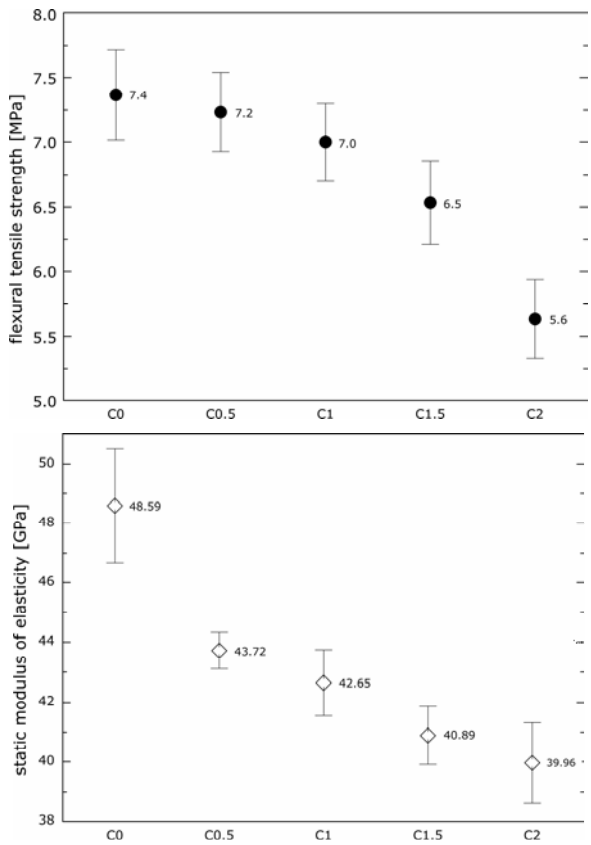

Fig. 6. Average flexural strength and modulus of elasticity after 28 days

Rys. 6. Średnia wytrzymałość na zginanie i średni moduł sprężystości po 28 dniach

The effect of PP fibers on compressive and flexural strength is not quite clear. There can be little or no chemical adhesion between the fiber and the matrix due to their chemical and physical inertness. It appears that a smooth surface made of PP fibers enhances this effect. Furthermore, the presence of polypropylene fibers in a cement paste contributes to the so-called wall effect while forming a film of water at the interface of fibers and the matrix. Since calcium ions are more

active in an aqueous environment, calcium hydroxide crystals are formed more easily and make the transition zone more porous. This phenomenon has a negative impact on the bond between the fibers and the matrix. Particularly, the abovementioned analyses can be associated with the results of splitting tensile strength tests. An addition of the smallest quantity of fibers at a level of 0.5% causes an increase in strength by 10.5%, while a further increase in the quantity of polypropylene fibers results in its rapid drop. In the case of other strength tests, the addition of fibers in each case results in a decrease in compressive strength, flexural strength and modulus of elasticity. In order to use the maximum fiber strength and improve the properties of the composite, it is necessary to strengthen the interfacial bond of the polypropylene fibers.

Contact angle and surface free energy

The measured contact angles of water and glycerine on the five concretes are included in Table 3.

TABLE 3. **Contact angle of high performance concretes with water and glycerine**

TABELA 3. **Kąt zwilżania wodą i gliceryną betonów wysokowartościowych**

Concrete type	Contact angle					
	water θ_w [°]			glycerine θ_g [°]		
	$t_1 = 0$	$t_2 = 5$	$t_3 = 40$	$t_1 = 0$	$t_2 = 5$	$t_2 = 40$
C0	71.7	69.6	49.3	75.1	73.4	54.2
C0.5	42.5	30.5	29.4	54.3	47.3	47.0
C1	49.1	40.5	35.2	53.2	47.6	43.6
C1.5	52.9	50.7	41.3	56.9	56.2	47.5
C2	65.3	51.1	40.1	69.3	55.1	46.2

By analyzing the examination results, it can be noticed that the contact angle values depend on the type of concrete. The results of contact angle measurements proved that all the glycerine contact angles (θ_g) were higher than the water contact angles (θ_w), and they decreased in the course of time. The highest contact angle was shown for concrete without fibers both at the beginning of the tests and after 40 minutes. The smallest contact angle with water was obtained by the concrete with the smallest addition of fibers - C0.5 and it was about 40% lower than that in the case of standard concrete both at the beginning of the study and at the end of it. With an increasing addition of fibers above 0.5%, the contact angle with water and glycerine increases. On the basis of the contact angle measurements, the SFE dispersion and polar components for all the analyzed concretes were calculated. The calculated SFE component values are included in Table 4.

The lowest surface free energy value $\gamma_S = 89.7$ mJ/m^2, which shows the weakest adhesion properties, was obtained for concrete without polypropylene fibers. At the beginning of the test, it is lower by 75.5% than the SFE of concrete with the addition of 0.5% fibers. Additionally, it can be seen that in all the cases, the SFE dispersion component, $\gamma_S^d = 89.45 \div 492.47$ mJ/m^2 constitutes a significantly larger proportion of the total SFE value (γ_S) than the polar component $\gamma_S^p = 0.01 \div 24.69$ mJ/m^2. Considering time variations (Figs. 4 and 7), it was found that over time, the dispersion component value (γ_S^d) and the total SFE value (γ_S) grew by 34% in the case of standard concrete C0, by 29% for C0.5, C1.5, C2 and by 43% - C1.

TABLE 4. **SFE components of standard concrete and concrete with fibers**

TABELA 4. **Składowe SEP betonów wzorcowego i z włóknami**

Concrete type	SFE component					
	Dispersive γ_S^d [mJ/m^2]			Polar γ_S^p [mJ/m^2]		
	$t_1 = 0$	$t_2 = 5$	$t_3 = 40$	$t_1 = 0$	$t_2 = 5$	$t_2 = 40$
C0	89.45	102.79	135.64	0.26	0.06	0.66
C0.5	355.37	470.74	492.47	12.03	22.04	24.69
C1	114.73	191.03	204.52	2.05	0.02	0.01
C1.5	112.93	152.20	160.53	1.50	0.07	0.41
C2	110.41	112.74	156.02	0.13	1.84	0.69

The graphic illustration of the total SFE obtained is shown in Figure 7.

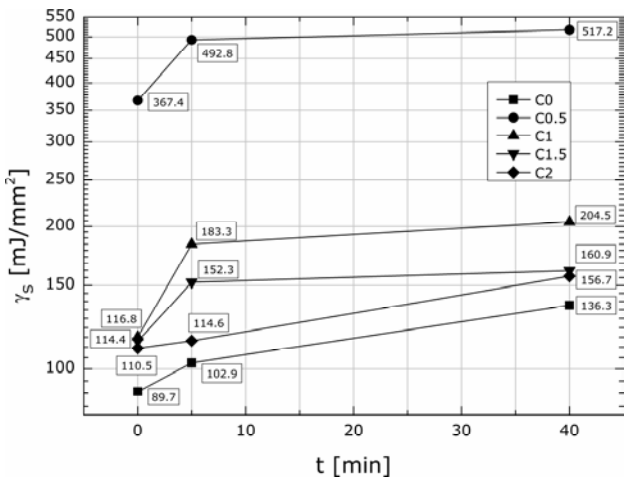

Fig. 7. Total SFE value of concretes at beginning of examination and after 5 and 40 minutes

Rys. 7. Sumaryczna wartość SEP betonów na początku badania oraz po 5 i 40 minutach

Scanning electron microscopy of the concrete

Figure 8 shows scanning images of high performance concrete C0 and fiber reinforced concretes C1 and C2 with fiber contents of 1 and 2% respectively.

Figure 8b, c show the distribution and the size of the polypropylene fibers. The fibers are arranged at random, and their diameter is in the range of 16÷40 µm. There are no visible pores in the standard concrete (Fig. 8a), however, there are minor scratches. A small number of fine pores and cracks was found in samples C1 and C2 which proved higher porosity and absorption as compared to concrete without fibers, as also confirmed by tests of the physical characteristics.

a)

b)

c)

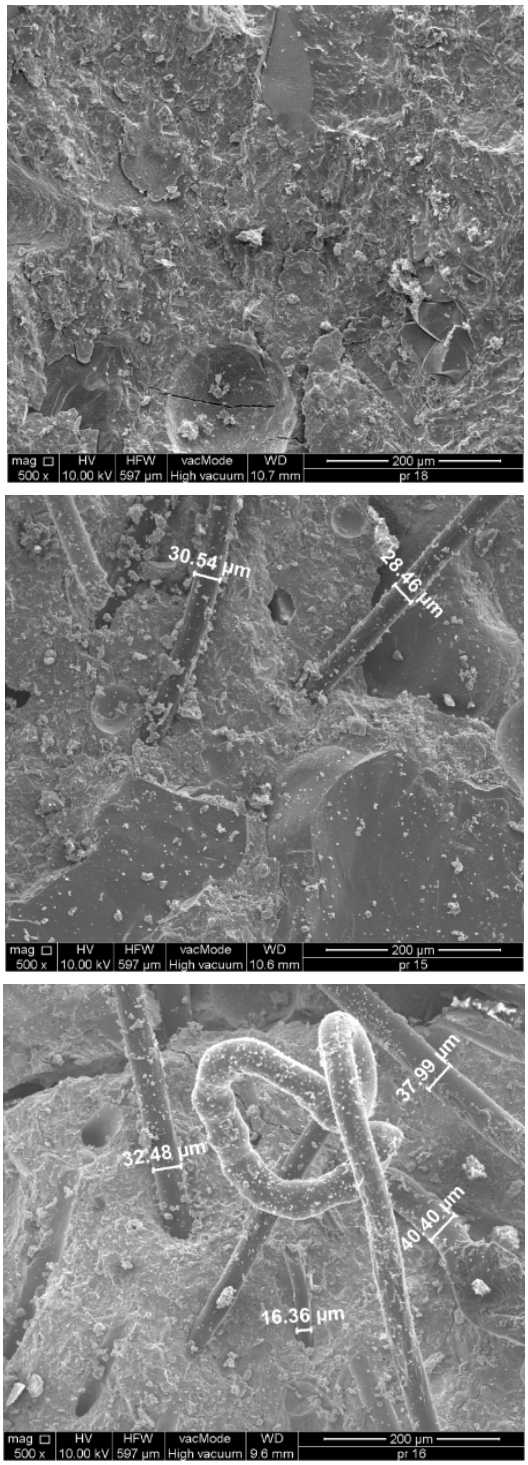

Fig. 8. Microscopic image (x500) of high performance concrete microstructure: a) without fibers, b) with 1% addition of fibers, c) with 2% addition of fibers

Rys. 8. Obraz mikrostruktury betonu wysokowartościowego (x500): a) bez włókien, b) z 1% dodatkiem włókien, c) z 2% dodatkiem włókien

Figure 9 presents microscopic pictures of HPC cement paste magnified 10 000 and 20 000 times.

This magnification allowed precise separation of the main chemical components of concrete. As can be seen, there is a crystallized C-S-H gel phase, which is the main component of cement paste and determines its physical and chemical properties.

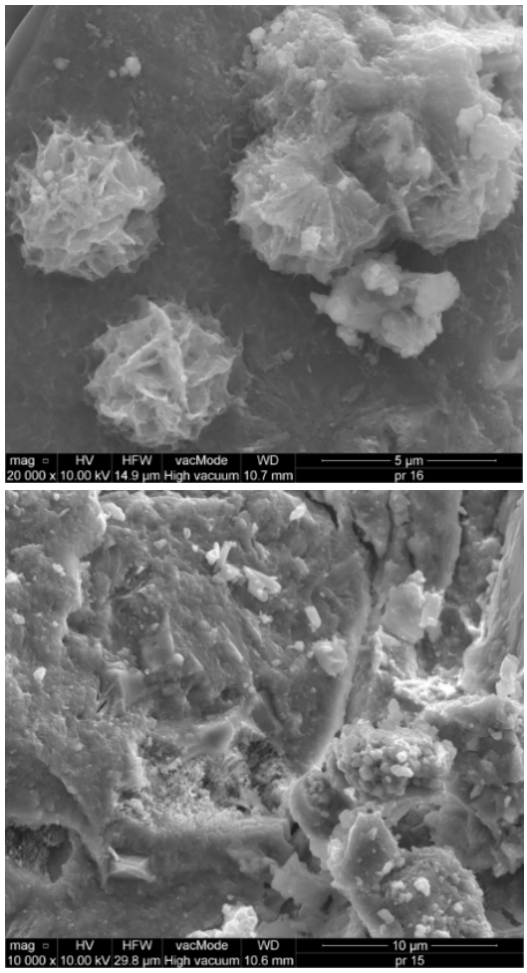

Fig. 9. Microscopic image of high performance concrete - C-S-H phase microstructure

Rys. 9. Obraz mikroskopowy betonu wysokowartościowego - mikrostruktura fazy C-S-H

SUMMARY

Measurement of the contact angle is one of the methods of monitoring changes in the wettability of porous materials. The use of a polypropylene fiber addition results in different wetting and adhesion properties of concrete, which are determined by the contact angle and the surface free energy.

Based on the obtained results of strength tests, one can observe an adverse effect of the addition of polypropylene fibers on the concrete compressive strength, flexural strength, and on the static modulus of elasticity. Only the average tensile splitting strength did not change or increased max. up to 10.5%. Obtaining significantly higher values of FRHPC splitting tensile strength than bending tensile strength is also extremely important.

It was found that the addition of fibers to high performance concrete contributes to obtaining different SFE values. With respect to standard concrete, the SFE value is from 1.2 to 4 times higher in the case of surfaces of fiber reinforced high performance concrete. The biggest SFE difference was observed for the lowest fiber content of 0.5%. This is due to the physical char-

acteristics of this concrete. Concrete with an 0.5% addition of fibers is characterized by the highest porosity, absorptivity, and the lowest density among the tested concretes. This indicates increased wettability and increased adhesion properties. In practice, this can result in its reduced resistance to corrosive agents such as moisture, frost, chloride, and sulfate corrosion.

It seems that the use of some sort of additives like SiO_2 nanoparticles causing physical and chemical action at the interface, can be regarded as helpful in improving the bond between the fibers and the matrix and, consequently, in increasing strength parameters.

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