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ABRASION RESISTANCE OF HIGH-PERORMANCE HYDRAULIC CONCRETE WITH POLYPROPYLENE FIBERS

ODPORNOŚĆ NA ŚCIERANIE HYDROTECHNICZNYCH BETONÓW WYSOKOWARTOŚCIOWYCH Z WŁÓKNAMI POLIROPYLENOWYMI

Key words:

abrasion resistance, high-performance concrete, polypropylene fibers

Słowa kluczowe:

odporność na ścieranie, betony wysokowartościowe, włókna polipropylenowe

Summary

The results of abrasion resistance test of high-performance hydraulic concretes with additions of 3 types of the polypropylene fibers are presented in the paper. The results are compared to the reference concrete without fibers. For the examination of the abrasion resistance of concretes two methods were selected: the underwater method that complies with American Standard ASTM C 1138 and the Bőhme disc method that complies with European Standard EN 13892-3.

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The performed tests indicated that the underwater method (ASTM C1138) may by used for evaluation of the abrasion resistance of the high-performance concretes in the case of the erosive action of waterborne rubble.

INTRODUCTION

Abrasive resistance of concrete depends of several parameters, such as aggregate properties, mixture material proportion, concrete strength, type, the quantity of added cement materials, addition of fibers, hardening conditions, and surface treatment. Many previous studies demonstrated that the abrasive resistance of concrete mostly depends on its compressive strength. The high quantity of cement in the mixture of these concretes causes an increase in hydration temperature and concrete shrinking, which generates a potential for the onset of cracks and the reduction of the service life of the structure. In order to increase the service life of a hydraulic structure and to retain it for as long as possible in a safe and reliable condition, the hydraulic concrete must have a high mechanical resistance. Therefore, in the majority of concrete mixtures, cement is in part replaced by additional mineral materials such as fly ash **[L. 1–3]**, silica powder **[L. 4]**, and blast furnace slag **[L. 5]** in order to reduce the hydration heat.

The concrete hydraulic structures exposed to erosion wear by waterborne rubble are often under the action of the other mechanical factors, like dynamic loadings or multiple variable loadings. Using high performance concretes (HPC) in the case of such intensive mechanical action is not always successful. Searching for possibilities of improving the resistance of the cement matrix to the aggressive environment action, including mechanical options, is very often connected with the introduction of various fibers into the matrix.

The addition of the steel fibers is often used in the case of the shock loadings and multiple variable loadings in hydraulic structures **[L. 6]**. The steel fibers, as a dispersed reinforcement, should stop crack propagation or transfer part of the forces after cracking. The basic feature of the steel-fiber-reinforced concrete is its resistance to fracture during bending. The addition of the steel fibers is also favourable for the mechanical properties of the concrete, like flexural strength, and the fatigue resistance of the modulus of elasticity **[L. 7–10].** Using steel fibers in concrete **[L. 11–12]** can significantly improve the resistance of the concrete to cavitation. However, the steel fibers do not always improve the erosion resistance of the concrete in hydraulic structures. In the case of the action of rubble dragged by water at speeds lower than 10 m/s, when the cavitation does not occur, **[L. 13]**, the increased wear of the steel-fiber-reinforced concrete has been observed, as compared to the concrete without fibers. The investigations **[L. 14–16]** into erosion of concretes at the low-speed abrasive mixture have showed that the addition of the steel fibers with a low aspect ratio ($\lambda \leq 50$) does not influence the abrasion resistance of the high-performance concretes and even causes a reduction of their erosion resistance compared to concrete without the fibers **[L. 17]**.

Besides steel fibers, polypropylene fibers are now often used in concrete structures (particularly in the surface layers). The polypropylene fibers are primarily used for the reduction of cracks in fresh concrete but also exhibit the secondary effects, improving a number of characteristics both of fresh and hardened concrete. The addition of fibers has a positive effect, because in the early phase (2–6 hours upon placing of concrete), they contribute to the reduction of the size of the cracks because they allow the concrete to endure higher internal stresses. The addition of fibers also improves the hydration of cement by reducing the separation of water from the fresh concrete. In a later period, in somewhat more cured concrete, the fibers bind the cracks and reduce the risk of concrete destruction **[L. 18–20]**. The polypropylene fibers in concrete significantly increase abrasion resistance **[L. 21–23]** and cavitation resistance **[L. 24–25]**. This property is ascribed to the quantity of energy absorbed when the fibers are separated, broken or extracted from concrete after failure.

EXPERIMENTAL STUDY

Raw materials and concrete mix composition

The materials used in this study were Portland cement CEM I 42,5N-HSR/NA, river sand with a density 2650 kg/m^3, crushed basalt with continuous grading size of 4–16 mm and specific density of 3050 kg/m^3, silica fume with a density of 2200 kg/m^3, a superplasticizer and three types of polypropylene fibers with constant a dosage rate of 0.9 kg/m^3. The chemical and physical properties of the fibers are presented in **Tab. 1** and **Fig. 1** shows the fibers used in test.

Table 1. Chemical and physical properties of fibers
Tabela 1. Chemiczne i fizyczne właściwości włókien

Type of fibers	Material	Length [mm]	Type/ shape	Density [g/cm^3]	Young's modulus [N/mm^2]	Melt Point [°C]	Ignition Point [°C]
F1	C3H6 polypropylene	19	fine	0.91	3800	145	570
F2	virgin homopolymer	graded 12–19	fine/ fibrillated	0.91	3400	162	593
F3	virgin homopolymer	19	fine/ fibrillated	0.91	3400	162	593

The mix proportions are listed in **Tab. 2**

Table 2. Compositions of concrete mixtures (kg/m³)
Tabela 2. Skład mieszanek betonowych (kg/m³)

Type of concrete	Cement	Water	Sand	Basalt	Silica Fume	Super-plasticizer	PP fibers
CO	450	135	630	1279	45	12.6	–
CF1	450	135	630	1279	45	12.6	0.9
CF2	450	135	630	1279	45	12.6	0.9
CF3	450	135	630	1279	45	12.6	0.9

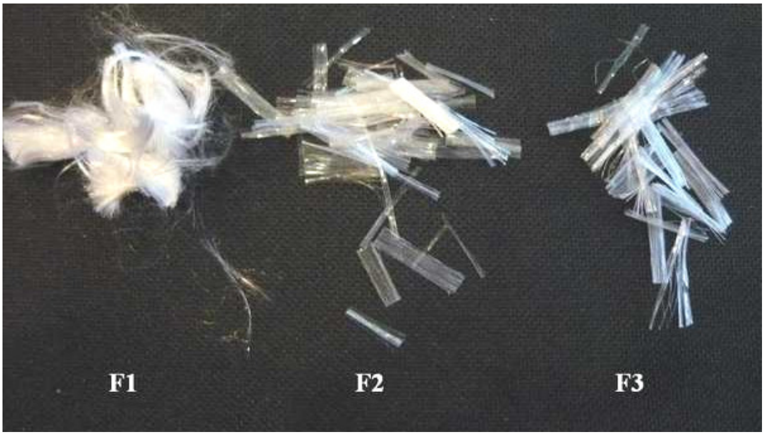

Fig. 1. Polypropylene fibers used in the test
Rys. 1. Włókna polipropylenowe zastosowane w badaniach

Test procedures

The abrasion resistance of concrete was evaluated according two methods: Bőhme disc which complies with European Standard EN 13892-3 and the "underwater method" complies with American Standard ASTM C 1138. The underwater method simulates the natural conditions of abrasive concrete wear and can be used for the comparative analysis of the abrasive resistance of standard and high-strength concrete. In this test, the concrete sample is subjected to an abrasive charge consisting of 70 chrome steel balls circulating in water over the concrete surface. A paddle rotating at 1200 rpm is used to cause the circulation of this abrasive charge. The mass loss and average depth of the abrasion--erosion are measured at 12-h intervals for 120 h. Three cylindrical samples measuring 100 mm in height and 300 mm in diameter were cast and used to evaluate the underwater abrasion resistance for each concrete. The samples were removed from the moulds after one day and stored in water at 20±2°C. After 28 days, the abrasion resistance was tested for the top-finished surfaces. The testing machine in used for this method is shown in **Fig. 2**.

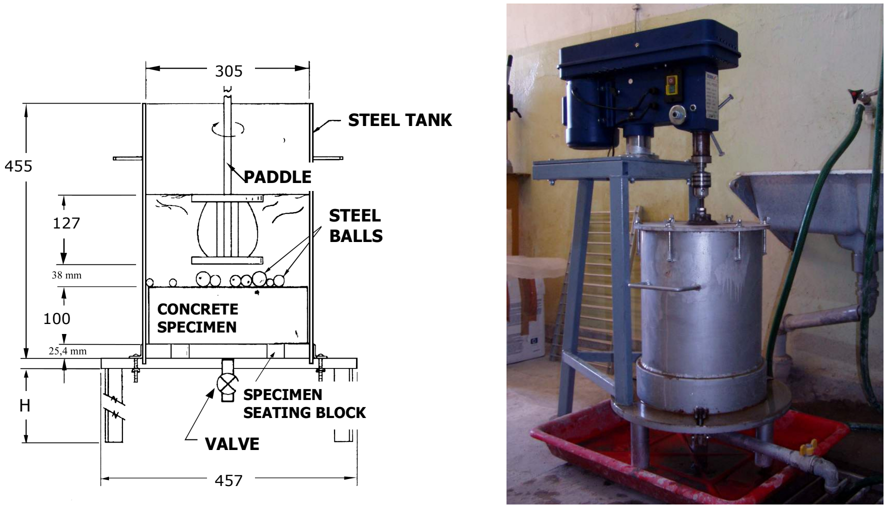

Fig. 2. Test apparatus according to ASTM C 1138
Rys. 2. Urządzenie badawcze wg ASTM C 1138

The mechanical abrasion resistance of concrete was evaluated according to the Bőhme disc method. The test specimens were cubes with an edge length of 71±1.5 mm. Specimens are placed on the test track of the Bőhme disc abrader on which a standard abrasive material is strewn. The disc is then rotated, and the specimens are subjected to an abrasive load of 294 N for 16 cycles, each consisting of 22 revolutions.

TEST RESULTS AND DISCUSION

The results of the tests of the mechanical properties of the concretes are presented in **Tab. 3**. **Fig**. **3** shows the comparison of the abrasion resistance test results of concrete specimens using the two methods – the underwater method and the Bőhme's disc method.

Table 3. Test results of concrete specimens
Tabela 3. Wyniki badań próbek betonowych

Type of concrete	CO	CF1	CF2	CF3
Mean depth of wear – Underwater abrasion test after 120 h [mm]				
DOW	3.84	2.71	2.30	2.21
Mean depth of wear – Bőhme disc [mm]				
DOW	1.85	1.77	1.87	1.85
Compressive strength after 28 days [MPa]				
$f_{c,28}$	94.5	105.6	100.1	105.2
Tensile splitting strength after 28 days [MPa]				
$f_{t,28}$	4.2	4.7	4.5	4.3

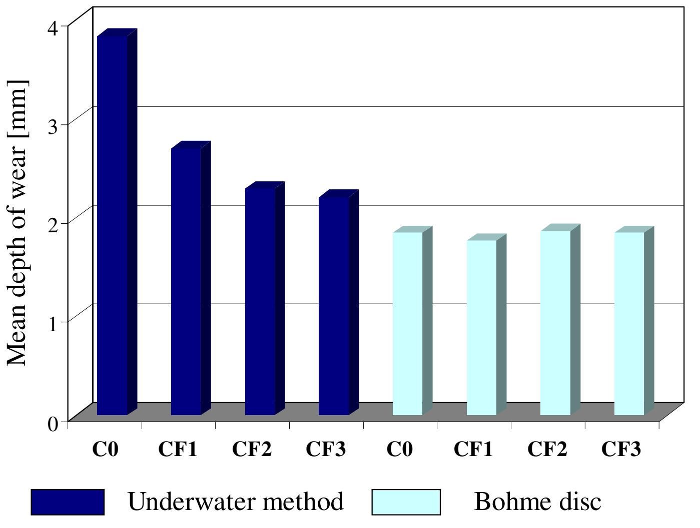

Fig. 3. Results of abrasion test of concrete specimens
Rys. 3. Wyniki badań ścieralności próbek betonowych

The method of testing on the Bőhme disc provides only slight discrimination. The average depth of loss, calculated from the loss of the mass of the specimen as well as by the measurement of the specimen dimensions after the test, was the same for concretes C0, CF2, and CF3. Only the specimens made from concrete CF demonstrated less abrasion damage than the other concretes. The abrasion of all specimens produced a smooth surface in every case. The results of the losses of the height and mass of the specimens after 120 hours of testing are more differentiated when using the underwater method. The lowest abrasion resistance was demonstrated by the specimens of the reference concrete C0. The average DOW of the concretes with fiber additions were much lower (by 30% to 60%).

Fig. 4 and **Fig. 5** present the photos of the surfaces of the specimens made from the reference concrete C0 and concrete CF3, after 120 hours of testing using the underwater method.

The clear difference can be observed between the appearance of the surface of the reference concrete C0 and the concretes reinforced with polypropylene fibers. The surface of the specimens with polypropylene fibers was worn much more uniformly during the test. In the case of the reference concrete, the more uneven and "washboard" surface was produced. The weaker cement matrix received more damage under the action of the wearing material from the harder basalt aggregate. The addition of the polypropylene fibers produced a strengt--hening of the cement matrix, which was demonstrated by more uniform wear of the surfaces. The concrete reinforced with fibers F3 demonstrated the highest abrasion resistance as indicated by the underwater testing.

Microscopic observations were carried out, including the topography of the surfaces of the specimens with the fibers. Moreover, analysis of the chemical composition using x-ray microanalysis (EDS) and the BSE images (**Fig. 6**) were also undertaken. None of these observations and analyses confirmed the presence of calcium hydroxide in the fiber-paste contact zone.

Fig. 4. Concrete specimen C0 after 120 h of abrasion test (underwater method)
Rys. 4. Próbka betonowa C0 po 120 h badań ścieralności (metoda podwodna)

Fig. 5. Concrete specimen CF3 after 120 h of abrasion test (underwater method)
Rys. 5. Próbka betonowa CF3 po 120 h badań ścieralności (metoda podwodna)

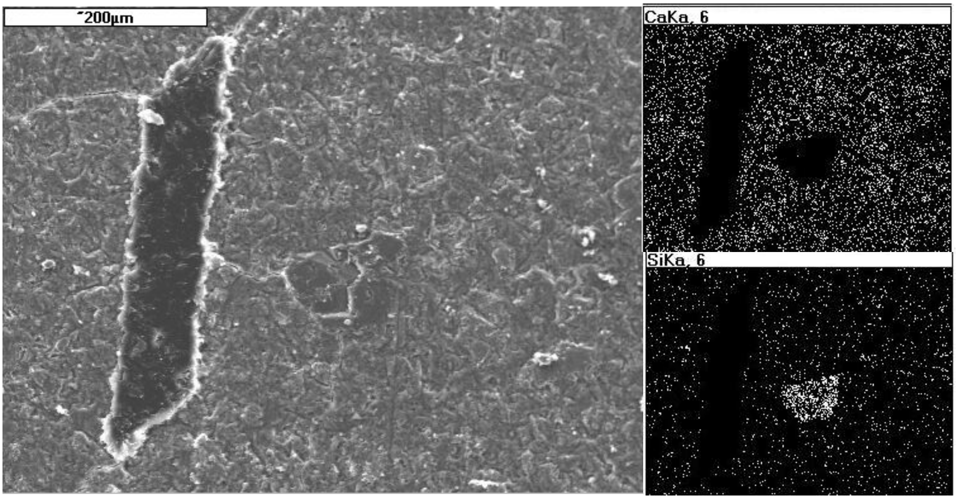

Fig. 6. SEM microphotograph of specimen surface in polypropylene fibers (CF3) after the abrasion test and mapping Ca and Si

Rys. 6. Obraz SEM powierzchni próbki z włóknami polipropylenowymi (CF3) po 120 godzinach badań ścieralności i mapy rozmieszczenia Ca i Si

CONCLUDING REMARKS

The obtained results indicate that the addition of the polypropylene fibers produces an increase in the resistance to abrasion of hydraulic concretes caused by waterborne-rubble action. The polypropylene fibers increased the compressive strength and tensile splitting strength of the concrete.

The performed tests and the previous investigations by the author **[L. 14]** lead to the conclusion that the underwater method, according to ASTM C1138, may be used for the evaluation of the abrasion resistance of the high-performance concretes in the case of the erosive action of waterborne rubble. The evaluation of the abrasion resistance of hydraulic concretes using the Bőhme disc is not possible. This is the result of the different mechanisms of the surface abrasion. Of the two methods, only the underwater method simulates the natural conditions of wear under the action of waterborne rubble.

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Streszczenie

W pracy przedstawiono wyniki badań ścieralności wysokowartościowych betonów hydrotechnicznych z dodatkiem 3 rodzajów włókien polipropylenowych. Wyniki badań porównano z betonem referencyjnym bez dodatku włókien. Badania odporności na ścieranie przeprowadzono dwiema różnymi metodami: metodą podwodną wg normy amerykańskiej ASTM C 1138 i metodą z użyciem tarczy Bőhmego stosowanej w Europie (wg PN--EN 13892-3). Z przeprowadzonych badań wynika, że do oceny odporności betonów wysokowartościowych na ścieranie wywołane oddziaływaniem erozyjnym rumowiska można stosować metodę podwodną wg ASTM C1138.