Effect of plasticizers, superplasticizers and silica fly ash on concrete water-resistance

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Concrete is one of the basic construction materials. It is a composite made of cement, water, coarse and fine aggregate. In the past, concrete was produced only with primary components, and it was often of poor quality. Nowadays, technological progress and scientific research allowed the concrete to be made with the use of chemical admixtures and mineral additives to modify and improve selected properties of both the concrete mixture and hardened concrete. Contrary to popular belief, obtaining concrete with suitable properties is not simple and the choice of mixture components requires professional knowledge. The care and quality is also extremely important. The paper presents the results of laboratory research concerning the impact of the plasticizer admixture—Betocrete-C17 and superplasticizer—Arpoment-O and mineral additive of silica fly ash on concrete water resistance. Capillarity, water permeability and water absorption of the concrete were determined. Additionally, a study of the consistency of fresh mixture was done and the hardened concrete compressive strength was tested.
Keywords: chemical additives, plasticizers, superplasticizers, silica fly ash, concrete water-resistantance

Introduction

Concrete water resistance is the resistance of the material in the case of water action in different forms, in different ways. It is a broad concept, consisting of different physical characteristics. This is an important feature especially in the case of concrete, which are to operate in an environment exposed to water. Water resistance allows to avoid the adverse effects of chemicals, if we are dealing with a chemically aggressive environment, as well as the destructive action of water during freezing temperatures. Water resistance is influenced by water absorption, capillarity and water proof features. Depending on the type of concrete, there are different requirements for the above properties of the concrete. The requirements for water absorption of concrete are questionable [1]. The problem lies in the weakness of the definition of absorption and the imperfections of test procedures aimed at determining it. There are publications on the research methodology of this property but the criteria for evaluation are not clear [2, 3]. Obtaining low water absorption is often done at the expense of deteriorating other important properties of concrete. Higher absorption often do not detract from the quality of concrete [4]. Capillarity results from the existence of unbalanced surface forces and depends on the number of pores and sizes of their diameters. The dynamics of capillary action in building materials is described in the article [5] and attempt to resolve the factors having the greatest impact on the growth of capillary is discussed in the article [6]. Waterproof concrete is achieved by appropriate, accurate selection of components of the concrete mix and by minimizing the porosity of the concrete. High water resistance, low water absorption and limited capillarity are determinants of waterproof concrete. In order to increase the water resistance of concrete, chemical additives or mineral supplements are added to the concrete mix. They reduce capillarity and capillary penetration of water into the concrete by reducing the permeability. They prevent both soaking of the material and the inflow of pressurized water. Plasticizers and superplasticizers are organic substances acting as dispersants while silica fly ash is a sealing additive.

Materials used in laboratory research

Cement

Concrete mixes used Portland cement CEM I 42.5 R characterized by high strength after 28 days, and the rapid progression of early strength, moderate heat of hydration and heat release kinetics, low shrinkage. This is obtained by grinding Portland clinker and a sulphate ingredient, which regulates the binding time. Properties of cement CEM I 42.5 R are presented in Table 1.

Table 1. Properties of cement CEM I 42.5 R

Properties	Requirements [7]
SO3 content [%]	≤4.0
Cl content [%]	≤0.1
Beginning of bonding [min]	≥60
End of bonding[min]	–
Volume change [mm]	≤10
Compressive strength [MPa] — after 2 days — after 28 days	 ≥20 ≥42.5≤62.5
Insoluble residue [%]	≤5.0
Loss on ignition [%]	≤5.0

Cement CEM I 42.5 R is recommended to be used for the production of cellular concrete, railroad track underlay, floor slabs, production of finished adhesives, mortars, vibropressed products, high strength concrete, paving slabs, curbs, paving stones.

Aggregate

To prepare concrete mixtures, fine aggregate—sand (0-4 mm) and gabbro aggregate (4-16 mm) were used. Gabbro is a kind of crushed stone having sharp edges. It comes from igneous deep water rocks, with coarsely crystalline structure, it is alkaline and its color ranges from gray to dark gray (due to the presence of dark minerals), it is similar to the diorite. It contains minerals such as quartz, orthoclase, plagioclase, but also amphibolite, pyroxene, mikrolin, biotite, olivine, bytownite. Figure 1 shows a graining curve of aggregate composition against limit curves recommended by the standard [8].

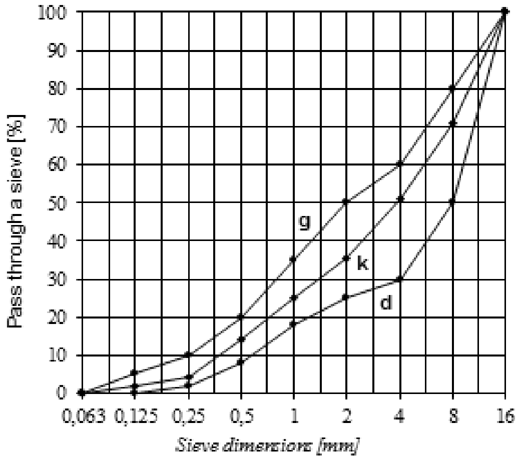

Figure 1. Graining curve of the projected aggregate composition of gravel-sand mix (k—graining curve, g and d—boundary curves)

Mixing water

Tap water meeting the requirements of the standard was used to make concrete mixtures [9]. Mixing water performs several functions. It initiates the curing process of cement—the main component of concrete—by reacting with it. In the process of hydration of the compounds contained in the cement, there are hydrates providing hardness of the blend formed. This is mainly bounding of water fixedly to the tricalcium aluminate. Another task of gauging water is to give the viscosity of the concrete mix and shaping its fluidity, depending on the desired consistency.

Chemical additives

Chemical additives: plasticizer Betocrete-C17 and superplasticizer Arpoment-O were used for concrete mixes. Betocrete-C17 is a liquid, inorganic admixture, which allows to create sealed concrete. With the sealing of concrete, it causes a significant increase in the durability of concrete. In the process of concrete hardening with Betocrete-C17 admixture, fibrous crystal forms appear, which are formed in the capillary pores throughout the period of the concrete acting with water. These crystals, decrease the diameter of the pores in the concrete and thus reduce the penetration of water through the concrete. The process of waterproofing concrete structure is stable. By increasing the density of the concrete, it is possible to obtain additional safeguard and protection of the reinforcing steel, because the rate of diffusion of chloride ions in the cement matrix is limited. Tests have proved that the use of the admixture allows: increasing the strength of the concrete of up to 25% compared to the reference concrete, the reduction of the mixing water by approx. 8% with keeping solid consistency, obtaining semi-liquid mixture at the required liquid consistency—it is recommended to use liquidizing additives. They are dispensed in an amount of 2-3% of the weight of cement to the concrete mix [10]. Arpoment-O is a naphthalene superplasticizer, liquid admixture of dark brown color, which only slightly aerates concrete and delays cement setting time. With the combination of lignosulfonate and naphthalene resin, it surrounds the cement grains giving them a uniform charge causing them to repel each other and also forming the layer of lubricant on the surface. This contributes to effective dispersion of the cement grains giving some fluidity to concrete mix. Arpoment-O acts as sealant and by maintaining solid consistency allows a reduction of the mixing water by 15-30%, which can help to increase the final strength of the concrete by 20-40%. It is appropriate for concrete with a high water resistance, during the period of high temperatures, the transportation of concrete at significant distances. It is dispensed to the concrete mix in the amount of 0.5-2.5% in relation to the weight of cement [11].

Mineral additives

As a mineral supplement to the concrete mix fly ash was used. This is a fraction in the fine-grained form. It is produced as a waste material from the combustion of coal or lignite, and therefore there are two types—limestone and silica. Fly ash, fulfilling the quality requirements of the standard, was used to prepare the concrete mixture [12]. Action of fly ash as an additive to the concrete mix: lowering the heat of hydration of cement, providing resistance to chemically aggressive environments, improving the binding of the cement, improving the tightness of the concrete structure and increasing the strength of concrete with passage of time. Fly ash can be used for the production of: concrete and reinforced concrete, concrete elements, cellular concrete, lightweight aggregate, building ceramics, cement and pozzolan adhesives, asphalt concrete. It allows to reduce the material production costs and to improve many technical features of produced materials [13]. It is dispensed to the concrete mix in an amount up to 25% relative to the weight of cement.

Concrete mixes designs

For laboratory tests, four mixes were prepared that differed only in the presence of admixture or the use of the additive and the amount of the added mixing water (reduced when using additives). Mixtures were prepared so that the concrete could meet certain requirements, such as: resistance to water at atmospheric pressure, resistance to hydrostatic pressure, reduced water absorption. Guidelines for the design of concrete mixtures are shown in Table 2.

Table 2. Guidelines for the design of concrete mixes

Foundation	Mark	Standard
Exposure class	XC2	[14]
Concrete strength class	C25/30	
The consistency of concrete mix	S3	
Abrams slump [mm]	100-150	

Water demand of aggregates was carried out for the plastic consistency S3 of concrete mix and taken from [15]. Table 3 shows the individual components per 1 m³ of concrete mix.

Table 3. The selection of components for 1 m³ of concrete

Compo-nents	Quantity of components per 1 m³ of concrete mix [kg]			
	Z-0	Z-1	Z-2	Z-3
Cement CEM I 42.5 R	283.06	283.06	283.06	283.06
Aggregate	1954.33	1954.33	1954.33	1883.56
Mixing water	169.84	155.68	155.68	169.84
2.5% Beto-crete-C17	–	7.08	–	–
1.8% Arpo-ment-O	–	–	5.10	–
25% fly ash	–	–	–	70.77
w/c ratio	0.60	0.55	0.55	0.60

Examination of concrete mixes

For the determination of the consistency of concrete mixtures the slump cone method was selected of several methods according to standard [16]. This is a method reliable for the case of using aggregates with a grain size of not more than 40 mm. The concrete mix is compacted in the form of a truncated conical shape (Abrams cone). Cone slump of concrete mix after removing the mold is a measure of its consistency. Class of the concrete consistency is determined according to the classification given in standard [14]. The obtained results of consistency of concrete mixtures are shown in Table 4 and graphically illustrated in Figure 2.

Table 4. Consistencies of concrete mixtures

Con-crete	Concrete type	w/c ratio	Cone slump [mm]
Z-0	Control concrete	0.60	110
Z-1	Control concreto + 2.5% Betocrete-C17	0.55	130
Z-2	Control concreto + 1.8% Arpoment-O	0.55	150
Z-3	Control concreto + 25% fly ash	0.60	120

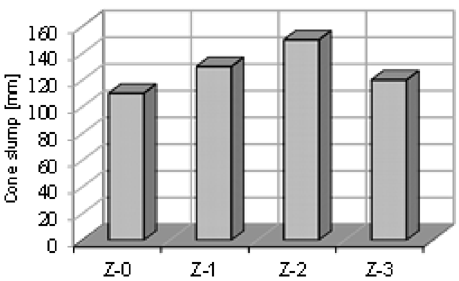

Figure 2. Consistencies of concrete mixtures according to cone slump method

Concrete tests

Examination of concrete compressive strength

Samples measuring 150x150x150 mm—three from each mixture were used for the study. The compressive strength test was performed according to standard [17], with a testing machine conforming to the requirements [18], and after 28 days of samples maturation. The strengths reached by the individual samples are shown in Table 5 and graphically illustrated in Figure 3.

Table 5. Concrete compressive strength

Concrete	Compressive strength [MPa]			
	P-1	P-2	P-3	Average
Z-0	27.21	36.03	25.22	29.49
Z-1	33.41	33.47	35.77	34.22
Z-2	38.45	35.18	44.66	39.43
Z-3	31.88	27.84	29.71	29.71

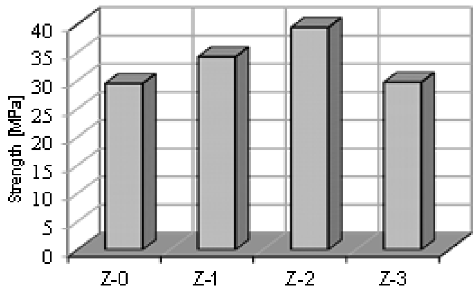

Figure 3. Compressive strength of concrete after 28 days of maturation

In order to assign concrete to the specific class of compressive strength, criteria shown in Table 6 were applied.

Table 6. Conformity criteria for concrete compressive strength according to the standard [14]

Production	Number of sample results	Criterion 1	Criterion 2
		Average of n results f_{cm}	Each individual resullt f_{ci}
		MPa	
Initial	3	$\geq f_{ck}+4$	$\geq f_{ck}-4$
Continuous	15	$\geq f_{ck}+1.48\delta$	$\geq f_{ck}-4$

f_{cm}: mean concrete compressive strength of the n results, f_{ck}: minimum characteristic strength determined on cubic samples $f_{ck,cube}$, f_{ci}: any single test result of concrete compressive strength

Concrete can be classified as a specific class only if both criteria are met. Only then, the real concrete class is determined. Table 7 shows classes of concrete compressive strength.

Table 7. Classes of concrete compressive strength

Con-crete	fck	Criterion 1		Criterion 2		Concrete class
		f_{cm}	f_{ck+4}	$f_{ci,min}$	f_{ck-4}	
	MPa					
Z–0	20	29.49	24	27.21	16	C16/20
Z–1	25	34.22	29	33.41	21	C20/25
Z–2	30	39.43	34	35.18	26	C25/30
Z–3	25	29.71	29	27.84	21	C20/25

Table 7 clearly shows that both criteria are fulfilled only for concrete Z-1, which has obtained a predetermined strength class C25/30. Cubic concrete samples modified with concrete admixtures showed significantly higher compressive strength after 28 days than concrete with the additive and unmodified concrete of basic composition. The maximum values were achieved for the Z-2 concrete with the superplasticizer admixture Apromenet-O—the average value of the compressive strength equals to 39.43 MPa, then Z-1 concrete admixture with a plasticizer Betocrete-C17—34.22 MPa. Concrete Z-3 with silica fly ash showed a higher minimum strength of 29.1 MPa in comparison with the control concrete Z-0 (29.49 MPa). Concrete modified with Arpoment-O (Z-2), with the highest compressive strength—39.43 MPa, showed the lowest water absorption—4.03%, low capillarity—39 mm, and a minimum water permeability—2.7 cm. In the case of concrete modified with fly ash, with compressive strength—29.71 MPa, water absorption was 4.83%, capillarity—54 mm and permeability—3.0 cm. Control concrete - without admixtures and additives, with the lowest compressive strength—29.49 MPa, showed the greatest absorption—6.50%, the highest capillarity—66 mm and the largest water permeability—5.8 cm. The results of concrete studies suggest a direct relationship between the compressive strength of concrete, water absorption, water permeability and capillarity. The higher the compressive strength the lower the water absorption, capillarity and water permeability.

The study of concrete absorption

The study of absorption of concrete samples was carried out according to the procedure specified in the standard [8]. Table 8 presents the mass of concrete samples in the dry state and Table 9 shows mass of samples in a fully saturated water absorption of respective samples. Concrete water absorption of each sample is also shown in Figure 4.

Table 8. Mass of dry samples

Concrete	Mass of dry samples [kg]			
	P-1	P-2	P-3	Average
Z-0	7.901	7.815	7.871	7.862
Z-1	7.905	7.845	7.913	7.888
Z-2	8.165	8.150	8.195	8.170
Z-3	8.038	8.005	8.060	8.034

Table 9. Mass in full water saturated and the water absorption of individual concrete samples

Concrete	Mass of water-saturated samples [kg]				Water absorption [%]
	P-1	P-2	P-3	P-4	
Z-0	8.359	8.405	8.355	8.373	6.50
Z-1	8.206	8.345	8.312	8.288	5.07
Z-2	8.511	8.495	8.491	8.499	4.03
Z-3	8.495	8.356	8.416	8.422	4.83

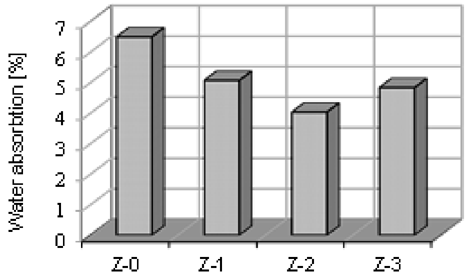

Figure 4. Water absorption of concrete samples

In accordance with the standard [8], the absorption of concrete should not be greater than 5% for concrete exposed directly to weather conditions and 9% in the case of concretes shielded from the direct effects of the weather.

Water absorption of tested concrete was 4.03-6.50%. Control concrete Z-0 achieved the worst result—6.50%. Slightly less water absorption—5.07% was achieved by concrete Z-2 mixed with plasticizer Betocrete-C17, then Z-3 with fly ash equal to 4.83%. Concrete Z-1 mixed with Arpoment-O had the lowest absorption—only 4.03%. All samples of different composition than the control Z-0 had lower water absorption. Both chemical and mineral additives showed a beneficial effect on reducing the water absorption of concrete. The decrease in absorption of of concrete modified with Arpoment-O was 38% relative to the control concrete, the with the admixture Betocrete-C17—22.00% and fly ash—25.69%.

The study of capillarity

Pulling water through the capillaries is closely associated with the concept of sorptivity, that is, the speed of penetration of water into the concrete with the participation of atmospheric pressure. It is the ability to take up water by means of capillary forces. Samples were placed in a vessel so as to be in contact with the water surface, and then the amount of water absorbed was measured after 24 hours, rate of water penetration during this time was determined. Table 10 shows the results of measuring the amount of capillary water absorbed. For samples surveyed, a bar graph—Figure 5 illustrates the results. The parameter characterizing the capillarity is also the speed at which it enters the concrete [19].

Table 10: Water capillary through concrete

Concrete	Height of pulled water column [cm]				Height of water h [mm]	Speed rate k [mm/h]
	P-1	P-2	P-3	Average		
Z-0	7.2	6.5	6.2	6.6	66	2.75
Z-1	5.6	5.2	5.4	5.4	54	2.25
Z-2	4.0	3.8	3.9	3.9	39	1.62
Z-3	5.9	5.5	4.9	5.4	54	2.25

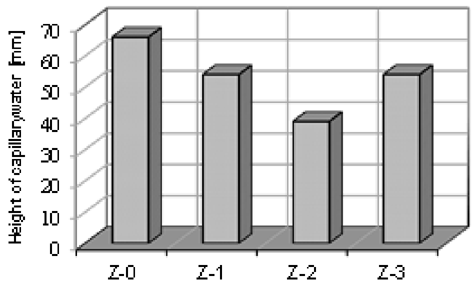

Figure 5. Capillarity of concrete

As a measure of capillary, h—the height of the water column pulled up and k—the speed at which the water penetrated the material were used. Most vulnerable to water penetration in comparison to the control concrete (h=66 mm, k=2.75 mm/h) proved to be Z-2 (Betocrete-C17) and Z-3 (fly ash) with equivalent values of h=54 mm and the same, resulting from h, k=2.25 mm/h. The best results were recorded for concrete containing Z-1 Arpoment-O. Water height h was different from the control concrete by 27 mm, measuring only 39 mm, while the water was getting much more slowly, at a speed of 1.62 mm/h.

Test of water transmission through concrete

The water permeability through concrete is determined by the degree of water resistance W2-W12 [8]. The study was performed on six samples of each of the four cubic mixtures with dimensions of 150×150×150 mm after 28 days of maturation according to standard [8]. Table 11 summarizes the results of the average penetration of water (Figure 6) and the degree of water resistance of concrete samples.

Table 11. Degree of concrete samples water resistance

Con-crete	Concrete samples						Average depth of penetra-tion [cm]	W[1)]
	P-1	P-2	P-3	P-4	P-5	P-6		
Z-0	6.3	5.8	4.9	6.2	6.1	5.7	5.8	W4
Z-1	4.2	3.5	3.6	4.1	3.8	4.0	3.8	W4
Z-2	2.0	2.8	3.2	2.5	2.8	2.6	2.7	W4
Z-3	3.9	3.5	2.8	2.9	3.2	3.4	3.0	W4

[1)]The degree of concrete water resistance.

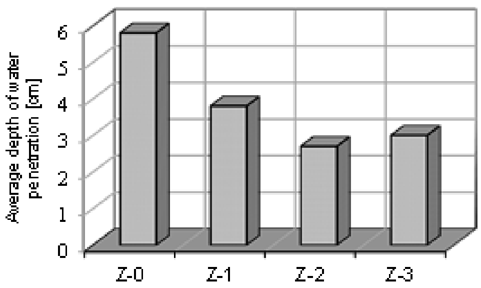

Figure 6. The water permeability through concrete

All samples for the study achieved the degree of water resistance W4, which means that none of them had signs of complete permeability under a constant pressure of 0.4 MPa. The minimum value and at the same time the best result was achieved by concrete Z-1 (Arpoment-O)—water column measured 2.7 cm depth in comparison to control sample Z-0 which allowed the water column measuring 5.8 cm. A similar result h=3 cm was reached by concrete with fly ash. The most permeable was concrete with Betocrete-C17 admixture with the result of 3.8 cm.

Conclusion

On the basis of the results analysis, it can be concluded that:

– Concretes of different composition differed in results in individual tests.
– Using admixtures improved the final compressive strength of the samples in comparison to unmodified concrete
– Adding the fly ash did not influence any change of concrete strength.
– Samples modified with chemical admixtures showed the highest water resistance. They allow to produce concrete resistant to water.
– Adding the silica fly ash decreased capillarity of water and decreased the depth of water penetration through hardened concrete mass.

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