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Sustainable Concretes – Through Reducing the Water Absorptivity to Improved Durability

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Abstract. Water absorptivity (WA) is one of the crucial parameters affecting the penetration of aggressive ions when concrete material is exposed to an aggressive environment and is closely linked with a depth of penetration of water under pressure into the concrete. Concrete used for prefabricated elements and structures as cesspits, manholes, pipe lines or parts of the wastewater treatment plants, has to meet a requirement for maximum water absorptivity of 6.0 wt. % in accordance with national and international standards. The article deals with a study of concretes' water absorptivity of the pre-cast products for environmental purpose, where the exposure class XA (chemical attack) is required. The research is focused on reducing WA by using various modification of standard mix design (Portland cement, water, fine and coarse aggregate, plasticizer), e.g. by using different cement types, cementous supplementary additives, admixtures, finest aggregate particles or by reducing water/binder ratio. The concretes of various mix design modifications were compared with a reference concrete in relation to the standard. The economical and environmental aspects were also taken into consideration.

Keywords: concrete technology, materials, water absorption, durability.

Conference topic: Environmental protection.

Introduction

Concrete is one of the most used civil engineering material due to its properties as adaptability to mould, speed of structures assembling, durability or cost of production (Neville, Brooks 2010; Mehta, Monteiro 2006). Durability is one of the crucial properties from the environmental point of view. That involves a fire resistance or health harmlessness, but especially also the resistance against physical, chemical and biological impacts (Neville 2011; Mehta, Monteiro 2006).

This article is concerned to water absorption as one of the parameters of concrete resistance to chemical corrosion that can be caused by carbonation, chlorides, sulphates, magnesium or many others compounds. In connection to concrete water absorption and environmental protection, it is necessary to note, that there can be seen two approaches. First of it is to reach the maximal concrete water absorption to make the concrete permeable for water. The importance of this resides in draining the urban areas of rain water with the purpose of reducing the overload sewer systems (Putra Jaya *et al.* 2014). Second approach is connected with producing the concrete with minimal water absorption value (Aïtcin 2005) for the structures with environmental purpose like sludge beds, seals for the foundation slabs or waste disposals, as well as for the parts of the sewer systems pipe lines or wastewater treatment plants. The durable concrete structures protect the environment from the leaks of dangerous compounds to soil and groundwater.

In the research was particularly monitored some aspects of test methods and impact of the water absorption test to the compression strength of samples (Bajza, Rouseková 2006). Testing methods and conditions are subjects of research e.g. in (De Schutter, Audenaert 2004; Castro *et al.* 2011; Zhang, Zong 2014).

The basic limit for water absorption of concrete exposed to the chemical corrosion (XA) is 6% of mass according to the technical standard STN EN 206/NA (national annexe) in the conditions of Slovak republic. To reach the required value of water absorption it is necessary to use knowledge of concrete technology, especially of its material engineering branch. Taking final costs into consideration is also necessary to achieve pursued intention, because of interconnection of environmental and economical sphere.

The objective of the paper was to study the effect of selected concrete's input materials to the final parameter – concrete water absorption. The optimal concrete mix receipt will be evaluated from the material technology, environmental and economical point of view.

Theory of concrete water absorption

The concrete water absorption (WA) can be defined as the proportion of concrete mass, that can be free fulfill by water (Svoboda 2013). It can be also determined as volume water absorption. The value of WA is calculated according to the following equations (STN 73 1316):

$$WA(mass) = \frac{m_w - m_d}{m_d} * 100\%, \quad (1)$$

where: m_w – satured sample mass; m_d – dried sample mass

$$WA(volume) = \frac{\rho_w - \rho_d}{\rho_{H_2O}} * 100\%, \quad (2)$$

where: ρ_w – satured sample density, ρ_d – dried sample density, ρ_{H_2O} – water density.

Based on the definition, it is obvious that there can be vacant spaces in the concrete what makes concrete to be porous (Mehta, Monteiro 2006). In normal state, this free voids (pores and capillaries) are occupied be air, but the damages can arise in the case, when this space is occupied by water involving aggressive chemical compounds that are able to deteriorate concrete structure. The most known chemical concrete deteriorations are carbonation and chloride and sulphate corrosion (Pavlíková, Keppert 2009).

The testing methods is prescribed in the technical standard STN 73 1316. The principle of this test is to measure the weight difference between saturated and oven dried sample. From the weight loose caused by water vaporization it is not difficult to determine also free volume in a sample. Mass WA is usual parameter and indicates porous ratio of concrete. By the authors' opinion, volume WA is more illustrative parameter that indicates amount of free (accessible) space in defined volume of concrete. Detailed procedure and the others working and calculating procedures are described in the part Methods.

There are two main factors that influence the water absorption the most: the maximum aggregate grain and water / binder ratio. As described in (Mehta, Monteiro 2006), the higher are the values of both these factors the higher value of WA will be achieved. It is caused by developing of the micro-crack structure in the concrete micro-structure at the interface zone between aggregate grains and cement paste (using bigger maximal grain means larger particular interface zones) and by formation of capillaries caused by excessive evaporation (especially by bleeding) of superfluous water. Both of these micro-crack systems subsequently connect voids made by entrapped air, what makes complex porous system and the concrete more permeable in the final. This research was more focused on second option, especially to dense the concrete micro-structure by using materials that are able either seal its micro-structure or to dense it by reducing water/binder ratio. As mentioned above, it is possible to influence the value of WA by some concrete input materials (Mehta, Monteiro 2006; Aïtcin 2005).

Materials and Methods

Concrete composites of various compositions based on the modification of the input materials were prepared. Reference materials included: Portland cement, three fractional aggregate, drinking water and superplasticizer. As modification materials were used: hydrophobic admixture, aggregate with the finer grains and blast furnace slag cement. The material's characteristic and the expected effects (Aïtcin 2005) on WA are as follows:

Cement CEM I 42.5 R

- Density: 3100 kg/m^3
- Portland cement with fast early strenght increase.
- Standard cement type with a universal use.

Cement CEM II/B-S 42.5 N

- Density: 3050 kg/m^3.
- Portland-slag cement with normal early strength.
- Blast furnace slag content between 21–35%.
- Expected effect on water absorption (mix e): decrease of wa value due to normal strenght growth and effect of blast furnance slag, that reacts with a residual portlandit to make denser microstructure.
- Blast furnance slag is considered to be waste, using which makes concrete more environmental building material.
- From the point of concrete technology view, this cement type is also used in hot weather condition and where higher durability concrete is required.

Aggregate

- Density: 2680 kg/m^3.
- Water Absorption: 1.5%.
- Natural pre-crushed aggregate from own mining; manufacturing by crushing, sieve-sorting and washing.
- Granularity curve was design as three-fraction.

- Expected effect of finer fraction adding on water absorption (mix b): improve fresh concrete rheology with the same water-binder ratio; a better compaction of the fresh concrete, what would lead to denser microstructure microstructure.

Drinking water

- Density: 1000 kg/m^3.

Plasticizer

- Density: 1060 kg/m^3.
- Based on polycarboxylates.
- Water-reduction admixture (superplasticizer).
- Expected effect of higher plasticizer content ad lower mix water content (mix d) on water absorption: decrease of the WA value due to reduction water-binder ratio by reducting needed mixing water; what is one of the most influencing factor of WA.
- Using plasticizer has common environmental aspect, for as much as it reduces needed content of mixing water up to 30%, therefore content of cement; however economical aspect of using has to be take into consideration.

Hydrophobic admixtuer

- Density: 1020 kg/m^3.
- Based on organic silica compound that acts as water and moisture displacer in hardened concrete.
- Expected effect of using the hydrophobic admixture (Mixture C) on water absorption: considerable decrease of the WA value, inherently of the intended use.

All concrete samples have been prepared at the concrete plant (Prefa, Sucany, Slovakia). The designed receipts of the fresh concrete mixtures and input materials weights of each batch are given in Table 1. Mixture A, consisted of CEM I, 3-fraction aggregate, water and plasticizer was considered as a reference mixture. Mixture B was a modification of mixture A by replacement of 20 wt.% of fine aggregate fraction 0/4 by even finer fraction of 0/0.7. In the Mixture C, hydrophobic admixture was used. Mixture D was set to decrease W/B ratio by rising of plasticizer content and reducing mixing water content. In Mixture E, there was used the CEM II/B-S instead of CEM I.

The reference mixture (A) was designed for 1m^3, the batch amout (28 L) was set according to amount of particle action (tests, samples and reserve). Input materials weights of modified mixtures (B-E) came out from composition of (A) batches. The mixing was performed first as dry mixing (cement+agggregate) and after adding water and admixture as wet mixing. Slump and air content was tested immediately after mixing finished. Sample of fresh concrete was putting in bowl and drying in oven to specify total water concrete in mix. From each of mixture A, B, C, E was taken 4 cube sample (a = 150mm), three of them consolidating for 10s in two layers (1–3) and another one (X) for 20s in two layer to observe the effect of consolidating time to WA. After that was filled testing mould weighed to set indicative fresh concrete density. 5 samples of mixture D were taken, considering zero slump (air content test was not performed), because there was a prediction of significant compressive strenght with set cement content. Three of samples of D (1–3) mixture were used for intended water absorption test – WA(1), another two (d1, d2) were used as comparative samples for compressive strenght tests. Real mix proportions per 1m^3 were calculated according to results of total water content.

The mould with samples was curing under local lab condition, demoulded after 3 days and put to the water bath up to 28th day since they were prepared. Consequently, the samples were taken out from water, the surface water was removed, the cubes were weighted and dried into owen at the temeperature 105°C±5°C untill the constant weight whereas the difference in weights of two measurement in 24 hours was lower than 0,1%. Appropriate calculations were performed.

Considering that the samples were not destructed, they should be used for another tests as repeat water absorption test –WA(2) and compressive strenght test (CST). In connection of CST, dimenssions of samples were measured and appriopriate features were calculated (contact area, volume, densities, compressive strenght f_c) and set (compressive force, weight before destruction).

Table 1. Fresh concrete mixtures and the properties

MIXTURE	A		B		C		D		E	
Description	Reference		Finner aggregate		Hydrophobic admixture		Lower water content with higher plasticizer content		Blast furnace cement	
Material	batch	m^3 (calc.)	batch	m^3 (calc.)	batch	m^3 (calc.)	batch	m^3 (calc.)	batch	m^3 (calc.)
CEM I 42.5 R (kg)	9.5	349	9.5	354	9.5	347	9.5	355	–	–

End of Table 1

MIXTURE	A	B	C	D	E	MIX-TURE	A	B	C	D
Description	Reference		Finner aggregate		Hydrophobic admixture		Lower water content with higher plasticizer content		Blast furnace cement	
CEM II/B-S 42.5 N (kg)	–	–	–	–	–	–	–	–	9.5	351
Aggregate 0/0.7 (kg)	–	–	5.0 (9.5%)	–	–	–	–	–	–	–
Aggregate 0/4 (kg)	25.0 (48%)	–	20.0 (39%)	–	25.0 (48%)	–	25.0 (46.5%)	–	25.0 (48%)	–
Aggregate 4/8 (kg)	5,0 (9.5%)	–	5.0 (9.5%)	–	5.0 (9.5%)	–	7.0 (13%)	–	5.0 (9.5%)	–
Aggregate 8/16 (kg)	22,0 (42.5%)	–	22.0 (42%)	–	22.0 (42.5%)	–	22.0 (40.5%)	–	22.0 (42.5%)	–
Agrregate tot, dry (kg)	50.63	1860	51.35	1914	50.67	1853	53.73	2006	51.14	1890
Aggregate tot, wa (kg)	51.39	1887	52.12	1943	51.43	1881	54.54	2036	51.91	1919
Water – batch (L)	4.0	–	4.0	–	4.0	–	3.43	–	4.0	–
Water – total (L)	5.37	197	4.65	173	5.33	195	3.70	138	4.86	180
Water – total (%)	8.193	–	7.100	–	8.193	–	5.619	–	7.422	–
Water – effective (L)	4.61	169	3.88	145	4.57	167	2.89	108	4.09	151
Plasticizer (kg) (% of cement)	0.032 0.32%	1.10	0.032 0.32%	1.12	0.021 0.22%	1.10	0.087 0.92%	3.08	0.032 0.32%	1.12
Hydroph. Admixture (kg) (% of cement)	–	–	–	–	0.040 0.42%	1.43	–	–	–	–
Calculated density ρv (kg/m^3) (L)	65.53 (27.22)	2406 (1000)	65.53 (26.85)	2443 (1000)	65.56 (27.34)	2398 (1000)	67.02 (26.79)	2502 (1000)	65.53 (27.06)	2422 (1000)
Costs	–	i	–	1.025i	–	1.040i	–	1.102i	–	0.956i
W/C –)	0.49	–	0.41	–	0.48	–	0.30	–	0.43	–
Slump (mm)	60–65	–	120	–	55	–	0	–	50	–
Air cont. (%)	1.25	–	1.5	–	1.7	–	NA	–	1.7	–

Results

Fresh concrete properties

The results of fresh concretes testing are reported in Table 1. A cone slump test, an air content test and a total water test were performed immediately after batch mixing. Total water content (%) was determined as:

$$W_{tot} = \frac{m_w - m_d}{m_w} * 100\%, \quad (3)$$

where: m_w – satured sample mass; m_d – dried sample mass.

All the air content tests may be considered as approximately the same. The case of the modification "D" will be discussed later. The result of the slump test for Mixture A was 60–65mm what matches up to consistency S2 and the total water content was approximately 8.2%. These results were taken into consideration as the reference results. The batches of the Mixtures C and E met the similar results, what was caused by similar proportion of input materials. A little bit lower slump of the Mixture E was caused by little bit lower content of water. Also the fresh concrete densities of these three receipts were similar. The slump of batch of the Mixture B is significant higher together with the lower total water content. It was caused by improvement a rheology of concrete, considering that the finer aggregate enhances a granularity and by this a flowingness of concrete. The lower need of water also caused the higher density of the fresh concrete. The batch of the Mixture D was markable different from the point of a rheology view. This concrete mix suggested composite of third type (Bareš 1988). The very low water content decreased the slump of fresh concrete at the minimum, but at the same time the consolidation was not make any problem. After starting vibrations (giving the concrete energy), the concrete started consolidating the same way as others batches. The lowest content of the water had also impact to the fresh concrete density that was the highest of the all batches. Due to difficulty of processing the sample, the air content test in this case was not performed.

Hardened concrete properties

The results of hardened concretes testing are reported in Table 2. The values of the density in the saturated state (ρ_w) more or less relate to the density of fresh concrete. The density in the dried state (ρ_d) is influenced by water absorption. The significant facts is, that the values of density in the saturated state before a compression strength test (ρ_{CST}) is lower approximately by 10–15 kg/m^3, what can be caused by processes during the drying the samples. In connection to the samples, that were undergone second WA test (Mixtures C and D) it had impact to its lower results. The values of the density in the saturated state before CST after second WA test did not change significantly.

The results of compression strength test turned into expected results in relation to reference Mixture A in the sense of total water content (Mixtures B and D) or input material (Mixture E). The impact of various type of processing after drying samples on the compression strength is not possible to evaluate in connection to very few results. The reference samples of batch D, which were not dried, proved that process of drying decreases the compression strength. It can also be observed by comparison of the 28 day compressive strength results from producing-control monitoring of similar concrete mix proportion produced by Concrete plants Prefa (Sucany, Slovakia).

Water absorption

The results of WA varied from 4.6 to 6.9% and from 10.7 up to 15.3% for mass and volume WA, respectively, regarding the reference Mixture A. The Mixtures B and C reached the similar values as Mixture A. In the case of modified Mixture B the result could be better if it would set for the same consistency, what should cause decrease water/binder ratio and also the WA value. Expected result was not achieved by modification in Mixture C in spite of using admixture intended exactly for this purpose. This could reside either in the admixture quality or in the amount of batches, where the effect of the admixture could not be develop. A little bit better result (–0.4%/–0.7%) compared to the reference receipt was achieved for mixture C, what can be explained either as lower W/B ratio but also as structure compacing effect of blast furnace slag. Modification D reached the best result, what was caused by the lowest water content (and also W/B ratio) and the densest structure.

Costs

The costs are calculatedd for 1m^3 of fresh concrete as summation of amount and particular products' costs of each input material. The reference A receipt's costs are represented by "i". Another mixes' costs are derived by multiplying the costs of receipt A by coefficient regarding the other mix costs: $i \times x$. From the economical point of view, the Mixture E achieved the lowest costs (96.3% of reference costs of Mixture A), what was caused by price of portland-slag cement. The highest cost was achieved for Mixture D (110.6% of reference costs of Mixture A), what was caused by using a higher content of plasticizer, which is the most expensive concrete input material.

Based on the results presented, taking into consideration all of technical, economical and environmental aspects, an optimal concrete mix receipt has been designed. The design was inspired by Mixtures B, D and E as their combination. In connection to the practical durable concrete design, requiring a low water absorption, the following receipt was suggested to have optimal composition with pretended properties (Table 3).

Table 2. Result from hardened concrete testing

	A				**B**				**C**				**D**					**E**			
	1	2	3	X	1	2	3	X	1	2	3	X	1	2	3	d1	d2	1	2	3	X
ρ_w kg/m^3	–	2387	2392	2400	2404	2387	2393	2397	2393	2404	2393	2393	2479	2468	2459	–	–	2413	2364	2396	2460
ρ_d kg/m^3	–	2234	2239	2247	2260	2233	2244	2247	2237	2253	2246	2240	2373	2359	2352	–	–	2269	2219	2247	2316
WA (1) mass vol. %	6.9 –	6.8 15.3	6.9 15.3	6.9 15.3	6.4 14.4	6.9 15.4	6.6 14.9	6.7 15.0	7.0 15.6	6.7 14.1	6.5 14.7	6.9 15.3	4.5 10.6	4.6 10.9	4.6 10.7	–	–	6.4 14.4	6.6 14.5	6.6 14.9	6.2 14.4
	6.9 **15.3**				**6.7** **14.9**				**6.8** **14.9**				**4.6** **10.7**			–	–	**6.5** **14.6**			
oper.	–	cooling down in water (CW)			cooling down in water				cooling down on air (CA) > water bath (WB)				cooling down on air > water bath			–	–	cooling down on air > water bath			
ρ_{CST} kg/m^3	–	2375	2381	2387	2391	2371	2379	2383	–	2388	–	2378	2471	2460	2452	2463	2468	2400	–	2381	–
f_c (day) MPa	–	30.2 (40)	29.5 (40)	30.7 (40)	34.0 (40)	32.7 (40)	33.6 (40)	33.6 (40)	–	30.5 (40)	–	33.6 (40)	54.3 (40)	57.0 (40)	51.9 (40)	69.0 (40)	67.1 (40)	39.1 (47)	–	35.2 (47)	–
ρ_w kg/m^3	–	–	–	–	–	–	–	–	2378	–	2379	–	–	–	–	–	–	–	2349	–	2446
ρ_d kg/m^3	–	–	–	–	–	–	–	–	2237	–	2246	–	–	–	–	–	–	–	2215	–	2312
WA (2) mass vol. %	–	–	–	–	–	–	–	–	6.3 14.1	–	5.9 13.3	–	–	–	–	–	–	–	6.1 13.4	–	5.8 13.4
oper.	–	–	–	–	–	–	–	–	CW	–	CA > WB	–	–	–	–	–	–	–	CW	–	CW
ρ_{CST} kg/m^3	–	–	–	–	–	–	–	–	2379	–	2379	–	–	–	–	–	–	–	2347	–	2443
f_c (day) MPa	–	–	–	–	–	–	–	–	32.9 (50)	–	30.2 (50)	–	–	–	–	–	–	–	37.2 (55)	–	37.7 (55)

Table 3. The final concrete mixture design with the pretended parameters.

Material	Mass (kg) per $1m^3$	Notes
CEM II/B-S 42,5 N	360	In connection to W/C ratio meets XC4 and XD3 conditions. Also XF1 and XA3 conditions can be met according to EN 206/NA
Aggregate 0/0.7	134	7% of A_{tot}
Aggregate 0/4	861	45% of A_{tot}
Aggregate 4/8	96	5% of A_{tot}
Aggregate 8/16	823	43% of A_{tot}
Water (effective)	140	W/C=0.39
Water (total)	169	
Plasticizer (polycarboxylatether)	2.1	0.58% of cement mass

The receipt is designed for a dry aggregate. Materials and its costs are selected of available source for the concrete mixing plant. The proposed mixture of density 2442 kg/m3, air content of 1.5%, and S3 consistency would meet the water absorption mass parameter <5% and permeability according STN EN 12390-8 <50 mm. In addition, the requirements for the XF1 and XA3 classes should be met by achieving a maximal depth of the penetration of water under pressure 50 mm according to EN 206/NA. The composites are designed to achieve a 28-day compression strength >55MPa what classifies them to the compressive strength class C45/55 at least. The costs for this receipt amount 1,021i, what means the slightly increase (+2.1%) against reference receipt A. It can be considered as acceptable due to possible achieved parameters.

Conclusions

The finding revealed that optimisation of technological process and even slight modification in materials inputs can significantly effect the final performance of concretes. The next research will be focused on investigation the real parameters of concrete composites with the proposed mixture. If only the pretended and measured real results were just very similar, there would be attained all the technological (rheology, consistency, strength, water absorption), environmental (durability related to WA, using portland-slag cement) and economical (costs related to achieved parameters) aspects.

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Contribution

A. Eštoková was resposible for conception and design of the work. R. Figmig was resposible for acquisition of data, analysis and interpretation of data and drafting the article. M. Smoláková was helpfull at revising the article.

Disclosure statement

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