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Hydrophobic shotcrete – a method to waterproof tunnels

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SUMMARY: Admixtures that make concrete hydrophobic are often based on siloxanes and are normally used for special applications. The siloxanes as admixtures are effective but often too expensive in comparison with, for example, an ordinary water repellent treatment. A hydrophobic impregnation gives a better effect, not only when the actual cost is compared but also in terms of reduced water transport. However, in a tunnel environment the humidity is often too high for a water repellent treatment and an admixture could be useful. The experiment on shotcrete with a hydrophobic admixture based on ethoxylated polyols and carboxyl acid show a significantly reduced water transport and it is a promising alternative.

KEY-WORDS: shotcrete, hydrophobic admixture, carboxyl acid, ethoxylated polyols

INTRODUCTION

Porous materials will always contain a certain amount of water in their natural environment. For concrete, which is a porous material, several durability problems are related to the moisture content inside the pores. The expansion of water upon freezing can cause severe damages to concrete if the pores are saturated. Reinforced concrete is also affected by the alkali silica reaction (ASR) as well as the corrosion of reinforcement bars both of which depend on the access of water. These are all problems that are linked to the degree of saturation in the pores. Moisture is not always the main reason for the problem but it is one of the most important parameters for the rate of the deterioration process.

Current water repellent agents mainly consist of alkylalkoxysilanes, are often used on concrete to prolong the service life of the structure. This is accomplished by protecting the reinforcement bars from chlorides and/or by changing the moisture content inside. When the concrete is treated with a water repellent agent the properties of the surface layer turn from hydrophilic to hydrophobic and thereby water droplets are stopped from entering, though allowing water vapour to pass through. This property change can reduce chloride ingress and stop rain from penetrating through the surface layer. However, a water repellent treatment applied on the surface has a clear disadvantage related to saturated pores in an environment with high humidity. As known, the effect of a hydrophobic impregnation is in most cases correlated to the penetration depth, which depends on the porosity, time and the degree of saturation inside the pores as illustrated in Fig. 1 [1]. (Time is defined as the period which the treated surface stays in contact with the water repellent.) However, there are situations where a surface impregnation is difficult to implement, as for example, inside a tunnel due to the often high humidity level inside the concrete.

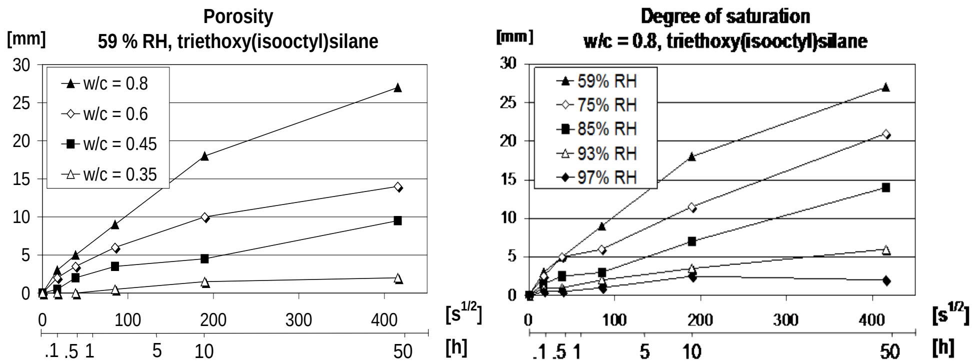

Figure 1. The influence of porosity, as illustrated for concrete mixtures of different water-cement ratio, degree of saturation and time on the visual penetration depth [1]. The time on the x-axis is the contact time with the impregnation agent.

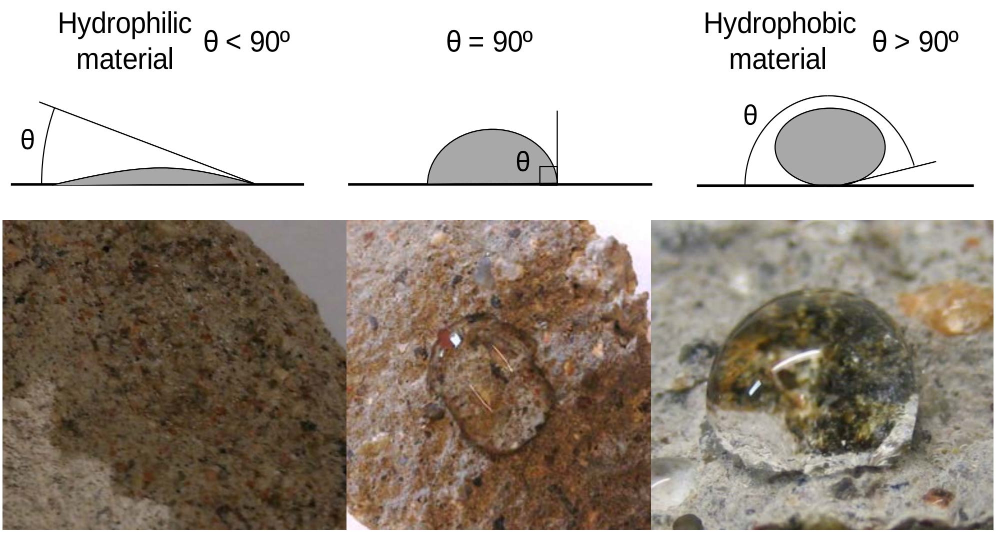

Figure 2. From the left to right: Hydrophilic concrete, concrete with a hydrophobic admixture and a concrete specimen treated with a alkylalkoxysilane water repellent and then cracked open [2].

Shotcrete is used in tunnels for several reasons, among them the prevention of leaks and having a water repellent layer would reduce the infiltration of deicing salts into the structure. Therefore, hydrophobic admixtures are of interest even if their effect is not as significant as in the case of a surface treatment. Nonetheless, as illustrated in Fig. 2, comparison of contact angles show that it can be useful.

METHODOLOGY

Two different shotcrete formulations were wet-sprayed in boxes, stored 1 week under water and then three weeks in 65% RH (relative humidity) before the test procedures were initiated. A sulfate resisting Portland cement with low alkali clinker and moderate heat development (CEM I 42.5N SR3 MH/LH) was used in the mixes and the aggregates from glaciofluvial deposits were well shaped. The superplasticizer used was a polycarboxylate ether type. One formulation used a water-cement ratio of 0.40, the other 0.55. The hydrophobic admixture investigated is based on dimerized dicarboxylic acid salt blended with ethoxylated polyols which is soluble in water before it reacts. The molecules react with divalent metal ions to form an insoluble rubber-like polymer within the concrete. The acid group coordinates strongly to calcium at any surface, and the polymer (hydrophobic part) will stand away from the surface and ensure a high contact angle towards water. The specific product is protected by one or more patents [3-7]. The applied dosage for the shotcrete formulations was 1.0% by volume of the concrete. The influence of a alkali-free accelerator was also studied and all the results are compared to an ordinary water repellent treatment based on isobutyltriethoxysilane applied twice as a liquid for 60 seconds, henceforth impregnated specimens. Samples without the hydrophobic admixture served as reference.

Capillary water absorption

The capillary water absorption coefficient A [$kg/m^2s^{1/2}$] was determined from the slope of the first part in the graph of weight increase versus time diagram before the capillary rise reached the height of the specimen. To be able to compare values, it is important that a uni-dimensional flow is ensured and that the sample is dry when the experiment is started. Cores with 100 mm in diameter were drilled from the wet sprayed concrete and cut into 30 mm thick plates. The first and last plates from each core were removed from the setup in order to avoid boundary effects. Finally they were placed inside an oven at 40°C for three months in order to ensure that the samples were completely dry (by weight) before the test procedure was initiated.

Drying

After the water absorption test, the specimens were immersed in water for about 2 months, which was the time required for the untreated reference and hydrophobized shotcrete specimens show the same weight gain. The specimens were not saturated with vacuum since this could fill the pores that normally would not be affected.

The surface treated specimens were placed so that they dried through the treated surface. Desiccation occurred in 65% RH and 20 °C.

A dehydration coefficient D [kg/m^2s] was calculated from the weight loss during the second day.

Frost resistance

The frost resistance was tested according to the Swedish standard SS 13 72 44 [8]. The method is a freeze/thaw resistance test in which the specimens are exposed to a 3% NaCl solution. The temperature varies from +20 °C to -18 °C over 24 h periods to complete one cycle. In the evaluation, the results are divided into four categories based on the amount of spalled material.

The test normally consists of 56 cycles but can be extended to 112 in some situations. One specimen went on to 112 cycles since it ended up between two of the above mentioned categories. Specimens surface treated with the water repellent were not subjected to this test.

Two series were conducted, the specimens were conditioned at either 65% RH or 100% RH for at least two weeks or until the test was performed. This was done with the objective to determine whether the results were affected by prior conditioning environment since a water-repellent admixture causes a significantly slower drying which theoretically could affect the humidity level inside the specimens at the start of the test given the short conditioning period prescribed in the standard.

RESULTS

Fig. 3 shows the difference in water repellent effect between the shotcrete without admixture and the one with. The effect is clear even if it is not quite as strong as if it was an ordinary surface applied water repellent treatment.

Figure 3. Water repellent effect on two drilled cores. On the left, a reference specimen showing the dark wet interior, and on the right, one with the hydrophobic admixture where there is not such a visible contrast. Both specimens had a 0.4 w/c-ratio.

Capillary water absorption

Table 1 shows the results from the water absorption experiments.

Table 1: Water absorption of the studied specimens. The last column shows the weight increase percentage when compared to the untreated reference. The comparisons are made for samples with the same w/c-ratio. A positive number means the water absorption is higher than that of the reference.

Capillary water absorption				
Sample		Capillary absorption coeff. A [$kg/m^2s^{1/2}$]	Average A_{AB} [$kg/m^2s^{1/2}$]	Weight increase [%]
Reference, w/c=0.40	A	0.0054	0.00495	
	B	0.0045		
Reference, w/c=0.40 (accelerator)	A	0.0104	0.00975	**97.0**
	B	0.0091		
Hydrophobic admixture, w/c=0.40	A	0.0024	0.0023	**-53.5**
	B	0.0022		
Hydrophobic admixture, w/c=0.40 (accelerator)	A	0.003	0.00245	**-50.5**
	B	0.0019		
Impregnated, w/c=0.40 (Isobutyltriethoxysilane)	A	0.0005	0.00045	**-90.9**
	B	0.0004		
Reference, w/c=0.55	A	0.0083	0.011	
	B	0.0137		
Hydrophobic admixture, w/c=0.55	A	0.0017	0.0016	**-85.5**
	B	0.0015		
Impregnated, w/c=0.55 (Isobutyltriethoxysilane)	A	0.0008	0.0007	**-93.6**
	B	0.0006		

From the table the following points can be noted regarding w/c = 0.40:

- The use of the accelerator resulted in a nearly two-fold increase in water absorption for the reference. The extra water contributed by the accelerator changed the hardening process is also likely to contribute to a more open pore structure as reflected by the capillary water absorption coefficient.
- The addition of the hydrophobic admixture resulted in an over 0.5 decrease of the capillary water absorption coefficient by more than half when compared with the reference. This also applies to the admixture in combination with the accelerator when compared to the reference without the accelerator.
- Comparison of the shotcretes with accelerator, the addition of the hydrophobic mixture results in a water absorption reduction of about 75%.
- The surface impregnation gave a reduction in water absorption of more than 90%.

For the case of the w/c = 0.55 formulations the following can be noted:

- The addition of the hydrophobic admixture has reduced water absorption by over 85% compared to the reference.
- The surface impregnation resulted in a 94% reduction in water absorption.

Drying

Table 2 shows the results of water desorption experiments.

Table 2. Water desorption of the investigated specimens. The last column shows the difference in percentage when compared to the reference. The comparison is made against the reference with the same w/c-ratio. A positive number means the water desorption is higher than the reference.

Drying				
Sample		Drying rate coeff. D [kg/m^{2}s]	Average D_{AB} [kg/m^{2}s]	Weight loss [%]
Reference, w/c=0.40	A	1.14358E-06	1.32E-06	
	B	1.48666E-06		
Reference, w/c=0.40 (accelerator)	A	1.82973E-06	1.5E-06	**14.3**
	B	1.17626E-06		
Hydrophobic admixture, w/c=0.40	A	5.39117E-07	5.88E-07	**-55.3**
	B	6.37139E-07		
Hydrophobic admixture, w/c=0.40 (accelerator)	A	1.09457E-06	9.48E-07	**-28.0**
	B	8.00508E-07		
Impregnated, w/c=0.40 (Isobutyltriethoxysilane)	A	4.24759E-07	4.98E-07	**-62.1**
	B	5.71791E-07		
Reference, w/c=0.55	A	1.9931E-06	1.86E-06	
	B	1.73171E-06		
Hydrophobic admixture, w/c=0.55	A	1.17626E-06	1.18E-06	**-36.4**
	B	1.19259E-06		
Impregnated, w/c=0.55 (Isobutyltriethoxysilane)	A	8.98529E-07	7.68E-07	**-58.8**
	B	6.37139E-07		

From the table the following points can be noted regarding w/c = 0.40 specimens:

- The use of the accelerator which resulted in sharply increased water absorption also provides a faster drying for the case of the reference specimens.
- The addition of the hydrophobic admixture slows down the drying rate significantly though not quite as much as for the surface impregnated specimens.

From the table the following is noted regarding w/c = 0.55:

- The drying rate is slower with the addition of the hydrophobic admixture though still considerably faster than the impregnated one.

Frost resistance

Two separate series were conducted, one in which the specimens were conditioned for two weeks at 100% RH before the test was initiated and one at 65% RH. In the evaluation, the results are divided into four categories based on the amount of spalled material: Very good, Good, Acceptable and Not acceptable. Since no samples ended up in the Acceptable this was not included in Table 3, where the results are shown.

Table 3: The results from the frost resistance test. The Acceptable category is not shown as no specimens fell into it.

Frost resistance							
		100 % RH			65 % RH		
Sample		Very good	Good	Not accept.	Very good	Good	Not accept.
Reference, w/c=0.40	A	x					
	B	x					
Reference, w/c=0.40 (accelerator)	A	x					
	B		x				
Hydrophobic admixture, w/c=0.40	A	x			x		
	B	x			x		
Hydrophobic admixture, w/c=0.40 (accelerator)	A	x				x	
	B		x			x	
Reference, w/c=0.55	A	x					
	B	x					
Hydrophobic admixture, w/c=0.55	A			X			x
	B			X	x		

From the results in Table 3 the following can be noted:

- All specimens with w/c = 0.40 scored good or very good whether the hydrophobic admixture was used or not.
- The use of the accelerator resulted in a worse rating for the case of the reference samples with 0.40 w/c ratio. 4 of 6 specimens with accelerator scored Good, while those without it scored Very good.
- For the 0.55 w/c ratio, the reference scored Very good, while those with the hydrophobic admixture 3 out of 4 scored Not acceptable the other being Very good, resulting in a wide spread in the results.
- The conditioning prior to the test appears not to have had a major impact on the outcome.

CONCLUDING REMARKS

Deterioration mechanisms of concrete structures are usually related to moisture level inside the hardened concrete. Moisture creates the condition for reinforcement corrosion and spalling, frost, chloride attack, alkali silica reactions, and leaching. Corrosion processes require both water and oxygen to start. By changing the concrete from hydrophilic to hydrophobic a lower moisture level environment is created that reduces the probability for the various deterioration processes to be initiated. In this study, a water-repellent admixture was tested in shotcrete to investigate whether this admixture specifically is an option for reducing moisture content in concrete structures in harsh environments. The conclusions, however, could also be likely to apply for other products in this category.

During the test-spraying of this hydrophobic shotcrete it was found to behave similarly to the usual shotcrete spraying. This should be considered a positive attribute as it will not require changes in routines. A clear water repellent effect was noted on the cracked concrete surfaces, although not as strong as with an ordinary surface applied water repellent treatment. With the hydrophobic admixture a water repellent effect throughout the matrix is obtained and not just a few millimeters at the surface which is usually the result of a surface impregnation. The compressive strength (28-day) was hardly affected by the admixture.

Two main points stand out from the obtained results:

- The addition of the hydrophobic admixture reduces water absorption significantly and the more porous the concrete, the greater the effect.
- The drying is slower in a shotcrete with the addition of the hydrophobic admixture and even here the effect is clearer for a porous concrete than a dense.

Similar results were obtained with other hydrophobic admixtures in previous studies [9].The effect of the hydrophobic admixture on frost resistance was also investigated and no appreciable effect was noted but the spread in the results for the samples with higher w/c ratio was great. One possible explanation for this may be that the slow drying of hydrophobic concrete may results in a higher humidity level at the start of the test procedure which might be disadvantageous. For this reason an alternative conditioning procedure was chosen but which did not significantly improve their performance. This requires further testing to determine the effect of the initial moisture content during this test.

The use of an accelerator provides several negative effects related to deterioration. The concrete will be open for the transport of water and harmful substances dissolved in water. The strength and frost resistance is lower. There may be many reasons for this but the increased amount of water in the shotcrete accelerator is one factor that probably also affects the cement hydration reactions. Again, further studies are required in order to draw conclusions about this.

Hydrophobic admixtures in concrete are of general interest since they may be applicable to many different situations.

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