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Performance of Hydrophobisation Techniques in Case of Reinforced Concrete Structures

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Abstract. Concrete is, unchangeably, one of the most frequently applied building materials, also in the case of bridges, overpasses or viaducts. Along with the aging of such structures, the degradation of concrete, which may accelerate the corrosion of reinforcing steel and drastically decrease the load-bearing capacity of the structure, becomes an important issue. The paper analyzes the possibilities of using deep hydrophobisation in repairing reinforced concrete engineering structures. The benefits of properly securing reinforced concrete structures from the damaging effects of UV radiation, the influence of harmful gases, or progression of chlorine induced corrosion have been presented, especially in regards to bridge structures. The need to calculate the costs of carrying out investments along with the expected costs of maintaining such structures, as well as the high share of costs connected with logistics, has also been indicated in the total costs of repair works.

1. Introduction

Repairs of engineering structures, and especially bridge constructions, always prove to be expensive undertakings. The realization of such works, depending on the level of degradation exhibited by structural elements, is complex and relatively time-consuming. At the same time, the closing of key transit routes generates indirect costs connected with obstructing traffic flow, and new routes often include roads which are not suited for the increased intensity of traffic. It can, therefore, be stated that the maximum possible increase of service life ought to become the aim of all participants of the building process, starting with investors, who most often comprised of self-government or central government units, all the way to the hired contractors. The significant costs of logistics of such building undertakings as repairs of engineering structures are especially problematic [1, 2]. The economic aspect is not, in point of fact, the only one in terms of which the necessity of repair works on engineering structures ought to be considered. These are, very often, technologically difficult tasks to carry out, in addition to being energy intensive, which must surely be perceived negatively in today's time of sustainable development [3, 4, 5].

The problem concerning the durability of reinforced concrete building structures is all the more difficult to solve considering that they constantly function in changeable weather conditions. One of the most effective as well as economically beneficial means of protecting concrete surfaces from the influence of an aggressive environment is a series of protective coating systems. Creating an impenetrable barrier that prevents harmful substances from penetrating into concrete, including, above all, chlorides derived from sea water and substances for de-icing road surface, does not, however, guarantee total success. Such a coating must be characterized by high durability and permeability of water vapour in order for excessive water to evaporate freely. Taking in consideration all of the above-mentioned aspects - one of the most effective means of securing concrete surfaces is hydrophobic impregnation, or providing the concrete surface with hydrophobic properties. The highest durability can in turn be obtained with the use of deep hydrophobisation [3, 4].

2. Harmful effects of the environment

Bridge constructions and roads are among the structures exposed to the highest risk of degradation (Figure 1). As a result of this, in accordance with the standard PN-EN 206-1:2014 Concrete. Part 1. Specification, performance, production and conformity [6], the appropriate classification of the structure should be carried out each time in order to select appropriate preventive measures (Figure 2).

Figure 1. Sample damage to reinforced concrete engineering structures caused by external factors [7]

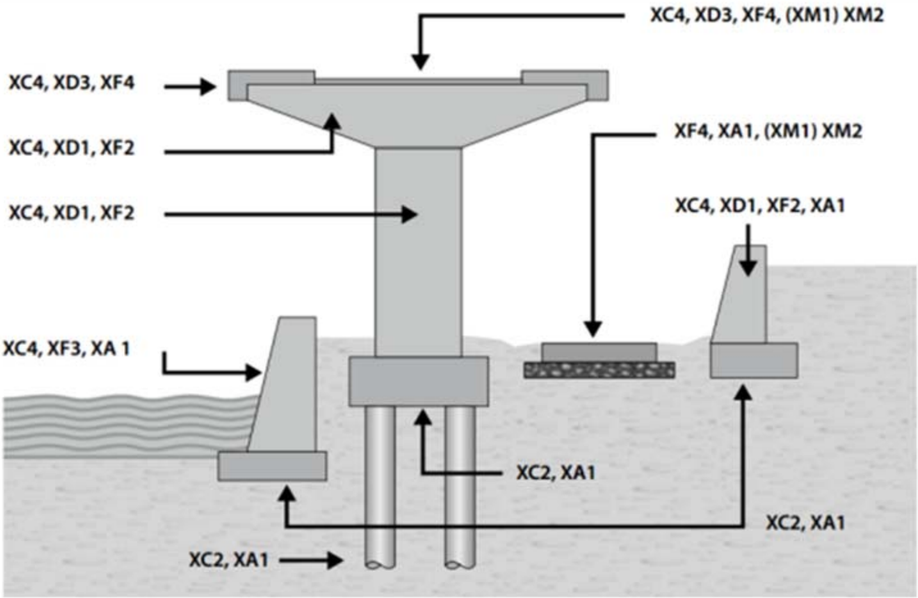

Figure 2. Examples of exposure classes in transportation construction [8]

Particular attention ought to be given to structural elements of viaducts and bridges falling into exposition classes XD3 and XC4, among others elements of bridges exposed to the effects of chloride containing aerosol particles, as well as those structural elements whose concrete surfaces are at risk of long-term contact with water [3, 7]. There are many circumstances which intensify the processes of damaging concrete, with the basic ones including [8]: improper compaction of the concrete mixture, incorrect care of concrete during the curing period, structural solutions which are not suited to the given conditions, increased temperature of use resulting in the acceleration of the course of chemical reactions, and the lack of conservation.

The problem of protecting concrete against the aggressive impact of the environment is especially problematic in the case of bridge and other engineering structures. Studies have shown that it is in fact chlorides, including the chlorides of salts used for de-icing, which initiate the fastest progressing degradation process. The depth of penetration by chlorides has been presented in Figure 3 [3, 4].

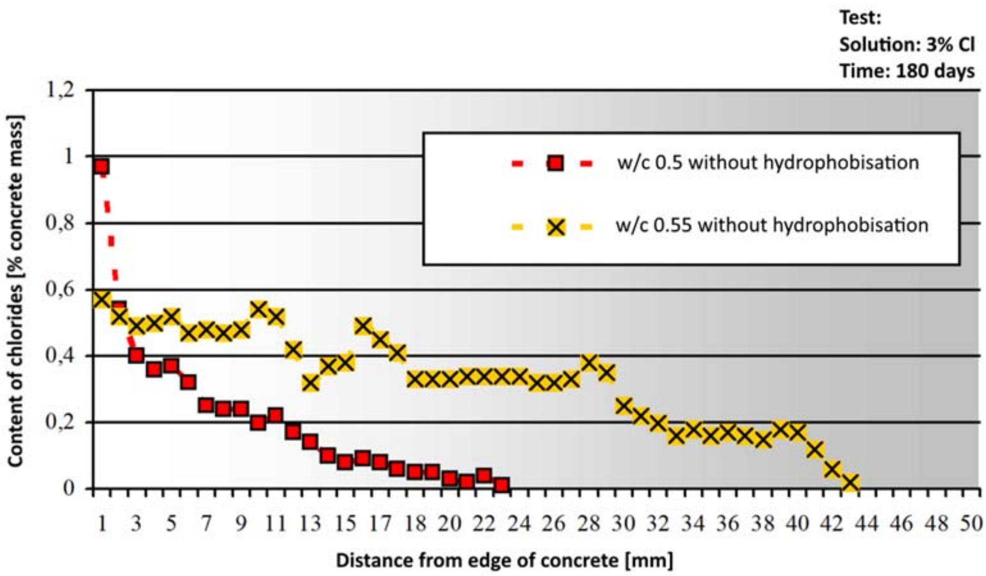

Figure 3. Depth of penetration by chlorides (3% Cl solution, time of 180 days) [3, 5]

If the high concentration of chlorides on the surface is a permanent situation, the corrosion process of steel usually occurs very quickly, especially in the case of concretes with a lower level of tightness [9, 10]. This thesis is confirmed by studies carried out in Poland as well as Germany [11]. The result clearly indicates that the occurrence of water mist around the structure is not detrimental to its concrete elements as it does not influence an increase in the content of chlorides on the concrete surface. Samples taken from a height of 0.4 m were characterized by the highest value of the chloride profile (0.01-0.097%), which confirms the thesis that chlorides sprayed together with water under pressure by vehicles are the most harmful to concrete structures.

3. Deep hydrophobisation of concretes

Analyses carried out over the years have confirmed that structures placed 0.5-4.0 m away from a road are exposed to the direct impact of being sprayed with water. The height of the area subjected to the effects of water reaches values of approx. 1.5-1.8 m. The described dependency has been presented in Figure 4. One of the basic steps which ought to be taken in order to increase the life of concrete structures is effectively eliminating moisture in this very, most at risk, zone of the structure. This can be achieved by ensuring tightness in the area of inevitable, constant contact with water characterized by a significant content of chlorides, e.g. by the impregnation of concrete.

Concrete impregnation involves saturating the surface of concrete with an impregnating agent without changing the form of the surface. The main aim is limiting the permeability of the concrete, and thus increasing resistance against the penetration of harmful chemical substances and increasing freeze-thaw durability. Impregnation is a secondary method - which means that it can be applied in the case of newly constructed structures as well as in the process of repairing existing ones [9].

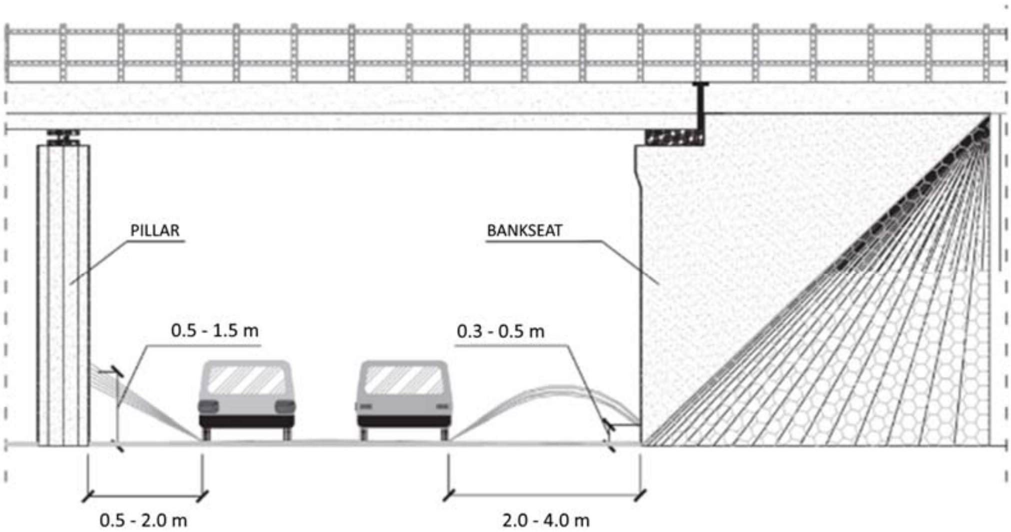

Figure 4. Zones of XD3 exposition class occurrence in the case of bridge structures [3]

One of the methods of impregnation is hydrophobisation (Figure 5), which relies on introducing a hydrophobising agent deep into the structure of the concrete and the closing of all pores. In this way, a protective layer is created, impenetrable to solutions containing harmful substances. The method has been known for a long time, though it was regarded as not very permanent. This stems from the fact that hydrophobising agents made on the base of solvents and emulsions were used, and such coatings needed to be reapplied approx. every 5 years. Ultraviolet Radiation along with water are responsible, above all, for such fast degradation of the protective coating. This problem was not solved until the development of a technology known as deep hydrophobisation. Previously applied hydrophobising agents penetrated the structure of the concrete to merely the depth of 2 mm, whereas the development of nanotechnology and introduction of deep hydrophobisation significantly improved the effects. The greater depth of penetration at the level of 6-8 mm is reflected in the durability and effectiveness of hydrophobisation.

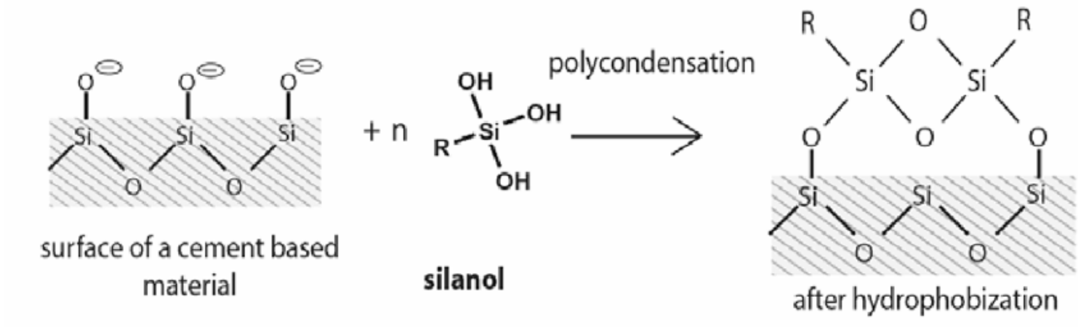

Figure 5. Model for the mechanism of alkaline catalysed reaction from silanes to polysiloxanes in cement based materials (reaction a: three ethanol molecules are released and silanol is formed; reaction b: polycondensation leads to a polysiloxane, which can be bonded (reaction c) to the surface of a cement based material [12]

Four kinds of substances are mainly used as hydrophobising agents: siloxanes, silanes, aqueous dispersions and solvent-based dispersions. The content of the active substance in the available products ranges from 20 to 100%. Figure 6 presents the penetration depth of various hydrophobic substances depending on the type of agent and water-cement ratio of the concrete.

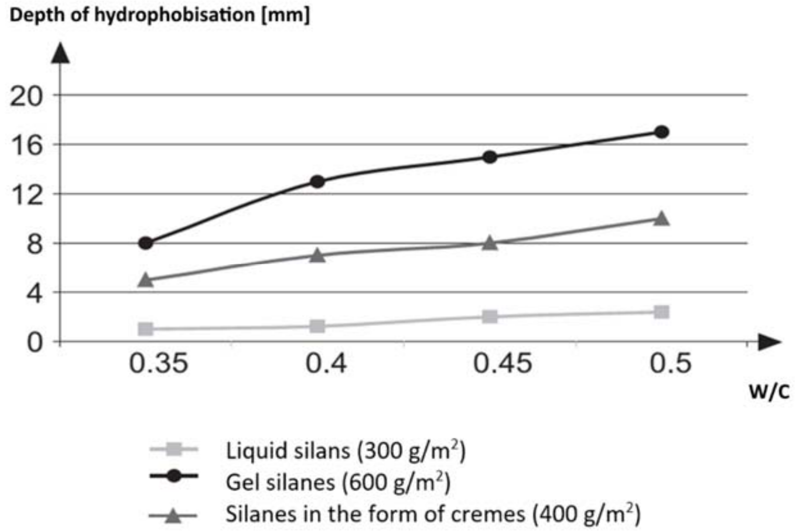

Figure 6. Depth of penetration by silanes depending on the type of agent and water-cement ratio of concrete [3]

When assessing the effectiveness of various hydrophobic agents, preparations of three different consistencies were tested. Upon applying hydrophobic agents in the form of a paste, gel and emulsion to concrete cubes of standard measurements of 15x15x15 cm, standard tests of water-tightness were performed. The characteristics of the individual hydrophobic agents divided based on their consistency have been presented in the table below (Table 1).

Table 1. Characteristics of assessed hydrophobic agents

Hydrophobic agent	Characteristics of hydrophobic agent
Agent in paste form	The agent in the form of a white paste is characterized by high penetrative ability of the substrate and reduces the absorption of water and harmful substances dissolved in it. It protects against the effect of water from melting snow and ice, and is characterized by low volatility and 80% content of the active substance (silane). It can be covered with other hydrophobising agents, as well as applied as a waterproof primer under acrylic varnishes.
Agent in gel form	Hydrophobising gel is characterized by an extremely high reduction of superficial absorbability as well as penetrability of substances dissolved in water. Moreover, it reveals high effectiveness in protecting against de-icing salts and the destructive effects of frost. Penetrating very deeply, it is characterized by low volatility. The content of the active substance (silane) is 90%. Freshly impregnated surfaces ought to be protected from the effects of water for approximately 24 hours.

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Agent in the form of an emulsion	This hydrophobising agent, based on silanes and siloxanes, has very high penetration abilities (also in the case of surfaces characterized by high density, such as washed concrete). It reduces the absorption of water and harmful substances contained within it. The drying process is non-sticky. The agent hydrophobises without decreasing the diffusion of water vapour and is characterized by a short drying time.

In order to ensure sufficiently long-lasting protection, a series of conditions must be met. The substrate must be load-bearing and free of any substances which may impair adhesion. Surface rush and deposits, and any loose particles must first be removed. Moreover, the substrate has to be dry (surface moisture content measured using a CM apparatus must be no more than 4%, and should be at least 28 days old). Forty concrete cubes measuring 15x15x15 cm (Figure 7) were prepared for testing. Twenty of them were made of C16/20 concrete, and twenty from C30/37 concrete. Five cubes of each kind of concrete were smeared with one type of agent. The remaining ten cubes (five cubes of each concrete type) were intended for assessing the initial water-tightness.

Figure 7. Concrete cubes prepared for testing water-tightness

Water pressure was changed progressively every 24 hours, in increments of 0.2 MPa, until signs of leakage occurred. If leakage was observed at the given pressure, water-tightness corresponding to lower pressure of a given increment for which leakage was not noted was determined for the analyzed sample. The following levels of water-tightness were distinguished: W2, W4, W6, W8, W10 and W12. The levels of water-tightness of structures are accepted depending on the pressure indicator. This indicator is equivalent to the ratio of the height of a water column (m) to the thickness of the barrier (m). It pertains to all structures which are exposed to the effects of water at a higher than normal pressure. These are most often fragments of structures located below the water table.

The results of the water-tightness of cubes obtained in the tests have been compiled in Table 2. A total of 40 cubic samples: 20 made of concrete with a higher water-cement ratio (lower tightness) and 20 from concrete with a lower water-cement ratio (higher tightness). The results of the water-tightness of cubes obtained in the tests have been compiled in Table 2. A total of 40 cubic samples: 20 made of concrete with a higher water-cement ratio (lower tightness) and 20 from concrete with a lower water-cement ratio (higher tightness). Five samples of each concrete were protected using substances in the form of a paste, gel and emulsion, with 5 remaining without any protection. The values of the table indicate the pressure in bars which the sample could be subjected to without noting leakage. A graph was prepared on the basis of the data (Figure 8).

Table 2. Compilation of results of water-tightness

	Agent in the form of a paste		Agent in the form of a gel		Agent in the form of an emulsion		Lack of protection	
	C16/20	C30/37	C16/20	C30/37	C16/20	C30/37	C16/20	C30/37
Sample No.	Max. pressure [bar]							
1	10	8	10	8	8	8	6	8
2	8	8	10	8	6	6	6	6
3	8	6	10	8	8	6	6	6
4	10	8	10	8	8	8	8	8
5	8	10	10	10	8	8	6	6
mean	**8.8**	**8**	**10**	**8.4**	**7.6**	**7**	**6.4**	**6.8**

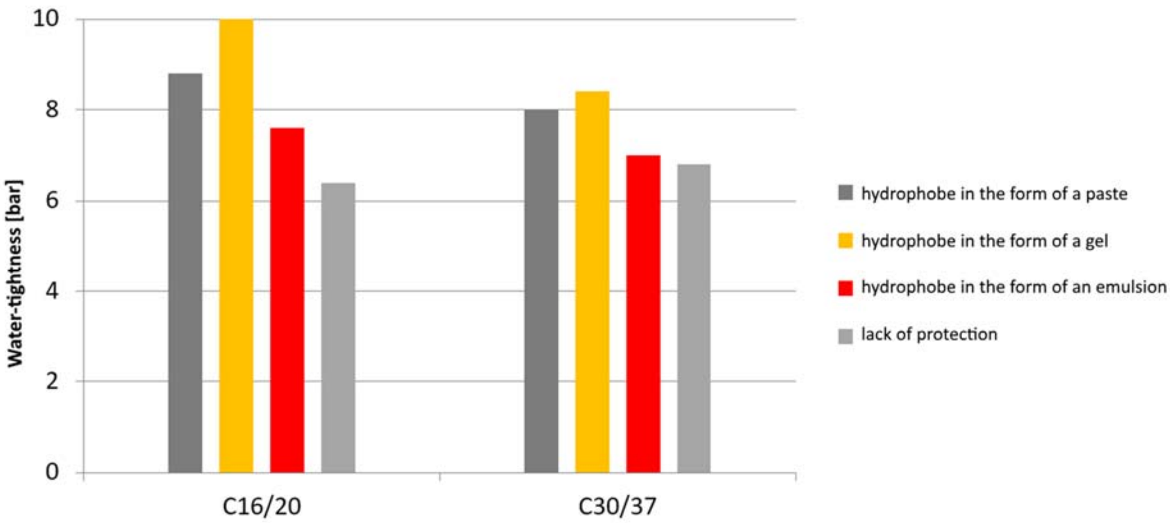

Figure 8. Results of water-tightness tests - effectiveness of various hydrophobic agents

The penetrating abilities of this agent are significantly lower than those of a gel or paste. The best effects were obtained in the case of protection with a hydrophobe in the form of a gel. Upon application of this highly viscous, waterless agent, a membrane is formed which protects against the agent flowing off, and additionally releases a silane to the inside. In such a way, it is possible for the agent to reach much greater depths. The hydrophobe in the form of a paste was found to yield poorer results as compared to the gel. The first reason behind the occurrence of such a situation is the fact that the agent in the form of a paste has 10% less active substance than the gel. Moreover, it does not possess properties making it possible to create a membrane which protects it against surface run-off.

4. Conclusions

Concrete is likely to remain one of the most popular materials used in construction. Activities aimed at protecting its surface are and will continue to be a current topic. Hydrophobisation is the best solution for securing structures against harmful factors. In order for the protection to be effective and long-lasting, a substance characterized by high permeability deep into the structure of concrete ought to be chosen. The higher the percentage of the active substance that enters the deeper parts of the material, the more problems aging factors (UV rays and water) will have in destroying the protective coating. In order to increase the probability of greater amounts of the active substance penetrating the concrete,

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the time that it is in contact with the surface should be as short as possible. The agent in the form of a gel turned out to be the best in this respect. It is worth noting that hydrophobisation was the most effective when applied to more porous concrete with a higher water-cement ratio. When there are more pore channels, the penetrative ability of the substance increases. For concrete characterized by very high tightness, hydrophobisation is less permanent, even upon application of the best agent, because the substance does not have the possibility to penetrate into deeper parts of the structure.

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