Possibilities of surface protection on road and airport pavements

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ABSTRACT: Concrete silicate structure durability of road pavements is significantly affected by the surrounding environment. It concerns climatic changes, including changes of temperatures, humidity, presence of soluble aggressive agents, vegetation microorganisms, etc. Consequently, expansion reactions in the concrete structure may appear and the distresses reduce its material durability. It is possible to significantly slow down the process of concrete pavement material breakdown by suitable secondary protection that does not form a continuous film on the surface.

In the paper we classified different secondary protection means based on declared chemical bases of the agents. The effect of secondary protection was laboratory tested through a modified method of describing the water absorption and determining resistance against alternate freezing in NaCl environment. We found the material bases of concrete secondary protection products have a crucial effect on the test results. In general, the water absorption results are not related to the results of alternate freezing in NaCl. The applicable mutual conversion cannot be made for this combination of laboratory tests.

Keywords: Durability, concrete, secondary protection, testing

1 INTRODUCTION

The concrete transfers all loading of the environment where the structures are built and must have material durability under static loading in structures. Based on general experience, it is expected that concrete durability may mostly reach 50 to 100 years, based on the structure type.

In the course of the 20th century cement production methods gradually changed and new ingredients and admixtures started to be used. The environment changes due to human activities and over the last decades in some localities there is more and more frequent occurrence of concrete structures whose material durability is significantly reduced. Regarding the Czech Republic, or Central Europe, this particularly concerns partial, discontinuous motorway segments and some airports. Regarding airports, an interesting fact is that fast material concrete destruction occurs regardless on whether the damaged areas (runways, stands, etc.) are loaded by traffic or not.

Core diagnostics by an electron microscope were performed for all cases of concretes with reduced material durability in the Czech Republic. Extremely high presence of expansive crystals and gels was found by chemical discreet analysis under the microscope. They were found exclusively in pores of hydrating cement sealants. In more than 1000 core analyses no sample of expansive or disintegrating aggregates was found in the structure. In all cases, concurrent occurrence of crystals (gels) of sulphate, alkali-silicate and calcareous expansion was identified (Figure 1).

All contractual qualitative parameters (with some rare exceptions) were maintained for the concrete production based on all available producers' and investors' documents and materials. Investors neither found, nor complained about any faults during construction.

Figure 1. Examples of different types of material destruction of concrete structure.

2 TECHNICAL ANALYSIS

Nowadays, concrete road pavements fail to meet the designed durability. Apparently, the problem is not based on construction indiscipline or keeping the right technology for construction, therefore, it is necessary to discover what happens. We need to start with hydration.

Cement binder hydration is a complex natural process. It has been described according to many different models. Each one of the models has its validity, nevertheless none of them deals with the issue of reduced material durability. If we view hydration as a natural process of gradual dissolving of cement (clinker minerals) and subsequent gradual recrystallisation from gels and solutions, Mendelev-Clapeyron equation can be used as an example (Nevosad, 1980). In an adjusted form it can be derived that the consumed energy A_h [J] during hydration from the time of mixing binder with water until the time t_h [s] may be in the form of (Feynman 1980 and Nevosad 2015):

$$A_h = \int_0^{t_h} \left(\frac{RTm}{\mu} - \frac{S_{pc}^4 m^5}{t^2 V^2} \right) dt. \quad (1)$$

from this it can be derived that theoretical hydration time t_h [s] is

$$t_h = \frac{m^2 S_{pc}^2}{V} \sqrt{\frac{\mu}{RT}}, \quad (2)$$

where R is the universal gas constant $8\,314.3 \text{ [J}^\circ\text{K}^{-1}\text{mol}^{-1}]$, T temperature [$^\circ\text{K}$], m binder mass [kg], μ mass of mean gram molecule [kgmol^{-1}], S_{pc} cement specific surface [m^2kg^{-1}], t time [s], V volume of hydration system [m^3].

Example: If we put in the relationship (2) average values for volume $V = 1 \text{ m}^3$, constant temperature $T = 293^\circ\text{K}$, $m = 350\text{kg}$, $S_{pc} = 300 \text{ m}^2\text{kg}^{-1}$, $\mu = 230 \text{ kgmol}^{-1}$, theoretical time of hydration will be around 14 years. Since there are no ideal conditions in concretes for free

courses of reactions according to (1), the real hydration time must be considerably longer in comparison with the theoretical one.

The relationships (1) and (2) define that the reaction takes place even with the presence of every potential reagent. The process is not only entered by clinker minerals, but also by foreign components. They are either discharged from binders, additives, and admixtures from other concrete mixture components, or they enter the concrete structure from the environment. If this occurs, the further hydration course is irreversibly affected.

In case any secondary protection of concrete surface is applied, it will have a certain effect in terms of further hydration continuation. The benefits of secondary protection should be significantly higher than its potential risks. Therefore, it is very important what criteria and where and in which structure they will be selected for the diagnostics of the secondary protection choice.

3 LABORATORY TESTS

If we follow the relationships (1) and (2), the hydration as a process is not defined in any relationship with strengths in concrete. This can be understood in such way that mechanical properties are just side properties of forming concrete. It is reflected in the fact that fresh concrete can have measurable strength immediately after compaction. This is known and confirmed, e.g. with small prefabricated products produced by the technology of vibropress. At the same time hydration as a process may theoretically run in such way that even when hydration is completed, the structures fail to reach the required strength. In extreme cases it may fail to reach even measurable strengths. This is also known.

The relationships (1) and (2) are conditioned by the presence of cement and certain amount of free water. Furthermore, the process is based on temperature, time and basic properties of the binder. The material durability will be the longest if the process is affected by as few changes as possible. This is related to an ability to limit the size of moisture gradients in the structure as well as the number of moisture cycles. These are phenomena related to the introduction of foreign substances in concrete and the amount of released hydrating products. The concrete sensitivity to changes in the environment humidity (rain, dry spells) may be defined by a suitable water absorption test. The concrete sensitivity to the surface breakdown by the introduced aggressive agents is usually defined by the test of combined effect of freezing and real aggressive agents.

3.1 *Modified water absorption test*

We modified the water absorption test so that the relationship (1) was accepted in the maximum extent. In regular intervals we measured the course and magnitude of concrete relative water absorption within a given time period. We experimentally verified with aerated and non-aerated concrete that 120 minutes of immersion is sufficient. The test on sufficiently matured specimens is performed in such way that the specimens are at first dried to constant mass. Thus, the lowest mass of the specimen is determined. Then the same specimens are immersed in water for 7 days and the highest specimen mass is determined. The difference in mass gives the maximum possible mass of water which the concrete specimen may absorb in common conditions (Grošek et al. 2019 and Hodakova et al. 2017).

Subsequently, the specimen is left to get dry in laboratory out of the storage chamber and without any protection and treatment until it reaches constant mass (usually approx. 14 days). The specimens keep the so-called balanced moisture, which is given by temperature and relative humidity of the laboratory environment. This makes the specimens ready for the test. Only in this phase the secondary protection is applied. It is applied over the whole surface, i.e. along all six sides in case of cubes. The water absorption measurement is performed after perfect drying/hardening of all compared secondary protection means.

The specimens are weighed before immersion and then fully immersed in water. They are lifted out from water in 15-min intervals, weighed and then immersed in water again. The result is converted into relative percentage of the degree of water saturation of every specimen for every time interval. The outcome is a time curve of the course of concrete water saturation. The kinetics of saturation of untreated concretes is compared to the kinetics of saturation of concretes with applied secondary protection.

3.2 *Combined effect of alternate freezing and aggressive agents*

The test is to closely simulate the conditions negating the hydration course description according to relationships (1) and (2). It is meant to be the most destructive combination of destructive environmental effects on concrete. We recommend to take into account long-term experience, which may differ in different regions. The condition is that when selecting this test, at least two combined destructive effects must be applied. The combined effect has an impact on concrete and its structure more destructively than the effect of the sum of two identical, individually testing effects.

In conditions of a landlock country, such as the Czech Republic, it is unnecessary to take into account the effects of the sea, blizzards, tornados, etc. However, very frequent changes in temperature above and below the freezing point occur in winter. Therefore, the combined effect of alternate freezing in the road salt solution is the most troublesome. Road salt is relatively frequently used for winter road maintenance. Czech standards conventionally replaced the road salt with 3% NaCl solution and specified in detail the temperature changes and delay of freezing cycles (ČSN 73 1326). The temperature difference ranges between -20°C and $+20^{\circ}\text{C}$ and one cycle duration is 2 hours. The mass of spontaneously broken off concrete particles is converted into units of g/m^2 in regular intervals, usually after 25 cycles. It is an extremely severe test for concretes, even when compared to other tests of the same type.

3.3 *Laboratory test results for specimens of 100/100/100 mm*

Based on the available means of concrete secondary protection, the selected products were those which

- are available in the Middle Europe,
- are applicable with universal low-pressure and high-pressure sprayers,
- are designed for application in the exterior,
- do not contain organic solvents (i.e. just emulsions, dispersions and solutions),
- penetrate the concrete top surface layer,
- do not form a continuous visible film on the treated concrete.

Twelve different products met these requirements. For their more detailed classification we only used the information specified by manufacturers, i.e. from material or technical sheets of the products. They are the basic available information materials. Users should get enough information from those to make a decision whether and which concrete secondary protection means to use.

We performed more detailed classification of the selected products based on the basic material bases of the secondary protection products. The first group are silicate-based products (silanes, siloxanes, water glass, and their combinations). The second one is a group of oil-based products (flax varnish, linseed oil, tung oil, etc.). The last group includes products without manufacturer's specification of the basic material basis. Those are products described as balanced substance mixtures (with no further information) or products which, without specified basic material bases, define the final effect (product crystallisation, waterproof surface, etc.).

Laboratory tests were performed on series of aerated and non-aerated concrete. The composition of concrete mixtures of aerated and non-aerated concretes differed just with the presence or absence of aerating agents.

3.3.1 Modified water absorption test

This modified water absorption test showed that in the course of the first 120 minutes after immersion the untreated concrete is continuously saturated by water in a non-linearly increasing function. The untreated concrete reached nearly 70% of its maximum saturation. The course of the relative water saturation is reduced for all 12 tested different secondary protection means The course of the relative water saturation is reduced for all 12 tested different secondary protection means in comparison to untreated concrete. The effect of material base of tested impregnations is significant for this test, differences are obvious in Figures 2 to 4.

Regarding silicates, Figure 2, there are two significant branches. One of them forms nearly water-impermeable treatment on the surface (values between 10 and 17%), the other one just slightly slows down the water absorption. Regarding oils, Figure 3, the most balanced and at the same time significant values of water absorption slowdown were reached within the scope of tested products. Regarding the group of secondary protection products with unspecified material bases, Figure 4, the overall water absorption slowdown is the best and the most balanced. Reached values are close to water-impermeability of the treated concrete surfaces (values between 10 and 18%).

The modified water absorption test reached roughly comparable results of secondary protection effects, both with aerated and non-aerated concretes. The absolute values of water mass that entered the concrete were higher with non-aerated concretes.

Figure 2. Comparison of the course of relative water absorption of untreated concrete and treated concrete through silicate-based secondary protection.

Figure 3. Comparison of the course of relative water absorption of untreated concrete and treated concrete through oil-based secondary protection.

Figure 4. Comparison of the course of relative water absorption of untreated concrete and treated concrete through secondary protection with unspecified bases.

3.3.2 Combined effect of alternate freezing in NaCl environment

The effect of material bases of tested impregnations is significant for this test as well. The waste mass reduction obvious in Figures 5 to 7 has different dependencies in comparison to the previous modified absorption tests. Some products of silicate-based group and the group of unspecified bases are, after 100 freezing cycles, even worse than the compared untreated concrete.

Figure 5. Comparison of breakdown of untreated concrete and treated concrete with silicate-based secondary protection during freezing in NaCl environment.

Figure 6. Comparison of breakdown of untreated concrete and treated concrete with oil-based secondary protection during freezing in NaCl environment.

Figure 7. Comparison of breakdown of untreated concrete and treated concrete with secondary protection without specified bases during freezing in NaCl environment.

The test was performed with the same specimens after the end of the modified water absorption tests. We obtained the direct relationship of results for each individual specimen with the aim to generally prove or refute the inter-relationship of these tests. The difference between the behaviour of aerated and non-aerated concrete is crucial for this test.

The testing continued further with aerated concretes and was interrupted after reaching 300 freezing cycles with NaCl solution (Czech standard). The damage of specimens was so minimal that it was still possible to continue. In the same freezing procedure in NaCl environment the non-aerated concretes completely disintegrated after 50 or 75 cycles. In the Czech Republic the criteria for demonstration tests for monolithic aerated concretes of road pavements are set to 150, and for control tests in constructions to 100 freezing cycles in NaCl environment.

4 CONCLUSION

Nowadays, some exposed exterior concrete structures, particularly motorways, airports, bridges, etc., face unusual problems. Despite the fact that all standards and regulations are met, quality materials are used, and the construction is performed without serious problems, the material durability of concretes is sometimes reduced. The situation is all the more serious that it occurs in similar extent for loaded and unloaded (not overrun) road pavement structures. The question is whether the reduced durability is caused by the effects that are sufficiently discussed by the existing projects.

If not, the current attitude to concrete needs to be corrected. We introduce one of the potential approaches. Here, the most important parameter is considered the concrete material durability instead of traditional concrete mechanical properties. This change allowed to view hydration as a process which is fully defined according to natural laws. There may be more mathematical notations, but we work with a physically mathematic relationship (1).

Is there any direct relationship between the changed priorities of the new concrete durability and the existing concrete strengths? There is not, since strength is not the direct outcome of the process description (1). There are just indirect relationships between material durability and concrete strengths.

It is not surprising since in most countries mass production of concrete with strengths even over 15 MPa immediately after compaction is very common. At that moment hydration does not even start. Specifically, this concerns small prefabricated products by vibropresses and others. On the other hand, some cases are known when a mixture comprising cement, fillers and water fails to reach typical, and in extreme cases actually measurable strengths, even after months. This is in accordance with the relationship (1).

Another problem is how to test material durability of concretes in laboratory as well as in construction sites. Every environment is different. The individual differences must be taken into account for the diagnostics and testing. Therefore, we believe that there should not be a universal test for the parameter of concrete material durability, as it is common with concrete strength determination.

The mentioned assessment of agents is useful for applications of additional secondary protection means which do not leave a continuous film on the concrete surface and enter into the concrete top surface. Regarding the applications to concrete road pavements, we selected our modified test of relative water absorption of concrete that lasts 120 minutes and where solid waste is determined after alternate freezing in NaCl environment.

The relative water absorption test simulates the slowdown effect of the surface protection against water absorption and evaporation from the concrete surface, Figures 2, 3 and 4. The waste mass after alternate freezing simulates the effect of surface protection against the silicate structure breakdown. The measured results were converted into relative values for the comparative untreated concrete, Figures 5, 6 and 7. This simplifies the idea about their effect.

The results in Figure 2 to Figure 7 show that the majority of secondary protection means that have very high relative effectiveness against water absorption and evaporation have low to very low relative protection effectiveness against the silicate structure breakdown in the environment of alternate freezing in NaCl. At the same time, the secondary protection means that have the highest relative effectiveness against the silicate structure breakdown in the environment of alternate freezing in NaCl have the lowest relative effectiveness against water absorption and evaporation.

The material basis of the tested secondary protection means appears to be very important as well. If resistance against alternate freezing in NaCl is required, the oil-based products (the most common in the Czech Republic) ranked the best. If resistance against concrete water absorption and evaporation is required, the best are the combined agents of so-called unspecified bases. Regarding the results, the silicate-based secondary protection products move along a wide range of results, most commonly in between the previously mentioned groups.

The tests for concrete material durability determination need to be carefully selected and assessed. As obvious from our results, it is unsubstantiated to derive concrete durability from the absorption results in relation to joint effects of frost and salts and vice-versa.

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