Fast material disintegration of cement concrete in the exterior

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Abstract. Over the recent years the amount of fast destruction defects of cement paste matrix has increased markedly for exposed concrete structures of highway and airport pavements. The accelerated destruction of silicate structure is unusual due to its irregular occurrence. It only occurs at 30 to 50% of newly built pavements (in continuous segments). The issue is applicable to loaded as well as unloaded pavements. Detailed diagnostics found that the probable cause is based on concurrently occurring expansive reactions in capillaries, cracks and pores in the cement paste matrix. In defect spots the presence of several expansive substances was proven, wherein the biggest question poses the unexpectedly high potassium concentration. Potassium is only contained at best in trace amounts in road concrete input components in the Czech Republic. Neither existing regulations nor standards sufficiently deal with this type of defects of cement concretes. If they mention the existence of this issue at all, they are just limited to recommendations. Since the modification of the existing commercially produced cements to pavements is still improbable, the solutions to this issue seem problematic.

1. Introduction

Quality of concrete structures or their concrete parts is evaluated based on the length of their service. Duration is rated among the decisive parameters for the evaluation of the quality of structures. In case it is significantly reduced, there are always good reasons to discover why. If they are found, the next step is searching and implementing suitable measures that reduce the probability of their recurrence in the future. The measures may be related to structure designing (static reasons), adaptation of concrete mixture composition properties (materials), changes in construction technology, type of maintenance, etc.

The prevailing opinion today believes that the material problems are not too crucial for concrete structures. Many issues can be dealt with by changed strength, a different reinforcement solution, changed shapes, or use of ingredients, admixtures and other components in the concrete mixture, etc. The set of these measures is not inexhaustible, it has its limits. Their research is continuously in progress, which is positive for development. Nevertheless, the environment impacts have such destructive effects on the existing concretes of the most exposed structures, that the above-mentioned scope of measures is clearly insufficient. Regarding particularly younger concrete surfaces of airports and highways, fast destruction of the silicate structure of concrete occurs at approximately half of the cases (line segments). With some exceptions the problem concerns the whole volume of the concrete pavement layer (or potentially concrete layers).
The new problem with materials is not manifested by the initial measurable reduced concrete compressive strength [1, 2]. It is indicated by a specific formation of cracks on the concrete surface. It is necessary to have some experience since the cracks in concrete also occur from other reasons. At first a network of fine cracks with the width lower than 0.1 mm, which are difficult to trace by a naked eye, appears on the surface. Over time these cracks interconnect and many of them further expand. They are already clearly visible from the widths of 0.3 mm. Subsequently, fine cracks of these widths (later even bigger) appear on the concrete surface. The cracks are disorderly arranged in irregular raster of usually 10 x 10 cm. The remaining initial cracks inside the surfaces of this raster do not expand in this phase. Subsequently, intensive surface dusting, and then chipping off of small pieces of concrete occurs. A specific feature is that the defect occurs irregularly and in variable intensity. Based on the performed diagnostics, the estimated occurrence of the defect ranges between 30 and 50% of volumes of all newly built concrete pavements in the Czech Republic. The defect occurrence is comparable on road pavements in operation (overrun) as well as on unoperated (unloaded by traffic) road pavements.

2. Experimental part

Airports and highways are specific monolithic concrete structures and there is an accelerated disintegration of silicate structure. A monolith, continuously built by finishers, often in thousands of m³ of concrete, is usually additionally cut into so-called contraction units after the initial hardening of concrete. This is the way to reduce/eliminate length/height (smaller) concrete deformations due to thermal expansion, drying and saturating, contact with subbase, operational loading, etc. Cutting is performed based on the real hardening of concrete within approx. 8 to 48 hours after concrete installation. It is a very risky operation, which is nowadays, on the basis of empiric experience, managed in such way that generally neither visible cracks appear, nor any other concrete damage occur.

Over the last decades surface networks of fine cracks have appeared on some newly built concrete pavements at the age from approx. 3 months. Over time they interconnect into continuous omnidirectional cracks. Irregular networks with areas around 100 to 150 mm or longitudinal cracks running through many slabs are formed. Their length may even exceed 100 meters. It is strange that these defects only occur at new concretes. Comparable damage of older concretes, i.e., over 20 years of age, is either non-existent or very marginal.

![Figure 1. Examples of visible crack networks on concrete pavements due to expansive reactions.](image)

We were able to take/obtain cores from all concrete highways in the Czech Republic and from several airports as well [3, 5]. All cores were used for taking samples for the diagnostics of point chemical analysis in a microscope. Products of multiple types of expansion, in different concentrations, on the surface, in the middle and at the bottom of the cores, were found at all damaged new concretes. Expansive gels and crystals were only found in pores, cracks and capillaries. No obvious damage of aggregates that would prove its presence in expansive reactions was found by this diagnostic. The fastest destruction of the silicate structure is caused, probably in the same degree, by sulphate and...
alkali expansion. Other types of expansive reactions cause slower disintegration in the whole volume of the silicate structure.

3. Results

In particular, it was potassium that stood out from the performed chemical analysis of expansive components. It was present even in extreme concentrations (even over 30%) in products of expansive minerals (gels). The analysis of concrete paste matrix was performed with scanning electron microscopy and energy dispersive spectroscopy (SEM/EDS). The use of a Tescan Vega LSU microscope was the principal method of examination. EDS was used for point and line analyses. The area distribution of selected elements was determined. Figure 2 and table 1 show an assessment example of more than 1000 performed tests, while samples were taken from upper and bottom of the concrete slabs.

We were surprised by the fact that potassium was not found in concrete aggregates, or at best in trace amounts. This fact and the presence of otherwise undamaged aggregates brought us to a conclusion that aggregate expansion in road concretes in the Czech Republic has not been a major problem so far.

![Figure 2. Ratios of main cations content – Analysis No. 1, example.](image)

| Table 1. Drill core of concrete pavement – chemical composition of concrete, example. |
|----------------------------------|----------------|----------------|----------------|
| Analysis No.                     | 1   | 2   | 3   |
| SiO₂                             | 48.82 | 59.7 | 48.85 |
| TiO₂                             | 0.0  | 0.0  | 0.24 |
| Al₂O₃                            | 31.39 | 4.3  | 34.28 |
| FeO                              | 1.93 | 2.0  | 2.05 |
| MnO                              | 0.0  | 0.0  | 0.0  |
| MgO                              | 1.82 | 0.7  | 2.48 |
| CaO                              | 3.52 | 25.9 | 0.96 |
| Na₂O                             | 0.80 | 2.0  | 1.27 |
| K₂O                              | 11.33 | 5.0  | 9.71 |
| SO₃                              | 0.15 | 0.0  | 0.0  |
| Cl                                | 0.24 | 0.4  | 0.16 |
| Sum                              | 100.00 | 100.00 | 100.00 |

The presence of potassium, which is a potential cofactor of alkali expansion, exclusively in pores, cracks and capillaries leads to a conclusion that expansive substances are transported by water/moisture.
in the structure of concrete. This movement is based on the thermal-moisture gradient. In the exterior the vector of humidity movement in time is very variable. It may be completely opposite within one day. It depends on current climatic conditions, on current amount of free water/moisture in concrete, on thermal-moisture conditions of the road subbase, or on all layers of the road structure, including the subgrade, etc.

The assumption of the decisive effect of thermal moisture gradients corresponds with the diagnosed fact that if potassium is presented in the concrete structure in more significant amounts, its concentration is very variable in the content of concretes in different points or places. The origin and formation of expansive minerals and gels in cement stone structure occurs during the hydration of the cement binder. The presence of other potential binders, except cement, is generally improbable for concrete road pavements.

Therefore, hydration cannot be perceived just as a separated relationship of components and properties of the concrete mixture. It is necessary to take into account potential reagents coming from the external environment that may secondarily enter hydration reactions. Such view may be respected by, for example, physical mathematical models. There are more forms of notations, we work with the hydration equation [2, 4].

\[ A_h = \int_0^t \left( \frac{RTm}{\mu} - \frac{S_{pc}m_5}{t^2V^2} \right) dt \] (1)

\( A_h (J) \) is energy consumed by hydration, R is universal gas constant (JK\(^{-1}\)mol\(^{-1}\)), T (K) temperature, m (kg) binder mass (cement) + mass of all external reagents, \( \mu \) (kgmol\(^{-1}\)) mass of reacting (dissolved) molecule, \( S_{pc} \) (m\(^2\)kg\(^{-1}\)) cement specific surface, t (s) time and V (m\(^3\)) is volume of hydrating cement/cement stone.

The relationship (1) ranks among the types of integrals we are still unable to solve. In case it is applied, it is always necessary to examine the definitional scope of validity in advance.

The equation has no relation to reached/reachable mechanic parameters of concrete/mortars. The equation makes it clear that, based on reactions over time, the mass m gradually decreases, and the hydration of consumed energy \( A_h \) increases. The equation has a character of a time decreasing function. The hydration is defined for time interval t, as long as the immediate increment of value \( \Delta A_h \) does not drop to value zero (in reality to a value close to zero for concretes). By using the equation, it is possible to determine theoretical time of hydration. When using common alitic Czech cements CEM I in the amount of 400 kg/m\(^3\), at the simplified calculation of average mass of basic clinker minerals, the theoretical duration is slightly over 16 years according to the above-mentioned equation. The real time will be many times longer, the prolongation is given by the fact that expected optimum reaction conditions cannot be reached with real concretes.

The equation shows that the most vulnerable hydration period is its initial time. The reaction is intensive and my easily be affected by the entered reagents. This can be explained by the fact that the existing fast expansive reactions in concrete are intensive just for newly cast concrete road pavements as well as by the fact that those fast expansive reactions do not occur or are minimal for older concrete in newly installed lanes. In addition, the equation explains that if expansive reactions in newly installed concrete occur comparably for overrun and unloaded pavements, it is a material, not static, defect.

We cannot get the answer from the equation why expansive reactions with the current fast disintegration of the silicate structure were nearly non-existent before. At the same time the construction of pavement layers remains similar. Neither the requirements for concrete, nor binding standards have changed dramatically technology-wise, the production is performed with conceptually the same technologies. In contrast to the past, two-layer concrete installation (it used to be one-layer installation) is preferred, qualitative requirements for aggregates have increased, and, instead of previously used road cement SC 70, CEM I 42.5R SC has been used (CEM II has been used on a trial as well since 2019).

Although the qualitative differences according to time based effective standards between previous SC 70 and CEM I 42.5R SC are virtually minimal. The material durability of the previous and current
road concretes is significantly different; it is worse nowadays. This holds despite the fact that the existing cements fully meet the standards, and the performance of concrete installation is closely checked by investors and contractors, and generally no more serious deviations from standards or regulations are found.

4. Discussions

Nowadays, cement concrete road pavements are an important part of the majority of main domestic airports and highways. They concern the existing structures and the new structures that are to be built in the future. Results from all concrete segments of highways in the Czech Republic and from several civil and military airports were processed. The destructive processes in the concrete structure are very variable. The most crucial for expansive reactions appears to be the position of structures. Even identical structure compositions and identical concrete under identical traffic loading have different dominant types of expansive reactions in different segments. The greatest differences are related to the amount of potassium, whose presence in cement stone capillaries ranged between 0 and more than 30%.

Regarding materials, i.e., concrete mixture components, the situation is given by available sources of raw materials. Nowadays, the only trouble-free component are aggregates. The selection criteria for road concretes are currently strict and we have not proven in the Czech Republic that expansive reactions apply to it.

Cements, ingredients, admixtures, and water are parts of the cement stone. The expansive reactions of these types, if they are contained by concrete, spread abundantly. If the aggressive substances are bound to modifications of gels or crystals in capillaries, cracks, etc., cavities, they are already involved in the hydration system. In other words, it is very difficult or impossible to remove them. The expansion than cannot be stopped by no other way than by permanent reduction of the present free water. Such measure must be dealt with very carefully. It is a double-edge solution since potential long-term lack of water in concrete has negative effect on further hydration process.

The design of road pavements is not derived from compressive strengths, but from flexural strengths [4, 6]. Regarding material durability of concrete, mechanical properties of concrete are not decisive. The long-term experience from road pavement concretes, where compressive strengths over approx. 30 MPa apply, any higher strengths generally fail to have an impact on concrete material durability.

In case there was an interest to make significant progress regarding components, the dominant potential is entirely outside the criteria of the effective standard for concrete. The existing cements meet all the parameters, however, there is still an error somewhere. An interest in this issue would also arise in the research and development of cement. Apparently, this demand from the side of road engineering is made in many other countries outside Europe. If we have the right information, even the most advanced countries worldwide have failed to succeed with this demand to cement producers. If it is possible to use other cements than CEM I equally, which has been possible for some time in many countries except the Czech Republic, it is undoubtedly a step in the right direction. However, if we are to deal with the above-mentioned expansion defects in full, with the reference to the mentioned relationship, bigger intervention, i.e., big step, may only be the solution. Today we do not know how far it is.

5. Conclusions

We are in the situation that it is desirable to deal with the current state. We can see a number of potential trends and issues, in terms of structures and materials. Regarding the structure issues of repairs of the existing roads, the following are concerned:

• Define and diagnose the presence of aggressive substances.
• Prove conditions of the real transfer of aggressive substances into concrete, not only those from the air, but particularly those from road subbase layers and subgrade.
• Find and verify practical solutions for the road layers and subsequent treatment, which prevents or at least slows down the transfer of aggressive substances into concrete.
• Find a way to effectively drain the joint in between the remained subbase and the new concrete pavement.
• Find protection to a new concrete pavement.
• Find a technologically safe way to dispose of/recycle the concrete affected by the destruction of silicate structure due to expansive reactions.

Regarding the structure issue for new constructions
• Find suitable diagnostics for research of potential contamination of the subgrade.
• Design more effective drainage of the subgrade with outlets off the road.
• Find and verify practical solutions for prevention or at least a slowdown of the transfer of aggressive substances into subbase road layers.
• Consider potential effective drainage of the joint in between the subbase and concrete road pavement.
• Find protection to new concrete pavements.

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