Causes of failures of industrial floors and concrete surfaces – case study

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Abstract. The article presents selected cases of damages to industrial floor and road concrete surfaces. he article presents 3 different objects in which damages were not connected with their excessive service load, but resulted from improper execution, design and underestimation of the effects of forced loads. In each presented case the description of damages was presented, the reasons for their occurrence were analysed and recommendations for repair were given.

1 Introduction

A floor or concrete surface is an external layer that absorbs service loads, which are transferred to deeper layers of the structure or to the ground. Most often it is a multi-layer system [1] which, in simple terms, consists of a substructure, a bonding or sliding layer and a top layer of concrete. The dimensioning of the surface begins with the determination of the acting loads, which are the basis for the adoption of appropriate thicknesses of individual layers. In many cases static calculations are not carried out, rather the guidelines contained in literature [2] or catalogues such as Rigid Surfaces Catalogue [11] are taken into account.

In the past, floors and surfaces were usually made of small-size elements made of stone, concrete, wooden cubes and even cast iron. Later on, openwork slabs were also used. Durability and preservation of service qualities of this type of surface depended mainly on a properly selected and constructed substructure. With the development of concrete technology, monolithic concrete began to be used on surfaces. Small-sized elements were replaced with large-size slabs. New structures were more resistant to local settlement and less sensitive to minor defects in the substructure, which in the case of small-size elements quickly manifested themselves in the formation of puddles, potholes and surface irregularities.

There are however numerous inconveniences associated with the construction of concrete surfaces on the construction site. It is necessary to ensure a sufficiently high concrete class resistant to the static and environmental loads, as well as the proper way of laying, compacting and curing. In a monolithic concrete structure, it is necessary to consider shrinkage, edge leveraging and, above all, the excessive cracking. Complete elimination of these phenomena may be difficult, or even impossible.

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Studies and normative documents in majority focus on the problems of floors and finishing layers design in residential and public buildings. It was not until the turn of the 20th and 21st century that concrete industrial floors became the subject of technical reports [8]. Previously, only several, already inoperative acts [7] considered them. Along with the development of fiber reinforced concrete (FRC) technology, there was a prevalent opinion among professionals that addition of fibres eliminates all problems related to the quality of concrete workmanship. Fibres were used as shrinkage control as well as the main reinforcement to carry static and dynamic loads (in the opinion of performers and designers added in order to eliminate shrinkage). Several objects were made with use of not only traditional steel rebar but also with addition of steel and polymer fibres.
Proper layer construction and application of the surface determine to a large extent its serviceability. Errors made during installation of each layer can result in various damages.

A typical system of industrial floor layers consists of: surface layer, adhesive layer, subfloor layer, protective or sliding layer, thermal/acoustic insulation, damp-proof insulation and subfloor or ceiling. Not all of the mentioned layers must always be present in the industrial floor, but each of the occurring elements, after careful analysis, should be properly selected for an individual case. In the simplest case, a concrete surface consists of two layers - the substructure and the top concrete.

One of the key factors in concrete surface design play different types of expansion joints. They can either be installed as a shrinkage joints or can serve as a tool against uneven settlement, swelling or changes in length caused by temperature difference.

2 Description and analysis of particular cases of floor and surface failures

2.1 Gas station concrete surface

The analyzed concrete surface, together with a service station in the middle, has the approximate shape of a trapezoid with a total surface area of approximately 730 m^2. On the basis of core drilling taken from the structure, the following layers were found:

- structural fiber reinforced concretes with a thickness of approx. 22 cm, troweled;
- layer of 0.2 mm thick PE membrane;
- sand layer with lean concrete substructure.

The expansion joints were made and filled with resin. The joints divide the concrete slab into fields with dimensions of approx. 4.5 x 4.5 m (locally maximum 6.0 x 4.0 m).

Almost the entire surface showed damage to the top layer of concrete, exhibited as an exposure of the aggregate. The inspection showed that the intensity of the phenomena varied between the spots and was highest on open areas and lowest under the roof. The network of microcracks could be visible after spraying the water on the area where the concrete has not yet worn and peeled off. The surface exhibited also corrosion of uncovered steel fiber that could be easily pulled from the concrete. During the inspection no other damage to the slab was found [Figures 1 and 2].

Fig. 1. The surface of the concrete in magnification. Visible corroded fibres.

Fig. 2. Damaged concrete surface.

The analysis of the design documentation, showed that surface design was only briefly described. The design documentation covered only the road industry. The descriptive and drawing part did not include information on the loads assumed in the project, traffic categories, anticipated types of vehicles, their tyres, etc. The project documentation contained only general provisions concerning the slab construction. The exposure class and other information concerning the conditions of the use of the surface were not given. The type and content of fibers were also not mentioned. The descriptive part did not include any surface preparation guide, i.e. the method of concreting, weather conditions appropriate for proper performance of works, the method and time of curing, the time appropriate for making cuts.

Analyzing meteorological data from the period of concreting, it was found that on the day of concrete works (03.08.2016), between 11 a.m. and 4 p.m., rainfall occurred. Rainfall also occurred in the following days. No records were found in the construction logs concerning the cutting of the slab, concrete recipe or weather conditions, or the method of protecting the surface of fresh concrete against atmospheric factors.

It was found that the damage resulted from poor concrete quality in the surface layer of the slab caused by a heavy rainfall. Moreover, the analyses showed that concrete of lower strength class than assumed in the project was used for the construction of the slab - the concrete class C25/30 was found as compared to the designed C30/37. Despite this, no cracks were found in the concrete slab that could indicate the wrong choice of its thickness and decreased strength. There were places with a smaller thickness than assumed in the project - locally 18.5-20.5 cm compared to the designed thickness of 22 cm.

The content of steel fibres found during testing of core samples was about 11 kg/m^3 and should be considered to be too low in relation to the usual quantities. There are no guidelines as to the fibre content and type of fibres in the project. The recommended steel fibre content of concrete is, according to different sources, within a range:

- 0.5-3.0% by volume (i.e. 39-235 kg/m^3) - Karwowska, Łapko [5], Katzer [9];
- 15-40 kg/m^3 - BAUTECH information materials
- 15-40 kg/m^3 - ArcelorMittal information materials
- >15 kg/m^3 - Pająk, Drobiec [4].

One of the reasons for the degradation of the surface layer of the concrete may have been heavy rainfall during concreting. The precipitation diluted the cement paste, significantly increased the w/c ratio. Low strength of the surface layer (approx. 10-15 mm) limits the protective properties of concrete in relation to steel fibres, which are subjected to corrosion. Corrosion of fibres additionally intensifies the process of surface degradation. Degradation of the top layer of the slab causes uncovering of the fibres occurring and their exposure. This caused the fibres to be easily torn out by vehicle tyres. Available technical literature indicates the problem of corrosion of steel fibres in concrete [5] of road surfaces.

The concrete needed to be repaired only in the top layer. It was recommended that the damaged layer be removed to a depth of approx. 15-20 mm. The layer should be replaced regarding road design guides. Consideration should also be given to how to reconstruct existing expansion joints.

2.2 Concrete surface on a Baltic Sea pier

In spring-winter 2014, a comprehensive renovation of a walking pier in a seaside town by the Baltic Sea was carried out. In the period of 2015-2017 the pier exhibited cracks and resin peel-offs of the surface layer. The repair of the floor and cap elements of the pier front was carried out between June and November 2014. Repair works included removal of the degraded concrete surface layer to the depth of about 60 mm and hydrodynamic cleaning (Figure 3b). In case of significant corrosion of the reinforcement, the missing sections of rebar and stirrup were filled in. The removal of concrete was extended to up to 150 mm in places of higher than expected concrete degradation. Vertical ribbed steel rods were driven into the concrete. The rebar of length of about 100 mm and a diameter of 12 mm made of 500 MPa steel was installed with a spacing of 9 pcs./m^2. The concrete surface was covered with a ϕ6 mm reinforcement grid with a mesh of 100 mm. The grid was covered with a layer of C30/37 F150 W8 concrete. After achieving adequate strength, an insulating layer of weber.tec Ergodur and weber.tec PU KV N resin was introduced.

On the basis of information obtained from the contractor, it was established that the first damage to the floor was observed already in the first year of its use. The longitudinal cracks run through whole dilation fields (Figure 3a). The presence of subsequent cracks was particularly visible after the winter. After the occurrence of damages, the cracks were temporarily sealed with resin. After 2.5 years of use, the number of cracks was so large that further temporary repairs seemed unjustified.

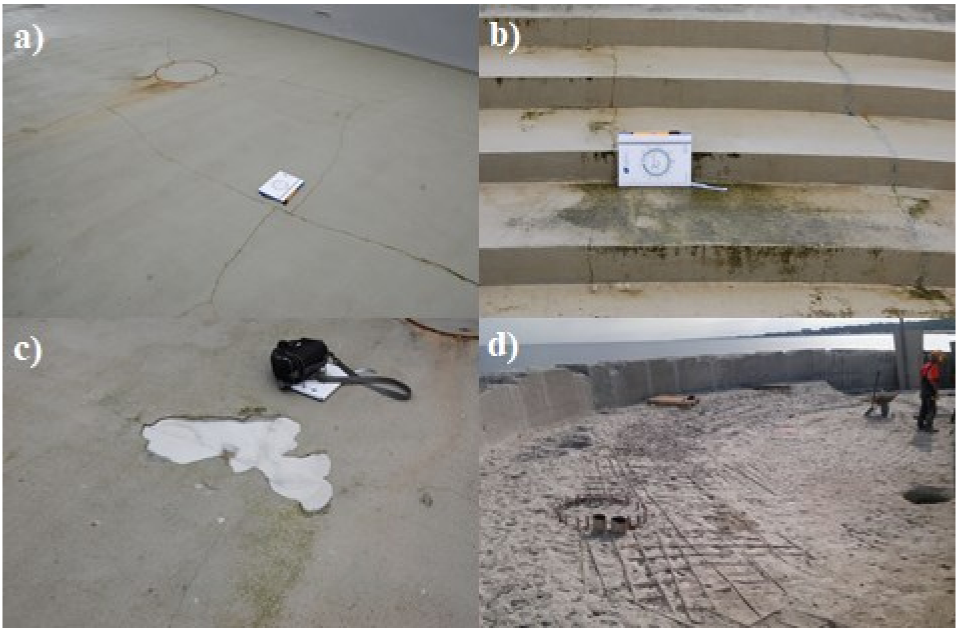

Fig. 3. a) Typical surface cracks in the pier front, b) Perpendicular cracking of the arched stairs, c) Resin detachment in cracking area, d) Subsurface prepared for top concrete.

Firstly, an inventory of cracks in the concrete pier front was carried out. As a result, it was noticed that the existing cracks with width of 0.1 to 0.5 mm create either an irregular grid with length of 1.20-1.90 m or spread radially from inspection wells (Figure 3a). Near the stairs, the cracks were mainly perpendicular to them. Those spread through the whole length of the run at a distance of about 1.20-1.50 m (Figure 3b). It was also noticed that in the cracked area the resin pulls off from the concrete substrate (Figure 3c). Floor damage is shown in Figure 4.

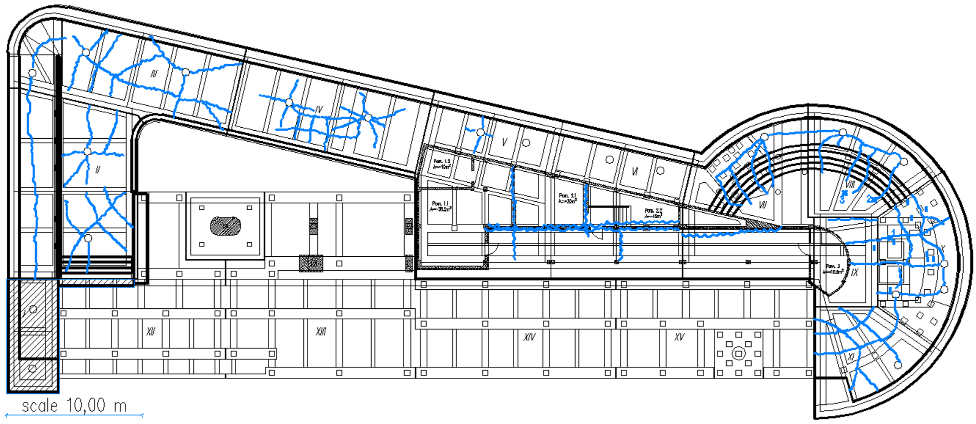

Fig. 4. Plan view of the pier with indicated damages location.

Cracks in the bottom platform floor on the front of the pier were a result of the adopted concrete casting on rough ground. Execution of a new layer of concrete which tends to shrink on a rough substrate, that is more than 40 years old (Figure 3d), led to tensile stress in the new concrete and consequently to cracking. The design documentation does not address the issue of protecting the floor against excessive cracking. Only the construction logbook mentions the use of shrinkage reinforcement, but does not specify the location of the reinforcing mesh. The contractor placed it directly on the uncovered "old" reinforcement. New reinforcement was therefore placed in the lower part of the concrete slab, so that it did not prevent excessive widening of shrinkage cracks. Even more so did not eliminate the possibility of their formation.

The amount of the reinforcement of the floor slab was calculated incorrectly. Assuming that the top concrete cracked along the thickness of 110 mm at medium stresses in the cross-section equal to 1.30 MPa, the force in reinforcement 143 kN per each meter of the floor slab is obtained, for the assumed reinforcement grid 6 every 100 mm (2.83 cm2/m) it gives stresses equal to 505 MPa, which is much higher than the value given in PN-EN 1992-1 Table 7.3N - 320 MPa for bar spacing of 100 mm and scratches of 0.3 mm (Equal 1).

$$\sigma_s = \frac{110mm \times 1000mm \times 1{,}30\frac{N}{mm^2}}{283\ mm^2} = \frac{143000}{283} = 505\ MPa > 320\ MPa \qquad (1)$$

Approximately the proper power of the reinforcement limiting the crack width to 0.3 mm can be assumed to be 4.47 cm2/m. The reinforcement should be placed in the upper layer of concrete. Verification calculations were carried out using MES [10], which confirmed the arrangement of the observed scratches.

The damages to the resin finish were also caused by the diffusion of moisture through weaker and previously cracked "old" concrete and cracking in the newly laid layer. Visual inspection of the core drillings showed that the sub-base concrete was cracked before the floor was laid. Cracking of the "old" concrete in the bottom resulted in the penetration of moisture from the backfill. After cracking of the surface layer the water vapor pressure increases directly under the resin layer resulting in spalling. During the renovation, no measures were taken to prevent this. The initial design assumed that the slab would be 25-30 cm thick. Core drillings indicate a local reduction in slab thickness by more than 50%.

Considering low service loads in relation to the overall deadweight, it was proposed to repair floor cracks by injecting and "gluing" the cracks with the use of elastic resins. It was recommended to carry out the injection using the gravitational method, or at low pressure due to the risk of detachment of the surface and raising the surface layer of concrete. It was recommended that the existing resin coatings should be grinded and remade, which allowed to reveal hidden cracks.

In the area where the bottom concrete was heavily cracked, it was recommended to completely remove damaged layers and restore the monolithic slab. Proper injection of the structure was impossible due to cracks running through both layers of concrete slabs. This could result in the resin leakage to the sand backfill.

2.3 Bus depot maneuver area surface

The said bus depot has the approximate shape of a parallelogram with a total area of approximately 635 m^2 and the dimensions of the sides of approximately 30 x 37 m and a width of 18 m. The slab was made with a gradient of 2.5% in a western direction. On the basis of inventory measurements of core drillings taken from the surface slab, it was found that the construction consists of the following layers:

1. Troweled surface concrete (25 cm);
2. Double layers of geotextiles;
3. Lean concerto (15 cm);
4. Reinforced soil.

There are visible expansion joints on the surface protected with rubber sealant. The slab was divided into fields with maximum dimensions close to 5 x 5 m. The arrangement of expansion joints is shown in Figure 6 a, b.

The object administrator did not manage to indicate exactly how long after concreting the initial cracks were observed. During the assessment of the technical condition of the surface in question, 3 years have passed since its execution.

Numerous cracks of 0.5 to 1.0 mm opening and regular arrangement with the dominant direction perpendicular to the slope of the slab were found. It can be assumed that the cracks observed were parallel to each other. The measured crack spacing ranged from about 0.5 to 1.7 m with the dominant value in the range 0.7-0.8 m (Figure 5). The length of the cracks varied from about 0.3-0.4 m to about 6.0 m. Crazing cracks were locally found on the troweled surface. Figure 6b shows the damages and the joints cuts.

Fig. 5. Prevalent cracking on the surface of concrete (55-80 cm spacing).

The tests showed that the mean compressive strength of the surface layer was 62.1 MPa (concrete class C50/60 determined on the basis of EN 13791:2008), i.e. much higher than the designed one (B40 as specified in the documentation).

In order to verify the correctness of the surface layer execution, the depth of the expansion joints was measured. Measured depth ranged from 35 to 60 mm (usually between of 40-50 mm). Some of the joints had a width corresponding to the width of the concrete diamond saw (approx. 4-5 mm), while some had an opening of approx. 10 mm with visible damages to sealing rubber. It was noticed that the expansion joints were typical for a saw-cuts made in a fresh concrete. No proper expansion joints with bituminous mass or doweled were found.

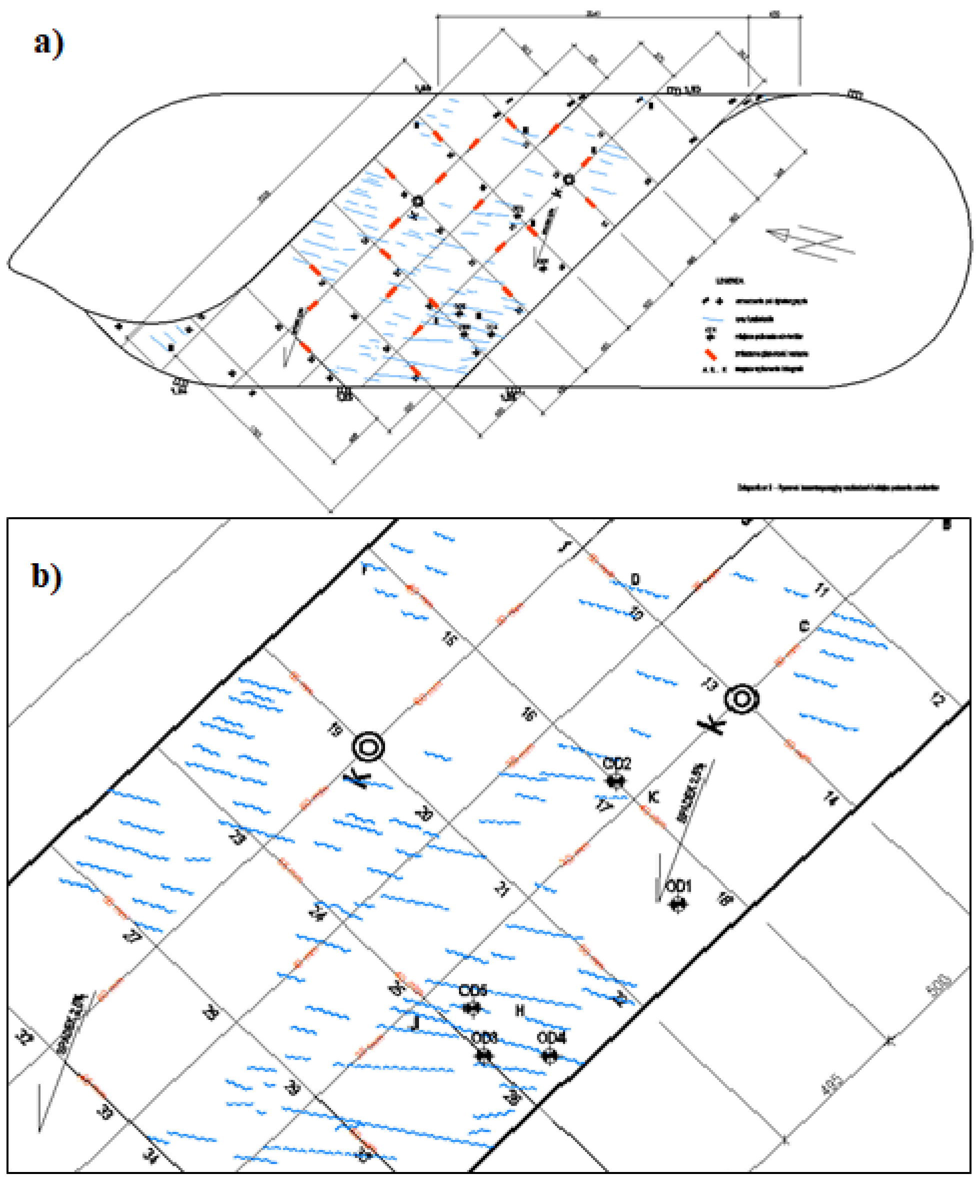

Fig. 6. a) Plan view of the maneuver area b) the dilation fields and cracks are indicated.

The project indicated the method of constructing the surfaces and parking spaces with the addition *"in order to minimize concrete shrinkage in the surface, apparent dilatations and full dilatations should be used"*. Further on, it is noted that *"the 25 cm thick wearing layer **should be reinforced**"*.

Analyzing the above, it can be concluded that the damage to the concrete surface resulted from the shrinkage of the concrete combined with thermal actions. The large-size surface layer in the plan was solely made of concrete, without reinforcement in the form of bars or fibers. In this type of construction, it is extremely important to make proper contraction joints to ensure the least possible friction between the concrete slab and the subbase. It should be noted that the assumed sizes of dilation fields were correct and amount to < 6 m. In the analyzed case, however, the cuts were too shallow.

A correct cut should reach the depth of 1/4 - 1/3 of the slab thickness [1, 2], so as to ensure that the concrete breaks exactly in the notch. With a slab thickness of 250 mm, the correct cut should be 65 - 85 mm deep. During the review of the expansion joints, the depth of the expansion joints was found to be smaller. The core sample taken through the joint showed that insufficient depth of the cut stopped the propagation of the crack, while numerous shrinkage cracks are visible in the vicinity of the cut. Incorrect cracking of the expansion joints is also evidenced by uneven destruction of the rubber sealant. There are numerous joints in which the joint material is strongly cracked (which is probably appropriate), as well as joints without visible damage.

The use of geotextile fabric as a sliding layer is also questionable. In case of laying a concrete slab on a lean concrete substructure, the proper solution is to use a single or double layer of 0.3 mm thick PE foil as a sliding layer. During concreting, cement milk penetrated the geotextile and "glued" it to the concrete slab. This phenomenon reduced the effectiveness of reducing friction between the base and top concrete. The lack of reinforcement of the slab, in turn, is the cause of large opening of the resulting cracks.

The concept of repair assumed the injection and filling of the resulting cracks with the use of binders based on elastic resins. It was recommended to carry out the injection using the gravitational method, or at low pressure due to the risk of detachment and elevating the surface layer of concrete. Due to the fact that during the injection works the concrete surface may have been damaged, it was recommended to grind down the existing concrete top layer at the depth of a few millimeters. Additional resin layer on top should be placed while maintaining the water tightness and cracks protrusion. It was recommended to deepen all expansion joints to the correct depth and then to fill them again with elastic material.

3 Summary

In all the presented cases, the damage to the surface was not related to the impact of imposed loads, but resulted from disregarding the basic guidelines for surface concrete design and preparation. It seems that the concrete surface is a relatively simple structure, and its design will be limited only to specifying the layout of individual layers. Designers and contractors forget that the shrinkage accompanying the concrete's setting process is the greater the higher the concrete class. The forces generated by it, in case of lack of possibility of deformation, are so great that they practically always lead to scratches. A frequent overlooking are also too shallow expansion joints. It appears that often the cuts are made only to the depth of 1/6 - 1/8 of the slab thickness, which does not guarantee concrete cracking in the joint. In case of heavily reinforced slabs cracks with small opening are acceptable. For concrete surfaces hard and non-deformable finish, excessive opening of cracks affects the aesthetics and lowers the durability of the structure.

The design of each surface or industrial floor should include a description and characteristics of the planned loads. Precise description and drawing of the layout of the layers, with particular emphasis on the requirements for the substructure and sliding layers. The exposure class (or classes) and the strength class and type of concrete should be indicated in the design. In case of application of dispersed reinforcement, the designer should indicate the type and content of fibres in the mixture. It is also advisable to specify in the documentation the appropriate consistency class, which can be verified at the construction site. The executive guidelines should specify the method and places of execution of individual expansion joints, and in case of cuts, their depth and time of execution. Before commencing concrete works, the frequency of concrete delivery, transport time and the method of its compaction should be planned. The concrete surface, which is usually a relatively thin slab with a large evaporation surface, is very sensitive to weather conditions during its execution. Rainfall, air temperature, sunshine and wind can cause damage to even well-designed floors.

In presented cases, the class of used concrete allowed for further repairs, however, these are usually very expensive and complex.

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