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An innovative constructional and technical method of using a prefabricated, dowelled reinforced concrete slab for effective repairs of airport pavements

Abstract: Airport pavements, constituting the ground part of the maneuvering area intended for the movement, parking and servicing of aircraft, are an extremely important element of the airport infrastructure. The main task of the pavement is to transfer utility loads from moving or standing aircraft. The technical condition of airport pavements, which should not raise any doubts, is a key element for ensuring the safety of air operations. The repair method consisting in the use of a prefabricated airport slab in the place of excessive degradation of existing slabs introduces a pioneering method of connecting slabs with adjacent slabs, creating a new construction quality that increases the spatial stiffness of the entire functional element of the pavement. The performed dimensioning and static - strength analysis of the prefabricated airport slab using the finite element method in the aspect of the global state of effort of the structure confirmed that the technical solution with the use of a dowel joint was properly designed, because it has a positive effect on the redistribution of loads transfer between cooperating prefabricated slabs. The conducted laboratory and field tests and operational features gave clearly positive results, which determine the purposefulness of the application and popularization of this repair method. The implementation experience gathered in the course of the work carried out allows to state the complete technical efficiency of the proposed design solution. Considering the relatively quick and easy replacement of the slabs without the need to introduce longer breaks in air traffic, this technology can be successfully used in both civil and military aviation. The potential of this technical solution can also be used in the repair of concrete road surfaces.

Keywords: Prefabricated slab; Airport; Airport pavements; Carrying capacity; Damage to concrete pavements; Dowels; Security

Introduction

As a result of the progressing globalization, air transport, both in passenger and cargo traffic, is currently the most dynamically developing branch of transport in the world. The benefits of this type of communication consist primarily in covering very large distances in the shortest possible time compared to land or sea transport [5]. The consistent and very dynamic growth of air operations means an increased load on airports, and to be precise - an increased impact of aircraft on airport pavements, which are part of the complex air transport system.

Due to their characteristic properties, airport pavements are mainly designed to take over the operational loads from the aircraft moving on them, and then transfer these loads to the lower structural layers and their redistribution in these layers. Properly designed airport pavement should ensure adequate load transfer in such a way that the impact of the landing gear on the pavement does not cause pavement destruction, which could pose a threat to operating aircraft.

The airport pavement, like any other engineering structure, is distinguished by the specific nature of the work [8]. The factors that distinguish the airport pavement include, first of all, the dependence on meteorological and climatic conditions, the specific nature of loads (static and dynamic), or the variable distribution of loads and speed during the roll-off and roll-out [10]. The specificity and dissimilarity of airport pavements differing from other surfaces, e.g. road pavements, also consists of a relatively high contact load, which is applied to a small area. Additionally, it is characterized by the high repeatability of loads in a small functional area of the airport. As a result, we deal with a situation where at the airport there are areas of the significant intensity of loads and those in which the generated load is sporadic [16].

Pavements made in the cement concrete technology, including pavements made of prefabricated concrete slabs, are one of the most popular and used methods of building airport pavements in Poland [19, 20]. Despite the many indisputable advantages of the concrete composite, the experience accompanying the operation of airport pavements shows, however, numerous phenomena of damage to these pavements [9]. As a result of static and dynamic variable loads generated by aircraft traffic, but also as a result of weather conditions, the use of de-icing agents and operating media resulting from aircraft maintenance [4], damage can be identified on these surfaces. Taking into account the pavements built of prefabricated slabs, in this case, we can indicate fatigue damage resulting from multiple operational loads (static and dynamic) and changes in the physical properties of the substrate on which the slab was placed. This type of damage leads to a reduction in the load-bearing capacity of the pavement, the formation of cracks, "keying" of the plates, chipping, and deformation of the grade line in the longitudinal and transverse slopes [12]. The most dangerous failures of concrete pavements, in which the scale of damage to a single airport slab makes it impossible to perform emergency repairs (local repair of chipping, chipping), pose a real threat to the safety of air operations by aircraft. As a consequence, it is necessary to search for new, effective, and quick technologies for the repair of damaged, single airport aprons. One of such methods is the possibility of using a prefabricated concrete slab, which can be an effective, local repair of the airport pavement, ensuring equivalent performance comparable to the existing adjacent slabs. Moreover, as shown by the experience gathered so far [3, 17, 18], a concrete prefabricated slab may even increase the load-bearing capacity of a given pavement. This phenomenon was also confirmed on the basis of the conducted own research.

This article presents a constructional and technical concept related to the use of an innovative pavement repair consisting of the incorporation of a prefabricated airport slab in the place of excessive pavement degradation of the existing slabs. The introduced innovative method of connecting the slab with the adjacent slabs creates a new design quality that increases the spatial stiffness of the entire functional element [16].

Development of a project of a prefabricated reinforced concrete slab

The subject of the study was to create a design and assumptions for a prefabricated, reinforced concrete airport slab with an element of slab cooperation in the form of a dowel joint. The computing plane that loaded the prefabricated plate was the Boeing 737-800 as the world's most popular medium-range narrow-body airliner. The pavement was a concrete slab 24 cm thick made of C35/45 class concrete (characteristic compressive strength for cubic samples equal to 45 MPa) and dimensions 2.5 x 5.0 m.

To calculate the multilayer system of airport pavements, the theory of elastic plates resting on a deformable substrate was used [16]. For the purposes of dimensioning, taking into account the interaction of the slab with the substrate, a model of the slab resting on an elastic substrate was adopted in the Winkler model. The design of the plates consisted of several successive stages. In the beginning, it was necessary to adopt appropriate initial parameters related to the selection of the calculation aircraft, especially in terms of the value of the transferred load and its distribution on the pavement. Then, calculations related to the static loads generated on the airport pavement had to be performed. The dimensioning of reinforced concrete pavements used for airport pavements was performed using the traditional method, i.e. the limit state method (MSG). Based on the calculations, it was determined that the slab will have top reinforcement and bottom reinforcement in the form of mesh made of A-III class steel bars (Figure **1**). Reinforcing steel is ribbed bars with a diameter of 12 mm and 16 mm.

1. The process of manufacturing prefabricated panels

According to the studies [6, 7, 8], the analysis of the cooperation of the slabs in the concrete airfield pavement showed that dowelling, i.e. the connection of the slabs by steel elements, ensures the cooperation of the adjacent slabs in transferring loads. The effectiveness of loading the slabs connected with dowels depends on many elements of the pavement structure, including: dowel diameter, spacing, type of foundation, concrete class, and others [1, 2]. The effectiveness of the entire dowel connection is the sum of the values of loads carried by individual dowels.

The classic solution of the dowel connection is based on the fact that one of the ends of the steel rod is rigidly fixed in the concrete slab, the other end can move in the adjacent slab, ensuring freedom of movement along the slab length [6]. This free end is usually placed in a steel sleeve. Dowel - a steel bar must be placed perpendicular to the front plane of the panels to be joined and parallel to their upper and lower surfaces. The fixed part of the dowel in the slab is an element of theoretically infinite length, which at a certain distance from the slab body turns into an elastic body [7].

Bearing in mind the above, in order to introduce the possibility of cooperation of the panels, and thus increase the spatial stiffness of the entire functional element, panel connections with dowels were designed (Fig. 2), adopting the following assumptions:

- the set load is the Boeing 737-800 computing aircraft,
- the plates were connected along the edges with steel dowels 60 cm long and circular with a diameter of 25 mm,
- the dowel spacing on the longer edge of the slab (5.0 m) was 62.5 cm,
- the dowel spacing on the shorter edge of the slab (2.5 m) was 55.0 cm.

Based on the calculations and analyzes carried out, it was proved that the strength condition of the dowel connections was met, therefore the dowel connection was designed correctly.

The technology of assembling a prefabricated airport slab

The replacement of concrete pavements in the prefabrication technology is used when there is a need to replace a part of the pavement, and the time allocated to decommissioning the pavement does not allow for the reconstruction of the pavement in the standard concreting process [16].

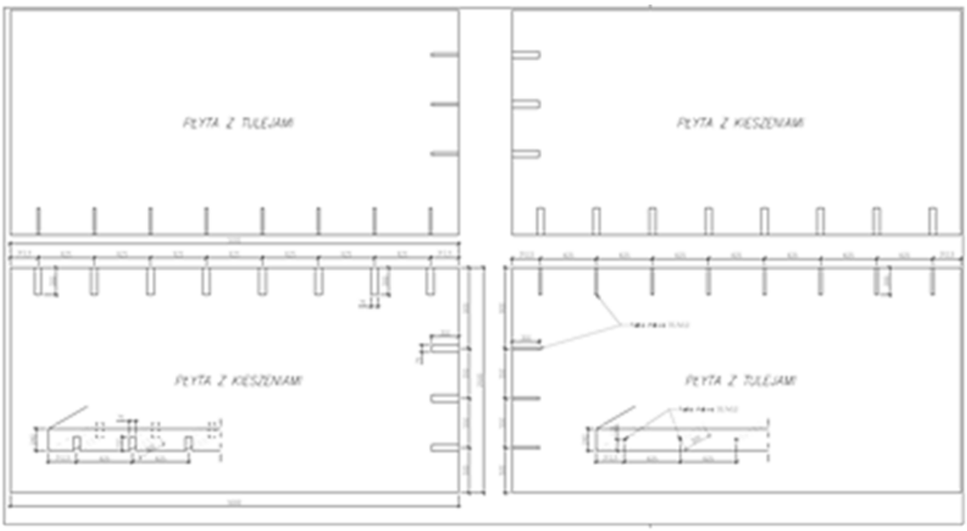
Before removing the damaged panels that have been selected for replacement, it is necessary to check in advance whether the adjacent panels are well stabilized and whether their surfaces can be reference planes when installing new panels. Moreover, before starting the works, the geometric measurement of the slab to be replaced due to the irregular dimensions of monolithic slabs should be performed by checking its length, width, and thickness. If necessary, the existing pavement should be cut to the desired dimensions so that the width of the expansion joints between adjacent boards does not exceed 30 mm. During the process of replacing the boards, we pay special attention to avoiding damaging the concrete of the adjacent boards, changing the arrangement and direction of the existing dowels and anchors, and damaging the substrate (foundation). To facilitate the demolition and to protect the adjacent panels against damage during the demolition, a 5-10 cm wide strip is cut along the entire perimeter.

The concrete base is supplemented with C16/20 class concrete in the so-called "Semi-dry" to the height of the existing foundation and compacted mechanically with a heavy vibrating plate. On the prepared and stable base, at four or six points of support of the prefabricated element, steel sheet washers with dimensions of 20 x 25 cm are placed up to such a height that the edges of the freely placed reinforced concrete slab on them do not deviate with the grading of the neighboring slabs (with an accuracy of ± 2 mm). Such precision of the foundation height is ensured by washers of various sheet thicknesses (0.5 - 4 mm). Steel washers, in addition to the function of precisely regulating the grade line for the foundation of the prefabricated element, also provide temporary support for the slab until the mortar obtains the required compressive strength of 10 MPa.

After the initial assembly, the space between the washers is filled with a non-shrinkage mortar intended for repairs of concrete and reinforced concrete structures in communication construction. The mortar is self-leveling and it is enough to part it with a leveling strip, or even smooth the surface with a steel float or a trowel. A freshly prepared mortar retains its properties for approx. 30 minutes. The mortar is poured with a slight allowance to avoid the formation of voids under the reinforced concrete slab. The excess mortar is squeezed out when the board is installed. As a result, the cavities and voids under the adjacent monolithic slabs are filled.

After the shrink-free mortar has been thoroughly spread, the installation of the prefabricated reinforced concrete slab with the help of a crane is started. The prefabricated slabs are lowered after their horizontal position and width of the envisaged surface gaps have been stabilized. The evenness of the surface is checked with a 4 m long patch, positioned so that its center is above the joint of the boards. The clearance between the batten and the surface of the adjacent pavement should not exceed 5 mm, while the edges of the panels should not protrude at the gaps more than 2 mm. In extreme cases, it is allowed to mill the top layer of the slab in order to adjust its ordinates to the ordinates of the adjacent slabs.

The arrangement of plates used in this technical solution, in accordance with the previously prepared design, consisted of 4 plates, i.e. two plates with pockets and two plates with sleeves (Figure **2**). Dowels are placed in the prefabricated slabs in which the sleeves are designed. The dowels are placed in the front wall of the technological belt in the previously designed and prepared holes, in accordance with the designed spacing, perpendicular to the wall plane and in half of the thickness of the dowel plate. The depth of the designed holes is ½ of the dowel length, while the hole diameter is about 2 mm greater than the dowel diameter.



2. The designed system of 4 prefabricated concrete panels

The plates with the designed pockets (Figure **3**) are placed on the prepared plates with dowels installed by means of a crane and their height is adjusted to each other.

3. Installation of the plate with pockets

After the final height adjustment of the prefabricated panels, injection is made through specially prepared holes equipped with applicators, through which the sealing substance is forced under the panel under appropriate pressure (for stabilization). It is necessary to seal the board joint with the substrate and adjacent elements beforehand in order to prevent the uncontrolled flow of the substance pressed under the board. The injection is performed immediately after the installation of the prefabricated panels. The injection material in the discussed experiment is a single-component, shrink-free, high-strength cement paste. It is a material with very fine grain size, low viscosity, and liquid consistency, intended for injection in soil, rocks, concrete, reinforced concrete, and masonry structures and for joining concrete, stone, and ceramic elements.

Tests of a prefabricated airport slab in cooperation with adjacent slabs
Laboratory tests

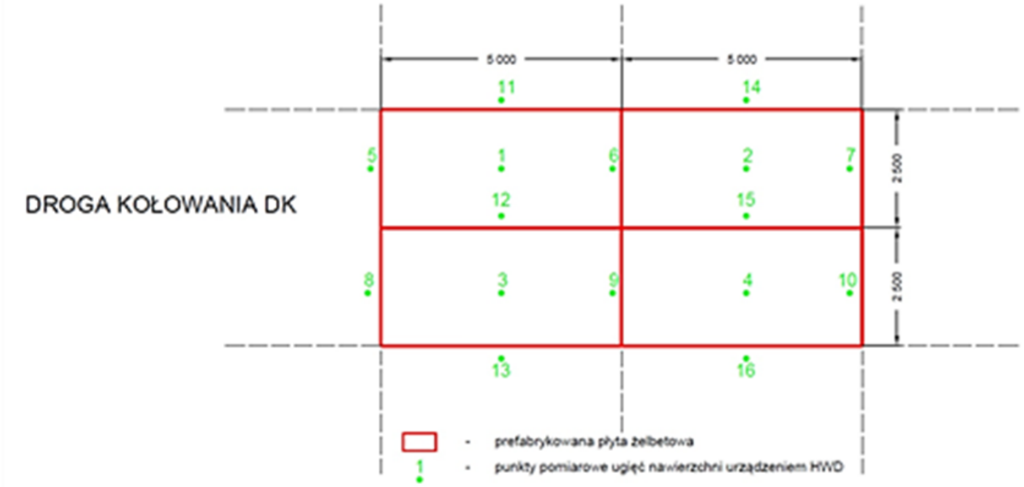
In order to verify the proposed design solution, laboratory tests were carried out on the material properties of the slab in terms of its durability, which included both the tests of mechanical properties and the physical properties of concrete. In terms of the analysis of the mechanical properties of concrete, the compressive strength and tensile strength were tested. As regards the analysis of the physical properties of concrete, tests of water absorption by weight and frost resistance were carried out. The tests were carried out on the basis of standards [11, 13, 14, 15].

Based on the conducted research, it was confirmed that:

- The cement concrete from which the prefabricated slab was made fulfilled the standard requirements for concrete class C35/45 in terms of compressive strength, reaching an average value equal to $f_{ci\,95} = (50{,}23 \pm 2{,}31)$ MPa,
- The cement concrete from which the prefabricated slab was made fulfilled the standard requirements for concrete class C35/45 in terms of tensile strength and bending, reaching an average value equal to $f_{cf\,95} = (7{,}35 \pm 1{,}54)$ MPa,
- The cement concrete from which the prefabricated slab was made fulfilled the standard requirements for concrete class C35/45 in terms of water absorption by weight, as its water absorption was $N_{w\,95} = (3{,}90 \pm 0{,}31)$ % and did not exceed the permissible value of 5%,
- The cement concrete from which the prefabricated slab was made met the requirements for the frost resistance degree F200, because the average value of the compressive strength of the comparative samples was $\Delta\ m_{F\,95} = (54{,}05 \pm 3{,}70)$ MPa, mass loss of samples after the test was less than 5% (0,22 ± 0,31) %, and the average decrease in compressive strength did not exceed 20%.

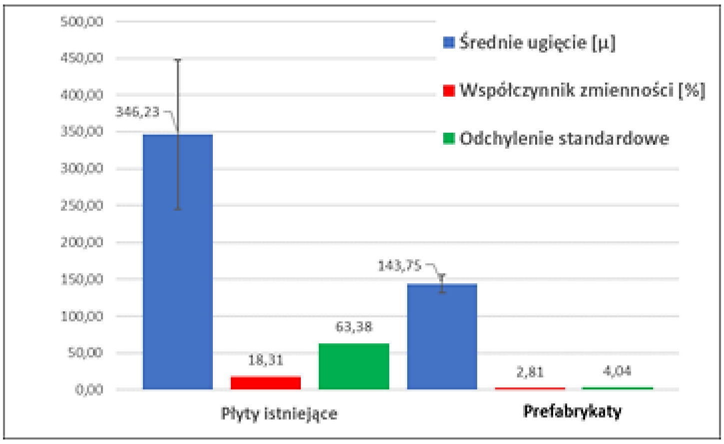
Field tests

The next stage was to conduct field tests of the airport slab in order to determine the load capacity of the paved surface repaired in this way and to compare it with the load capacity of the surrounding pavement. The tests were carried out on the airport taxiway. The pavement load-bearing capacity tests were carried out using the HWD heavy airport deflection meter. The first measurement session concerned the testing of existing panels (the so-called comparative system). Subsequent load capacity tests concerned newly built boards with the option of cooperation with adjacent boards (Figure **4**). The conducted field tests showed that the subsoil under the structure of the tested pavement, at the time of its testing, can be assessed as soils of the load capacity category B (average load capacity), with the subsoil reaction coefficient k= 100 MN/m^3. This information was then used to calculate the PCN classification number of the pavement.



4. Deflection measurement plan on the assessed reinforced concrete slab (after replacement) and on adjacent slabs

The obtained results of the load capacity tests confirm that the newly used system with the prefabricated slab has a higher load capacity than the reference system (the existing one). The average value of deflections measured on prefabricated slabs d_{95} = (143,75 ± 11,82) µm is 59% lower than the average value of deflections measured on the comparative slabs d_{95} = (346,23 ± 101,34) µm. In addition, the average value of the calculated equivalent module of the pavement structure with prefabricated slabs $E_{z\ 95}$ = (3 900,58 ± 182,64) MPa was indicated, which is 135% higher than the equivalent module determined for the comparative structure $E_{z\ 95}$ = (1 661,32 ± 472,22) MPa (Figure **5**).



5. Comparison of deflection values for existing and prefabricated slabs (slabs replaced) with error bars

On the basis of the above, it was found that the technology used with the use of a prefabricated airport slab contributed to a significant improvement in the load-bearing capacity of the tested fragments of airport pavements. In accordance with the ACN-PCN methodology defined by ICAO, the number of allowable air operations on the existing panels was calculated in relation to the number of operations on the newly embedded prefabricated panels. The conducted analysis proves that the PCN ratio of 52 / R / B / W / T is reliable for the pavement structure under assessment, and the number of permissible air operations is 255,000 (when calculating the reference Boeing 737-800). As a consequence, the number of permissible air operations increased by 76% compared to the system with existing plates (Table **1**).

Tab. 1. Results of the pavement load capacity assessment for the PCN 52 index

Functional element of the airport	PCN load index	Total number of air operations
Existing boards	**52/R/B/W/T**	**145 000**
New prefabs	**52/R/B/W/T**	**255 000**

Study of the cooperation of plates

Taking into account the aspect of using the panel connection by means of dowelling technology, the cooperation of the panels, both with the existing panels and with each other, was analyzed and calculated. On the basis of the obtained results, it was found that there is correct cooperation between the newly installed prefabricated plates and the existing airport plates of the taxiway because the average value of the load transfer coefficient was J_{95} = (81,28 ± 8,03) %. At the same time, the average value of the load transfer coefficient only for the cooperation of new prefabricated slabs using the dowelling option was J_{95} = (90,38 ± 3,77) % (Table **2**).

The results presented above clearly confirm that there is proper cooperation between the prefabricated panels, and the load transfer between the panels is at a very high level. As a consequence, it significantly reduces the stresses and deflections in the slab, and thus the damage to the pavement, which is a very desirable phenomenon.

Tab. 2. Results of cooperation of prefabricated slabs

Measurement point	Tension under the slab [kPa]	Drop force [kN]	Sensor deflection No.2 [μm]	Sensor deflection No.3[μm]	J [%]	J [%] only prefabricated items
5	1241,00	197,42	177,40	143,80	81,10	
6 (only prefabricated items)	1241,00	197,34	159,60	145,20	91,00	91,00
7	1244,00	197,85	225,00	155,50	69,10	
8	1243,00	197,61	143,90	128,90	89,60	
9 (only prefabricated items)	1240,00	197,21	155,30	136,30	87,80	87,80
10	1245,00	197,98	259,20	127,90	49,30	
11	1246,00	198,22	162,40	142,30	87,60	
12 (only prefabricated items)	1243,00	197,69	122,50	112,80	92,10	92,10
13	1246,00	198,17	185,40	144,30	77,80	
14	1244,00	197,90	162,70	137,10	84,30	
15 (only prefabricated items)	1243,00	197,61	118,60	107,40	90,60	90,60
16	1245,00	198,06	186,90	140,30	75,10	
Average value	1243,42	197,76	171,58	135,15	81,28	90,38
Standard deviation s	1,98	0,33	39,94	13,87	12,36	1,83
Standard deviation of the mean $\bar{s}$	1,14	0,19	23,06	8,01	7,14	1,06
The *k*-factor for the t-Student distribution	2,20	2,20	2,20	2,20	2,20	3,18
Confidence interval of the arithmetic mean	2,51	0,42	50,75	17,63	15,71	3,36
Calibration uncertainty $u_d(x)$	4,40	0,30	5,40	5,40	1,30	1,30
The experimenter's uncertainty $u_e(x)$	0,01	0,01	0,01	0,01	0,01	0,01
Compound standard uncertainty $u_c(x)$	2,60	0,20	11,94	5,08	3,65	1,18
Extended uncertainty $U(x)$	5,73	0,43	26,29	11,17	8,03	3,77
Coefficient of variation %	0,16	0,17	23,28	10,27	15,21	2,02

Research on operational features

At a further stage of the research, the operational parameters of the prefabricated airfield slab proposed in the research experiment were checked, i.e. roughness, texture, and evenness.

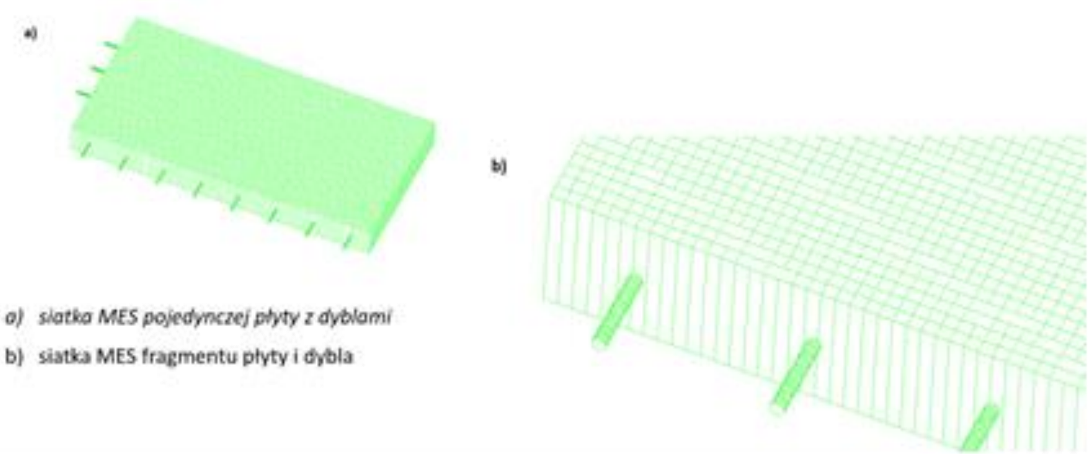
Based on the research, it was found that:

- the average value of the coefficient of friction on the assessed airport pavements was μ_{95} = (0,62 ± 0,04). The surface of the assessed functional element of the airport obtained average values of the friction coefficient higher than the normative value for the airport pavements "in operation", which is 0.50,

- The tested airport pavement made of prefabricated slabs was characterized by an average texture depth at a very high level, equal to ETD_{95} = 0,71 ± 0,11 with the required standard minimum of 0.25,
- the condition of evenness in the longitudinal direction, assessed in accordance with the adopted criteria, was at a very good level (the average defectiveness is W_{95} = (2,80 ± 1,02) %),
- the state of evenness in the transverse direction, assessed in accordance with the adopted criteria, was also very good (the average defectiveness is W_{95} = (0,00 ± 0,04) %).

Static and strength analysis of a prefabricated airport slab using the Finite Element Method (FEM)

The next stage of the research was the static and strength analysis of the prefabricated airport slab using the Finite Element Method. For the sizing and analysis of the slabs, it was assumed that the pavement would be loaded with the traffic of aircraft moving on it, and the calculation aircraft selected for the analysis was also the Boeing 737-800. The scope of the research included the analysis of loaded, prefabricated concrete slabs connected with each other by dowelling in terms of the global state of effort of the structure (stresses, strains). The analysis takes into account the stress states in dowels connecting adjacent slabs. The FEM model of the structure was made as a shell-beam system, because a single slab consisted of shell elements, while a single dowel consisted of beam elements (Figure **6**). Taking into account the fact that the shell-beam system was used for the FEM simulation, the Mises reduced stress was the most favorable value of stresses. This hypothesis allows for the determination of the moment at which a material subjected to a complex state of stress will lose its elastic properties. From a technical point of view, this gives 99% confidence in the application of this hypothesis.



6. Shell and beam model of the analyzed structure

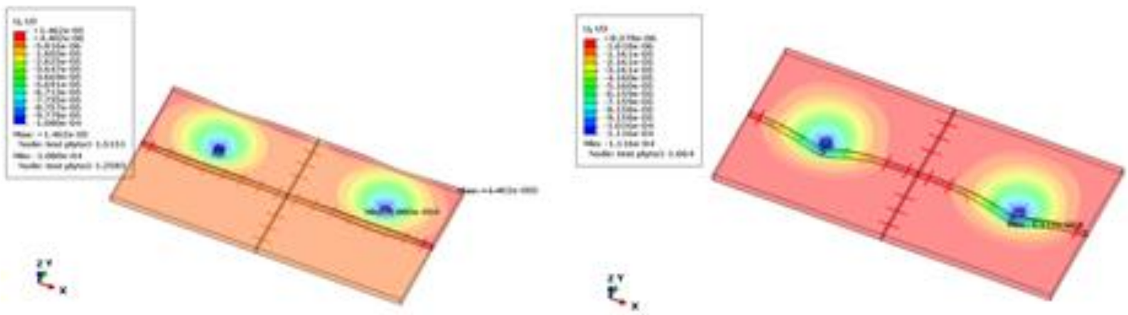
For the purposes of this research, in order to reflect the real traffic of aircraft on the taxiway, the FEM analysis was carried out in two different variants of the airport apron loading [16]. The first variant concerned the analysis of the loading of the plane's main shin in its central part (Figure **7**). In the second variant, the load was applied at the edge of the airport apron, 375 mm from its edge. In both cases, the spacing of the load on the plates was maintained in accordance with the gauge of the main leg for the Boeing 737-800.

Based on the FEM analyses carried out, it was found that:

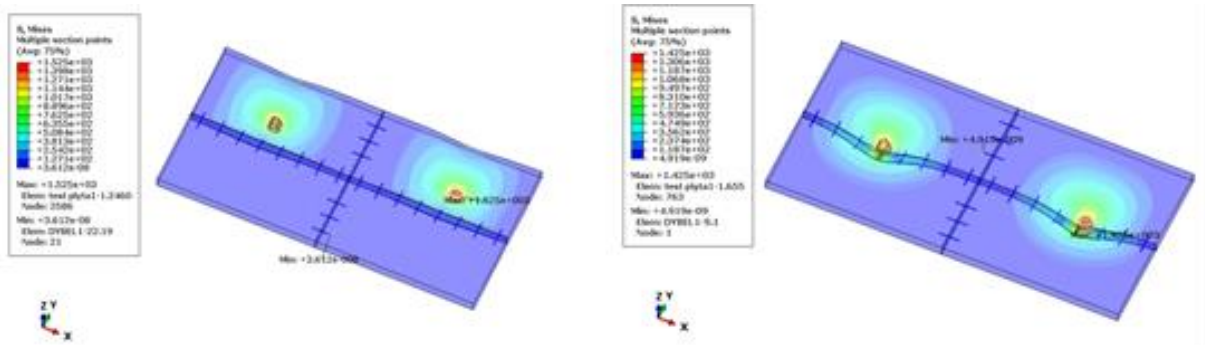
- there will be no cracking in the tested slabs because the maximum main stress is much lower than the tensile strength of the concrete, variant I (1,591 kPa <5,790 kPa), variant II (1,505 kPa <5,790 kPa),
- the maximum value of the main (tensile) deformation is 0.00004 and occurs at the center point of load application. It should be emphasized that in accordance with the value adopted in engineering practice, the deformation of cracking in the tension of concrete is at the level of 0.00035. Therefore, scratching in the concrete slab should not occur because the permissible deformation values have not been exceeded (0,00004 < 0,00035),
- despite the symmetrically applied load on the plates, the stress state is not fully symmetrical - the right plate is slightly more stressed. This is due to the contact phenomena of dowels,
- the maximum vertical displacement of the plates for the option I is 0.01 mm and occurs in the central point of load application; the maximum vertical displacement of the plates for variant II is 0.008 mm and occurs in the central point of load application (Figure **8**),
- the maximum stress in dowels for variant I is 56.08 kPa, for variant II it is 123.40 kPa. The maximum tangential (shear) stresses occur in the middle of the dowel length (at the junction of two plates), in the expansion joint space,
- visualization of the global state of stresses and strains shows how the dowels and the edges of adjacent plates are deformed (Figure **9**).

Static and endurance analysis, and comparative analysis confirm that the shell-beam model used in the simulation allowed for the assessment of the global stress state of the structure, taking into account the bending state.

7. Loading of the airport apron in its center - option I



8. Contour map of U3 vertical displacements in the airport apron in the shell-beam model



9. Contour map visualizing the global stress and strain state

Summary

Airport pavements, constituting the ground part of the maneuvering area intended for the movement, parking, and servicing of aircraft, are an extremely important element of the airport infrastructure. The main task of the pavement is to transfer the utility loads from moving or standing aircraft. The technical condition of the pavement, which should not raise any doubts, is a key element in ensuring the safety of air operations.

Considering airports, where it is necessary to carry out repair works on airport pavements, and at the same time, there is no possibility of transferring traffic to a backup runway or other taxiways, the most important factor from the economic point of view is the shortest possible time of repair activities and commissioning of the repaired object in such a technical condition that will ensure the safe performance of air operations. As a consequence of the above, it is necessary to search for new, effective, and quick technologies for the repair of damaged airport aprons, which must be performed within a specific time regime.

One of such methods proposed by the authors of this article is the possibility of using a prefabricated concrete slab cooperating with adjacent slabs. Importantly, the duration of all corrective actions using the method in question does not exceed 5 hours and they can be performed both during the day and at night, at different times of the year, and in different weather conditions. The proposed method, compared to other methods of carrying out repairs using prefabricated elements used both in Poland and in the world, is a pioneering solution due to the introduction of the element of cooperation between the panels and the total time needed to perform the repair task, which in the case of airports is an extremely important argument.

The advantages of the prefabricated airport slab presented in this article as well as the laboratory and field tests carried out, which gave unambiguously positive results, determine the advisability of its use and dissemination. The implementation experience gathered in the course of the work and the use of repair technology with the use of a prefabricated slab at the airport allow us to state the complete technical efficiency of this design solution. Considering the relatively quick and easy replacement of the plates without the need for longer breaks in air traffic, this technology can be successfully used in both civil and military aviation.

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