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AN ATTEMPT TO IDENTIFY CONCRETE STRENGTH PARAMETERS BY SIMULATING STANDARDIZED TESTS

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Abstract – This study focuses on transport infrastructure, particularly the construction and maintenance of concrete airport pavements, which are crucial for aviation transport safety. The main objective of the research was to evaluate the effectiveness of standard methods for determining the strength of concrete used in airport slabs (LWS) and road slabs (MON). The study employed the finite element method (FEM), comparing its results with experimental data. Simulations of concrete compression and bending tests were conducted in accordance with procedures described in standardization documents. The research results confirmed the usefulness of standard methods for testing and determining concrete strength. At the same time, the study highlighted the limitations of simplified calculation formulas contained in the standards. This research was carried out with the support of the Interdisciplinary Centre for Mathematical and Computational Modelling at the University of Warsaw (ICM UW).

Key words – airfield, concrete pavement, finite element method, simulation, standard, transport, strength

JEL Classification – L61, L74

INTRODUCTION

Testing the strength of concrete is essential for ensuring the structural integrity and longevity of concrete constructions [1]. The latest methods for evaluating concrete strength combine traditional testing approaches with modern technological advancements. Traditional tests such as the compressive strength test, which measures how much pressure concrete can withstand, and the tensile and flexural strength tests, which determine the material's resistance to bending and stretching, remain foundational. Meanwhile, non-destructive techniques like Ultrasonic Pulse Velocity (UPV) and rebound hammer tests have grown more sophisticated with digital enhancements, offering insights into concrete's condition without damaging it. Innovations also include methods that utilize digital image correlation for a non-contact way to assess strength and the development of cracks, and the maturity method, which tracks strength development over time through embedded sensors. These advancements improve the accuracy, efficiency, and comprehensiveness of concrete strength assessments, combining the reliability of time-tested methods with the precision of cutting-edge technology.

Numerical simulation through the Finite Element Method (FEM) serves as an effective tool aiding the identification of parameter values for material models, such as concrete [2]. This technique not only facilitates a deeper understanding of the behaviour of various materials but also contributes to the development of more advanced and safer engineering structures through proper calibration of material models. The execution of simulations encompasses a series of stages, starting from numerical modelling aimed at faithfully reflecting the real properties of the material, including its resistance to various loads and phenomena such as creep or cracking. The next step involves selecting an appropriate material model from the available options, ranging from simple linear-elastic models to more complex models accounting for plasticity and damage, which is crucial for the accuracy of the simulation. Typically, the next step, material model calibration, is a process of adjusting its parameters based on experimental data, such as Young's modulus or compressive strength. This stage requires conducting a series of simulations with different sets of parameters and comparing their outcomes with experimental observations to find the most suitable set. Verification and validation of the model are the final essential steps, during which it is checked whether the model adequately reflects the behavior of the structure under various loads.

Optimization and parameter identification become key processes when experimental data is limited. In this work, the author utilized the inversion technique, adjusting the model parameters in such a way as to minimize the differences between simulation results and experimental data, illustrated by the example of compressing concrete samples. The inversion method, which allows for determining model parameter values based on observed data, reverses the typical modelling process, which is particularly useful when direct measurements of some parameters are difficult. Although this is a process requiring significant computational power and advanced numerical techniques, especially in the case of complex models and nonlinear problems, its application allows for more accurate identification and assessment of material parameters, which is crucial for mechanical engineering and structural design.

The author of the paper identified the parameters of the concrete material model through the implementation of a simulation of the standardized concrete compression test. Using the thus developed concrete material model, they conducted a numerical simulation of the standardized concrete bending test.

1. COMPRESSION TEST BASED ON THE POLISH STANDARD

The material model parameters for concrete were identified based on data obtained from the compression simulations of concrete samples. Following the existing standards, initially defined by PN-88 B-06250 [10] and later updated by PN-EN 206 [12], the methodology for assessing compressive strength for ordinary concrete was described. The testing procedure requires the preparation of samples in the form of cubes with side dimensions of 15 cm, which are then placed in a strength machine between two compression plates. The process of increasing the compressive force is carried out gradually and evenly, at a speed specified by the standard, for example, 2.4 MPa/s. During the test, the maximum compressive force leading to the sample's destruction and the maximum material deformation are recorded. The results of the compression test are then compared with the limit values established in the standard for the various concrete strength classes. Analysis of this data allows for the assessment of the compressive strength of the material under investigation.

1.1. BENDING TEST BASED ON THE POLISH STANDARD

The material parameters obtained during the compression test were used to conduct a bending test simulation. This process is defined by the standard PN-EN 12390-5 [9], which specifies the methodology for assessing the flexural strength of concrete samples. The description of the procedure includes several key stages: starting from the preparation of samples, through their proper placement in the strength machine on two supports with a diameter of 20 to 40 mm. The bending force is applied in the central part of the sample - this is one of the two possible variants of the procedure - and is increased gradually, at a speed consistent with the standard, which corresponds to a stress increase in the range of 40 to 60 kPa/s. During the test, the maximum bending force leading to the sample's breakage and the deflection of the sample at various points are recorded. The obtained results are then compared with the limit values specified in the specification for the tested type of material. Based on this, the flexural strength of the tested concrete is assessed.

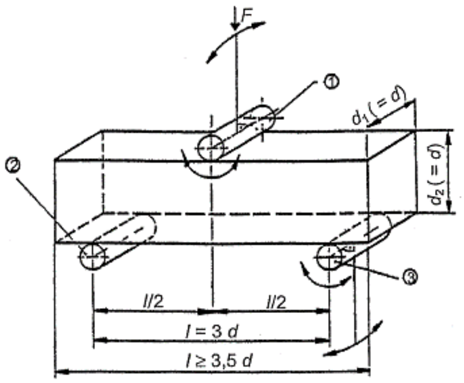

Fig. 1. Diagram of loading a concrete sample in 3-point bending [9]

Fig. 2. Vötsch climatic chamber and INSTRON strength machine used in the research (WITPiS materials)

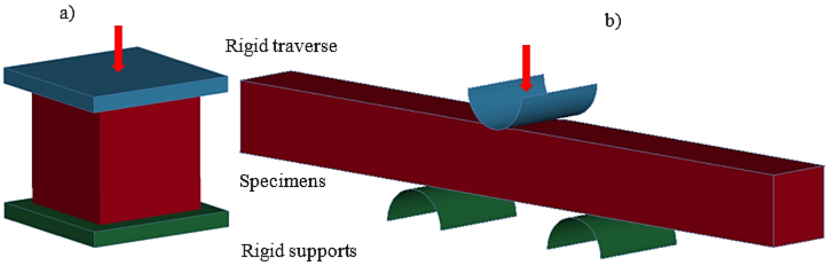

Fig. 3. FEM Physical model: a) - for compression, b) - for bending (own materials)

2. DESCRIPTION OF THE EXPERIMENT

To verify the developed model, experiments were conducted, involving the compression of concrete samples in accordance with the guidelines contained in source PN-88 B-06250 [10]. These studies were carried out at the Military Institute of Armored and Automotive Technology, using available laboratory equipment, including the Vötsch climatic chamber and the INSTRON strength machine (Fig. 2).

The experiments were conducted on standard cubes with side 150 mm made of C30/37 [12] (B40 according to the standard PN-EN 1994-1-2:2008. Eurokod 4 [11] class cement concrete, which matured for 28 days. Ten samples were used for testing. The purpose of these studies was to examine the compressive strength of the concrete. An analysis of many samples was carried out, enabling the estimation of the average strength of the tested concrete at 73 MPa, with an average displacement of 3.5 mm (corresponding to a strain of 0.0035 m/m).

3. NUMERICAL SIMULATION

3.1. SELECTION OF METHOD AND COMPUTATIONAL TOOL

To achieve the objectives of this work, numerical simulation using the Finite Element Method (FEM) was applied, which was implemented with the LS-DYNA software [4-5]. Two geometric models of rectangular concrete samples, adapted for compression and bending tests, were constructed in accordance with the requirements specified in the relevant standards [10]. The geometry of the samples was defined using a regular grid of SOLID-type finite elements, with the size of the element side being 5 mm. Experimental elements such as the traverse and supports were represented using a grid of RIGID elements. The movement of the traverse was simulated by applying a force *F(t),* acting perpendicular to the axis of the samples, with the force increasing from zero to a maximum value exceeding the strength of the samples. To represent the interaction between the supports, traverse, and surface of the samples, a SURFACE_TO_SURFACE contact model was used, taking into account friction. The supports were immobilized by applying appropriate constraints (RY). The presented FEM model was detailed in the attached drawing (Fig. 3).

3.2. SELECTION OF MATERIAL MODEL FOR SIMULATION

In the context of Finite Element Method (FEM) simulations regarding the behavior of concrete under load, currently two material models dominate: MAT_CSCM_CONCRETE (MAT159) and MAT_

CONCRETE_DAMAGE_REL3 (MAT072R3) [7, 14], chosen for their proven accuracy in calculations [5, 8]. Both models offer unique properties and differ in simulation applications due to their specific features. The MAT159 model, also known as the Continuous Surface Cap Model (CSCM) [4], focuses on advanced replication of cracks in concrete, enabling precise modelling of their propagation and crushing phenomena [13, 15]. It is indispensable in simulations requiring a deep understanding of the structure's behaviour post-cracking and with large deformations, such as collisions, explosions, or other scenarios involving significant distortions. Due to the detailed modelling of cracks, MAT159 is more computationally demanding, which may result in longer processing times and higher hardware requirements.

The MAT072R3 model [6], based on damage theory, allows for the modelling of material degradation under load by representing damage as changes in material properties. It is preferred in simulations focused on the overall plasticization and degradation of the material, where detailed tracking of individual cracks is not necessary. This model is typically less complex computationally than MAT159, making it more accessible for simulations requiring faster calculation times [3].

The choice between MAT159 and MAT072R3 should be dictated by the specifics of the engineering problem, accuracy requirements of the simulation, available computational resources, and user preferences regarding concrete damage modelling. Both models require precise calibration and parameterization based on experimental data, although this process may differ due to their different approaches to modelling damage and cracks. Despite MAT159 being more time-consuming and requiring more advanced data analysis for the calibration of parameters related to cracking, it is often considered more reliable in simulations of static loads. It offers extensive modelling capabilities, including elastic behaviours, plastic definitions, plasticity surface definitions, damage, the influence of deformation rate, and kinematic hardening, though this also comes with greater complexity and computational requirements. Since the chosen material model MAT_159 requires the specification of many parameter values, related to the damage model, equation of state, fracture and friction, the program's default values were adopted as well tested and documented.

3.3. DEFINING THE ULTIMATE STRENGTH LIMIT STATE

In the analysis of concrete strength, determining the moment at which the material loses its strength under increasing load is crucial. Current methodologies, described in standards, however, do not provide clear guidelines in this respect. Therefore, in engineering practice, it is necessary to rely on the analysis of *F(t)* or *RY(t)* curves, showing the relationship between force and time or displacement. Most often, identifying the moment of strength loss comes down to determining the point on the curve where the load reaches its maximum value, signalling that the sample is no longer capable of carrying a greater load. This interpretation is relatively simple and correlates with generally accepted methods of assessing material strength.

In more detailed analyses, the critical moment can be understood as the beginning of noticeable plastic deformation, which can be determined based on the change in the slope of the load-deformation curve. This signifies the material's transition into a nonlinear behaviour state, where the increase in deformation is no longer proportional to the increase in load. In advanced studies, the moment of strength loss can also be defined by the appearance of microcracks, which requires the use of specialized measurement techniques, such as acoustic emission, for its direct observation. Another method involves determining the moment at which the total energy absorbed by the sample until breaking reaches its maximum value, implying an analysis of the area under the load-deformation curve, especially useful in the study of brittle materials. During experiments, organoleptic methods can also be utilized. The analysis of sounds emitted during the destruction of concrete samples allows them to be categorized into stages: from silence in the initial phase, through the first cracks resulting from the appearance of cracks to louder cracks signalling the approach to maximum strength and the final loud crack or bang, indicating the collapse of the material structure. Visual observations also allow for the identification of several phases of destruction: from the appearance of microcracks, through the development of cracks, to the chipping away of fragments, the merging of cracks, and the formation of distinct lines of destruction.

4. DATA FOR VERIFICATION

The model was verified by comparing the results from the experiment and numerical calculations related to the three-point bending of a concrete sample.

4.1. REDUCED STRESSES IN A BENT BEAM

In the calculations of reduced stresses for a beam subjected to bending, there are several approaches that stem from the adopted theories of material strength. Among them, the formula defining the reduced stress according to the Huber-Mises-Hencky hypothesis is commonly used in the field of mechanical and civil engineering. This hypothesis finds particular application in the analysis of ductile (plastic) materials. The formula is presented as follows (1):

$$\sigma_{red}=\sqrt{\sigma_x^2+\sigma_y^2-\sigma_x\sigma_y+3\left(\tau_{xy}^2\right)} \tag{1}$$

where:

σ_{red} - reduced stress,

σ_x^2 - normal stress in the *x* direction (along the axis of the beam),

σ_y^2 - normal stress in the y direction (perpendicular to the beam's axis, often assumed to be zero in the case of pure bending),

τ_{xy}^2 - shear stress acting in the XY cross-sectional plane.

The formulas specified in the standard PN-EN 12390-5:2019-08 [9] refer to the case of a bending beam without the presence of lateral forces (pure bending), where the normal stress due to the bending moment is dominant. Since there is then $\sigma_y = 0$ and $\tau_{xy} = 0$, therefore formula (1) can be simplified, resulting in formula (2):

$$\sigma_{red} = \sigma_x = \frac{M}{W} \tag{2}$$

where:

M - bending moment acting on the beam section (equal to ¼ FL),

W - section modulus of the beam.

It is important to note that these formulas omit stresses caused by shear forces, which can be significant in certain cases, especially near supports or the point of force application. In such situations, where $\sigma_y = 0$ and $\tau_{xy} \neq 0$, it is necessary to use the full formula (1). The analysis of a beam section with dimensions of 10x10 cm, based on supports placed at a distance of 30 cm, taking into account the shear stresses τ_{xy}, shows that the value of the reduced stress σ_{red} increases by about 30%. The normal stress σ_y is approximately 450 Pa, and the shear stress τ_{xy} is about 150 Pa per unit of load F, which gives the value of reduced stress for the beam, considering both bending and shear stresses (3), at about 520 Pa. Hence, it follows that the values of reduced stresses, defined in the standard [9-12], may be underestimated, which should be taken into account when determining the safety factor or apply Zhuravsky's approach for beams with rectangular cross-section:

$$\tau_{xy} = 1.5\frac{F}{A} \tag{3}$$

5. SIMULATION PROCESS FLOW

The conducted numerical calculations employed an explicit technique with a short time interval of 0.1 microseconds. Despite this, due to the extensive duration of the simulated experiment, which was in accordance with the requirements specified in the standards, the total computation time turned out to be significantly long. This was the case even though a highly efficient computational server was used.

5.1. COMPRESSION SIMULATION OF A CONCRETE SAMPLE

As mentioned earlier, a key aspect of evaluating the obtained results was identifying the moment when the load applied to the compressed sample reaches its maximum. At this critical point, the increase in load had to be stopped, and the calculations finalized. The moment when the load reached its maximum value was determined based on monitoring the values of the reaction forces *RY(t)* (vertical) on the constraints of the lower, stationary compression plate (Fig. 4).

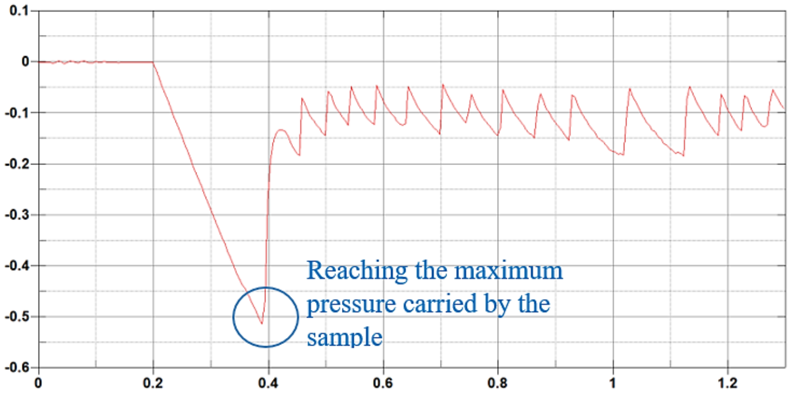

Fig. 4. Values of reaction force RY [N] as a function of time [s] in one of the vertical constraints of the lower pressure plate

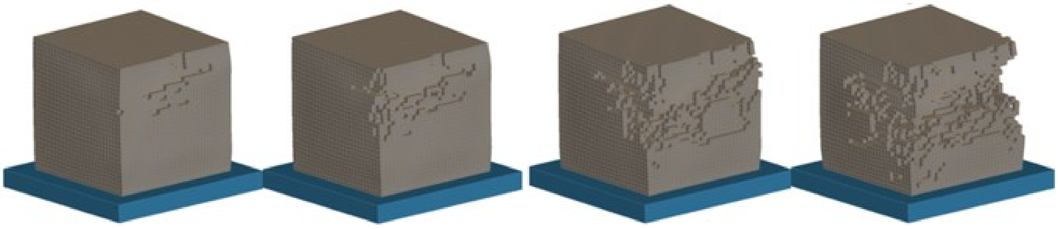

Fig. 5. Example development of deformation increase and structure destruction in a selected sample with a side of 15 cm (own material)

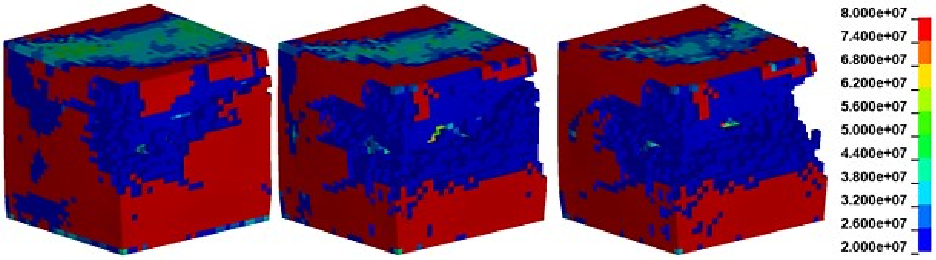

Fig. 6. Example development of pressure increase in a selected sample [**Pa**]

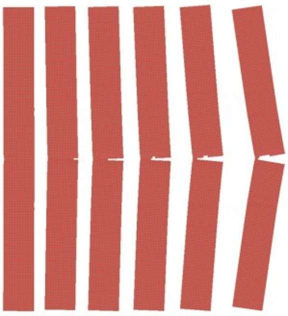

Fig. 7. Crack development in a bent concrete sample of 100x10x10 cm (**own materials**)

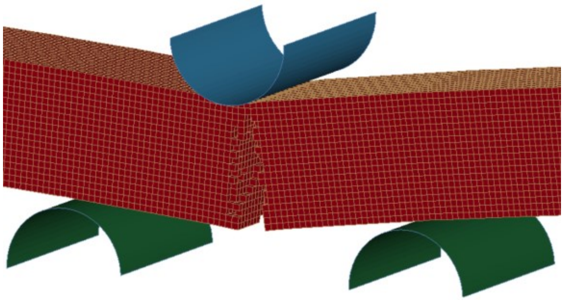

Fig. 8. View of the crack in a bent concrete sample at a selected loading momen (**own materials**)

As a result of the numerical calculations, among other things, spatial distributions of stresses, pressures, as well as the degree of destruction of the sample at specific time instants, every 1 millisecond, were obtained. Example visualizations of these distributions are presented in Figure 5 and Figure 6.

The measured values of compressive stresses, determined in accordance with standard [10], and displacements showed high conformity with experimental results. These data have been compiled in Table 1.

Table 1. Compilation of results obtained from experiment and numerically calculated

Indicator	Result of the experiment (average)	FEM simulation result	% relative difference
Reduced stress [MPa]	73	80	8
Displacement [mm]	3.5	3.0	16
Strain [%]	3.5	3.0	16

This conformity confirms the proper selection of the material model for concrete (MAT159) and the accuracy in determining its parameters. However, it is important to emphasize the occurrence of significant differences in the values of displacements and stresses recorded during the experiment, reaching values of 2.6 mm and 24 MPa, respectively.

5.2. BENDING SIMULATION OF A CONCRETE SAMPLE

A numerical simulation of the bending test was conducted using the material model that had been verified during the compression tests. The visualization of individual stages of increasing load was presented in Figure 7.

The value of the limit force at which the intensification of crack development occurs was measured to be *max(F(t))* = 32 kN. According to formula (1), this corresponds to a reduced stress σ_{red} of 14.4 MPa and 16.6 MPa, respectively without and with considering the effect of shear forces.

CONCLUSIONS

The research aimed to calibrate a concrete material model by identifying parameters based on a compression test, and then using this model to simulate the bending of concrete to estimate its strength. The durability of concrete in aviation transportation infrastructure is crucial due to the exceptional loads that occur on airport runways. Durable concrete ensures long-term resistance to repeated impacts and temperature changes, minimizing the risk of cracks and damage. Without adequately strong concrete, the infrastructure could quickly degrade, posing a threat to both aircraft and passengers. The study involved an experimental compression test of B40 class concrete samples according to the standard and numerical simulations using the finite element method (FEM) with LS-DYNA software. In the FEM simulations, the MAT_CSCM_CONCRETE model (MAT159), which accurately represents cracking and damage in concrete, was used. Simulations of compressing the samples were conducted to calibrate the material model's parameters to match the experimental data. The reliable calibration obtained allowed for the simulation of bending samples and the estimation of their strength. As part of the conducted research, a material model of concrete was developed and experimentally verified, which was then used to assess the strength of concrete samples subjected to bending. However, it is important to note that the calculations of ultimate stresses, carried out according to standard by inserting the value of the maximum limit load max(F(t)) into formula number (1), do not allow for direct comparison with the stress values obtained in simulations. Such comparison is complex and often not very valuable, as the actual stresses in a beam subjected to bending can differ from those theoretically predicted. In real or quasi-real conditions, such as simulations, factors such as local effects, the influence of shear forces near supports and at points of concentrated force application, material heterogeneity, as well as boundary conditions and the method of fixation play a significant role. These can introduce additional torsional moments near connections. The compression simulation results showed good agreement with the experiment, with a deviation of 8% for reduced stresses and 16% for displacement/deformation. This indicates the correct selection of the MAT159 material model and accurate determination of its parameters. Subsequently, a bending simulation of the sample was conducted, where the development of cracks was monitored. The measured value of the limit force, at which crack intensification occurred, was 32 kN. Converting this force into reduced stress according to the standard yielded a value of 14.4-16.6 MPa, depending on whether shear stresses were considered.

In summary, theoretical calculations are a implification, assuming idealizations aimed at facilitating analysis. As shown by the conducted work, this can lead to an overestimation of the predicted material strength. In engineering practice, to more accurately reflect the actual stress state in structural elements, numerical methods such as the finite element method (FEM) are often used, which allow for the consideration of the discussed factors. However, the author states that direct comparison of ultimate stresses from standard formulas with FEM simulations is complex, as standard formulas are a simplification, and real conditions include local effects, the influence of shear forces, material heterogeneity, etc. Therefore, numerical methods, such as FEM, allow for a more accurate assessment of the stress state in structural elements. Despite obtaining satisfactory simulation results, the author sees the need to perform a sensitivity analysis of the model using highly advanced concrete material models, such as: MAT_WINFRITH_CONCRETE, which accounts for concrete cracking and reinforcement;

MAT_CONCRETE_DAMAGE_PLASTIC_MODEL, which is an advanced plasticity and damage model that considers triaxial effects; and MAT_CDPM, which incorporates the definition of the yield surface.

PRÓBA IDENTYFIKACJI PARAMETRÓW WYTRZYMAŁOŚCIOWYCH BETONU Z WYKORZYSTANIEM SYMULACJI ZNORMALIZOWANYCH TESTÓW

Niniejsza praca dotyczy infrastruktury transportowej, skupiając się na budowie i utrzymaniu betonowych nawierzchni lotniskowych, kluczowych dla bezpieczeństwa transportu lotniczego. Głównym celem badania była ocena skuteczności standardowych metod określania wytrzymałości betonu stosowanego w płytach lotniskowych (LWS) oraz płytach drogowych (MON). W pracy wykorzystano metodę elementów skończonych (MES), zestawiając jej wyniki z danymi eksperymentalnymi. Przeprowadzono symulacje prób ściskania i zginania betonu zgodnie z procedurami opisanymi w dokumentach normalizacyjnych. Wyniki badań potwierdziły przydatność standardowych metod badania i oznaczania wytrzymałości betonu. Jednocześnie wskazano na ograniczenia uproszczonych formuł obliczeniowych zawartych w normach. Badania zostały przeprowadzone przy wsparciu Interdyscyplinarnego Centrum Modelowania Matematycznego i Komputerowego Uniwersytetu Warszawskiego (ICM UW).

Słowa kluczowe: lotnisko, metoda elementów skończonych, nawierzchnia betonowa, symulacja, norma, transport, wytrzymałość.

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