ABSTRACT
of the dissertation submitted for the degree of Doctor of Philosophy (PhD) in the field of study 8D071 - “Engineering and Engineering Science”, within the educational programme 8D07102 - “Mechanical Engineering”.

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DEVELOPMENT AND JUSTIFICATION OF PARAMETERS OF A MOUNTED IMPACT-ROTOR WORKING EQUIPMENT FOR DESTRUCTION OF SNOW-ICE FORMATIONS

The dissertation was carried out within the framework of the State Programme of Infrastructure Development of the Republic of Kazakhstan “Nurly Zhol” for 2020-2025, as part of the requirements for the award of the Doctor of Philosophy (PhD) degree in the field of study 8D071 - “Engineering and Engineering Science”, under the PhD educational programme 8D07102 - “Mechanical Engineering”

Relevance of the dissertation work. One of the relevant problems faced by municipal and road maintenance services during the winter months is the cleaning and removal of ice and snow-ice formations (SIF) that accumulate on the bearing surfaces of roads and sidewalks. These formations significantly impede pedestrian movement and driving, and in some cases make them impossible.

Snow and ice deposits accumulating on roads and pedestrian sidewalks, according to their physical properties and external characteristics, can be divided into unconsolidated, cohesionless snow (loose), compacted, rolled snow and transparent glassy ice. For loose snow, the coefficient of adhesion between the tire and the snow-covered surface decreases to 0.2; for rolled snow the coefficient of adhesion between the tire and the surface is 0.01-0.25; and in case of glassy ice formation the coefficient of adhesion between the tire and the surface is 0.08-0.15. For comparison, the coefficient of adhesion for dry asphalt is 0.7-0.8.

The coefficient of tire-road adhesion affects vehicle mileage, braking distance, and transportation cost, and it has a significant impact on the emission of exhaust gases. Field observations show that, under icy conditions, vehicle braking distances increase by 2.5-6 times, while fuel consumption may rise by up to 85%.

At present, various methods are used to combat icing on roads and sidewalks.

The main approaches include:

- applying chemical anti-icing agents and liquids to road surfaces;
- mechanical treatment by uncontrolled impact;
- thermal treatment;
- applying friction materials, such as sand, including pre-heated materials.

The most universal and effective method appears to be the mechanical breaking and removal of ice. However, the existing mechanical equipment currently in use has a major drawback - the risk of damaging the load-bearing surface of the road (or pavement) during the clearing of SIF. In addition, it requires significant energy expenditure for ice fragmentation, which increases over time as the density and therefore the strength (hardness) of the ice increases - a parameter that determines its resistance to destructive impact. As a result, not all mechanical tools for ice removal, which unpredictably affect both the ice and the road surface, are currently recommended for use and are often employed only as a necessary compromise.

The lack of studies on the operational process of new, promising mounted impact-rotor equipment for destruction of snow-ice formations on roads, and the need to determine the effect of geometric and weight parameters of the impact icebreaker on resistance forces and torque, define the **relevance of this research.**

The relevance and anticipated social impact of this work are driven by the expected reduction in winter traffic accidents and pedestrian injuries in Kazakhstan. Moreover, since the new ice-breaking machines will enable faster road clearance, vehicles will spend less time in traffic congestion, leading to a reduction in exhaust gas emissions.

The **idea of this dissertation** is the development and justification of parameters for new and efficient methods and machines for the mechanical fragmentation of ice, capable of promptly ensuring the operability and integrity of the surface layer of the serviced road after snow and SIF removal. This is achieved by the controlled and adjustable direction and impact force of the icebreaker on SIF, depending on their physical properties.

The **problem** addressed in this dissertation lies in the difficulty of ensuring effective and uninterrupted operation of urban and intercity transport during winter temperature fluctuations, which lead to the formation of ice films on road surfaces. The breaking of such ice layers presents challenges due to the lack of specialized machinery and equipment, the development and parameter justification of which are presented in this dissertation research.

The **main hypothesis of this dissertation** lies in the possibility of increasing the efficiency of mechanical removal of ice films and SIF from the road surface without damaging it, by applying controlled impact blows of the icebreaker hammers, while maintaining minimal energy consumption.

The analysis of studies on the dissertation topic revealed a high demand among road maintenance organizations for highly efficient and energy-saving equipment designed for winter maintenance of pedestrian sidewalks and roadways.

Such tasks can be performed by using effective mounted or other types of equipment, in which the working action on the SIF is, for example, an impact - the most energy-intensive and effective type of action for material destruction. However, to avoid damaging the load-bearing layer of the road, the impact must be applied in such a way as to prevent concentrated stress and penetration of active forces through the SIF into the road layer. This can be achieved by controlled adjustment of the generated impact force, ensuring that it exceeds the compressive strength of the ice, but remains below the strength of asphalt concrete, allowing the ice to be fractured without significant damage to the road surface.

The **aim of this dissertation research** is to establish relationships and regularities that describe the working process of mounted impact-rotor equipment for destruction of snow-ice formations on roads.

The objectives of the dissertation are:

- To perform an analysis of the current state of methods for combating ice formation on roads and sidewalks, as well as a constructive analysis of patent and scientific-technical data concerning the design of mounted impact-rotor equipment for destruction of ice and snow-ice formations (SIF);

- To develop and study a mechanical-mathematical model describing the inertial penetration of a spherical hammer into a deformable ice layer;

- To develop experimental methodologies, stands, and equipment for empirical verification of ice destruction patterns on road surfaces, and to compare the experimental results with analytically obtained data;

- To propose a design of mounted impact-rotor working equipment for destruction of ice and snow-ice formations (SIF) using hammers of various geometric shapes, ensuring maximum efficiency of ice and SIF removal from road surfaces.

The **object of the research** is the working process of mounted impact-rotor equipment designed for destruction of ice and snow-ice formations on road surfaces.

The **subject of the research** is the patterns of the working process involved in the interaction between impact-rotor equipment and ice formations on roads.

The scientific work is based on the development and theoretical justification of new methods of operation for mounted equipment used in winter road maintenance and urban infrastructure servicing, with the goal of achieving maximum efficiency at minimal energy consumption.

The scientific novelty of the research lies in:

- The experimental confirmation of the hypothesis regarding the possibility of effective mechanical crushing and removal of ice films and SIF from road surfaces without damaging them by means of inertial hammer impacts;

- The theoretical determination of the components of resistance forces arising during the interaction of the impact-rotor icebreaker with the destroyed ice, depending on the geometric parameters of the inertial elements, their operating speed, and the rotational frequency of the rotor;

- The mechanical-mathematical model of spherical hammer penetration into a deformable ice layer, as well as a theoretical-empirical model describing the relationship between the degree of ice destruction and the parameters of spherical impact hammers;

- The experimental determination of the depth of hammer penetration into the ice during its destruction by an impact tool with a spherical tip;

- The experimental results of comparative accelerated tests for reliability, performance, functionality, and fault tolerance of icebreaker working sections equipped with spherical hammers on flexible rods;

The scientific and practical significance of the research lies in the development of new, highly efficient equipment designed for combating SIF on road surfaces.

The **practical significance** of the research lies in:

- The development of technical documentation and the design of a ready-made, original, mounted experimental impact-rotor icebreaker, capable of effectively performing mechanical destruction of ice crusts on road surfaces;

- The creation of a methodology for calculating the parameters of a new replaceable rotary-milling impact icebreaker, mounted on a base tractor vehicle, ensuring efficient mechanical destruction of the ice cover;

- The development of an experimental test bench for accelerated testing of working sections of impact-rotor icebreaking equipment, which made it possible to determine their operability, functionality, and reliability.

- The introduction of design solutions for a new mounted impact-rotor working unit for the destruction of ice and SIF, confirmed by six patents of the Republic of Kazakhstan, a published international PCT patent application (indexed in Web of Science), and one Eurasian patent for an invention.

The following scientific statements are **submitted for defense**:

- The use of mounted impact-rotor equipment with inertial hammers of various geometric shapes for destroying ice and SIF makes it possible to effectively clean road surfaces from ice while preserving the integrity of the road pavement;

- The resistance of ice to tangential shear forces, both on smooth and rough surfaces, is on average 20% higher than its resistance to separation, which indicates the practical impossibility of removing the ice film by shear alone, mechanical destruction (crushing) and cleaning using inertial hammers is required;

- The regularities of the influence of ice thickness and temperature variations on the power consumption required for its crushing have been established;

- When the mass of the impactor is m=0,5 kg and the diameter of its spherical working surface is r=0,03 m, complete destruction of ice with a thickness of h_i=0,1 м at an ambient temperature of t^o_a=20ºC occurs without the sphere contacting the concrete surface, while energy consumption for crushing ice and SIF on roads is reduced by up to 25% without loss of productivity;

- The destruction of SIF is not influenced by the externally applied force, but rather by the kinetic energy supplied to it, and specifically by the portion of that energy that is expended on performing the useful work of SIF crushing - that is, the part converted into potential stress energy arising within the body of the SIF during its deformation, which subsequently leads to its fracture or fragmentation.

During his doctoral studies, Bugayev A.B. worked as a junior research associate on state-funded projects of the Ministry of Science and Higher Education of the Republic of Kazakhstan (awarded through competitive selection) in 2018-2020: Project No. AP05130746 “Mechanized Complex for Road and Pavement Cleaning During Winter Conditions” and in 2021-2023: Project No. AP09260192 “Development of Innovative Milling-Rotor Snow Removal Equipment with Enhanced Operational Efficiency.”

The research results were duly documented and implemented in the production process of East Kazakhstan Branch of “Eurotechservice K” Limited Liability Partnership, Ust-Kamenogorsk city.

Summary. The first chapter of the dissertation presents an analysis of the state of the art in combating ice formation on roads and sidewalks, as well as an overview of previous research. It includes a review of patent and technical solutions for rotary ice breakers and defines the goals and objectives of the study.

The second chapter provides the theoretical justification and modeling of the working elements for ice destruction. It describes the interaction process between the inertial-impact working equipment and SIF, presents a mechanical-mathematical model of the penetration of a spherical striker into a deformable ice layer, and develops a mathematical model of the impact-force interaction between the spherical striker and the elastically deformable ice layer.

The third chapter is devoted to the methodology of experimental studies of ice destruction by inertial impact strikers of the ice-breaking device. It outlines the stages, objectives, and general scheme of the experimental work, as well as the experimental methods used under laboratory conditions. A theoretical-empirical model is presented, showing the dependence of ice cover destruction on the parameters of spherical impact strikers. The chapter also describes the results of comparative accelerated tests for reliability of the ice breaker's working sections with spherical strikers on flexible rods and includes the verification of the theoretical collision model of SIF with the impact strikers by experimental means.

The fourth chapter provides a review and recommendations for the design and selection of the optimal configuration of the mounted impact-rotor working equipment intended for the destruction of snow-ice formations.

Personal contribution of the dissertation author. The dissertation research was carried out independently by the author. The author conducted a patent analysis of existing designs and a review of theoretical studies in the field of ice-scaling machines.

He described the process of interaction between the working equipment of inertial-impact action and the SIF.

He developed and studied theoretical models and prerequisites for designing inertial-impact ice-scaling working equipment. He developed a mathematical model of the impact-force interaction between a spherical striker and an elastically deformable ice layer. He designed and built experimental test benches for accelerated testing of the ice-scaler's working section, as well as full-scale working equipment to evaluate the performance of the prototype ice-scaler under natural industrial conditions. He carried out empirical adjustments of the theoretical dependencies. He conducted full-scale experimental studies of the mounted ice-scaling working equipment with spherical strikers. He performed comparative accelerated reliability tests of ice-scaler working sections with spherical strikers mounted on flexible rods.

Publication and approbation of the research. The main provisions of the dissertation have been published in 19 scientific works, including, 2 articles indexed in the Scopus database with a percentile above 35 and 1 patent for an invention cited in the Web of Science database, in 1 article recommended by the Committee for Quality Assurance in the Sphere of Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, in 1 Eurasian patent and 8 patents for inventions of the Republic of Kazakhstan, in 3 research reports registered with the National Center for State Scientific and Technical Expertise (NCSTE), in 2 articles included in the Russian Science Citation Index (RSCI) abstract database. All publications present the materials and results of theoretical and experimental studies of the working process of mechanical removal of ice coating from road surfaces. These studies provide insights into the processes occurring both within the ice mass and in the contact zone between the ice layer and the spherical striker on a flexible rod, allowing for the selection of optimal parameters for the ice-removal process and for the design parameters of the working elements of rotary ice-scaling machines. Additionally, the dissertation materials were presented in 4 abstracts at international scientific, practical, and methodological conferences.

The research results were reported and discussed at international scientific conferences, including: the VII International Scientific and Technical Conference of Students, Master's Degree Students, and Young Scientists "Creativity of Youth for Innovative Development of Kazakhstan", East Kazakhstan Technical University (EKTU), 2021; the International Scientific and Practical Conference "Integration of Science, Education, and Production - the Basis for Implementing the Nation's Plan" (Saginov Readings No. 12), June 18-19, 2020, Ministry of Education and Science of the Republic of Kazakhstan (MES RK), Karaganda Technical University (KarTU), 2020; the VI International Scientific and Practical Conference "Science and Education in the Modern World: Challenges of the 21st Century" (Section 4: Technical Sciences), Public Association "Bobek", Nur-Sultan, 2020.

Structure and scope of the dissertation. The dissertation is presented on 189 pages of typescript and consists of a list of symbols and abbreviations, an introduction, four chapters, and a conclusion. It includes 131 figures, 16 tables, a list of references comprising 128 sources, and six appendices.

The author expresses sincere gratitude to the staff of the Department of Road Construction Machinery of the Moscow Automobile and Road Construction State Technical University (MADI) and personally to its Head, Kustarev Gennadiy Vladimirovich for their assistance and consultations during the experimental work. The author also thanks A.Zh. Baigunusov, Director of "Oskemen-Tazalyk" LLP, and V.K. Dydyshko, Director of the East Kazakhstan Branch of "Eurotechservice K" LLP, for their help and support in organizing the commission and implementing the prototype ice-scaling machine in production.

Research results and main conclusions. The dissertation presents new scientifically substantiated results, the application of which provides a solution to an important applied problem - the development of a methodology for calculating the design parameters of an ice-scaling machine intended for the mechanical cleaning of road surfaces from ice coatings. The proposed design ensures efficient high-speed removal of snow and ice formations from roads with minimal energy consumption.

The results of the theoretical and experimental studies of the working process of a rotary ice-scaling machine equipped with spherical strikers on flexible rods make it possible to draw a number of general conclusions and provide practical recommendations for selecting the parameters of the working tools and the operating modes of machines of this type:

1. A mechanical-mathematical model of ice fracturing has been developed, which makes it possible to correctly select in advance the parameters and design of the ice-breaking sections of the ice-scaling machine. The operation of these sections

will be most effective for the current ice conditions, its thickness and strength, while simultaneously preserving the integrity of the road surface.

2. The shear resistance of ice to tangential forces, both on smooth and rough surfaces, is on average 20% higher than its tensile resistance. This indicates the practical impossibility of removing an ice film solely by shear forces; therefore, its destruction (fragmentation) and removal must be carried out by mechanical means, such as rotating inertial strikers;

3. Based on the results of experiments and their computer processing, an empirical refinement of the initial mathematical relationship was performed, resulting in a new refined theoretical-empirical formula that links the parameters of the inertial strikers of the ice-scaling machine with spherical impact heads to the characteristics of the SIF.

4. To perform empirical correction of the derived theoretical formulas and obtain relationships suitable for practical use, experiments were conducted on the destruction of ice by spherical strikers with different masses (m) and radii (R) of the working surface. As a result, a dependence was established between the thickness of the fractured ice and the mass of the spherical striker, and the actual stresses at which the ice failure occurred were determined. These stresses were used for empirical correction and refinement of the theoretical dependencies employed in the calculation of the ice destruction process caused by the impact of a spherical striker.

5. When the spherical striker operates on a surface not covered with ice, shadow-like marks remain from the impact, but the surface itself is not damaged, which confirms the validity of the author's hypothesis regarding the possibility of destroying the ice layer on road surfaces without damaging the pavement itself.

6. It was found that, in all experimental cycles, the actual thickness (h) of the destroyed ice was 7-8 times greater than the calculated penetration depth (w) of the striker into the ice. Based on this finding, additional computational dependencies were derived to determine the mass and impact velocity of the spherical striker required to destroy ice of a given thickness.

7. As a result of the planned tests of the experimental prototype (EP), several dependencies (graphs) were obtained, including: the variation of the crushing force of the SIF with respect to the mass of the striker (WE); the dependence on the operating speed; the variation of the resisting moment of ice crushing with the height of the SIF; the adjustment of the dynamic destruction force with respect to the SIF thickness; and the dependence of the impact power on the thickness of the SIF and ice, the weight of the striker, and the temperature. When verifying the adequacy of the theoretical model, the discrepancy between theoretical and experimental results was within 5-15%;

8. The selection of the optimal configuration of various strikers for the ice-scaling working equipment (WE), according to the refined methodology, makes it possible to reduce energy consumption by up to 25% for SIF crushing and removal from road surfaces, while maintaining the same productivity and ensuring complete preservation of the road's surface layer.

9. The industrial verification of the mathematical model describing the collision between inertial strikers and the SIF demonstrated that, when the drive shaft of the

ice-scaler rotates together with the replaceable sections and inertial strikers in the direction of travel, the power required for SIF crushing is 2-3 times lower than when rotating in the opposite direction.

10. In the planned experiment involving ice-layer the drop of a spherical striker, the selected parameters - mass m=0,5 kg and diameter of the working spherical part d=0,05 m, made it possible to completely destroy SIF of thickness h_i=14 mm, at an ambient temperature of $t^0{}_a$= -20^{0}C, in a single impact, when the sphere was dropped from a height of h_s=1200 mm. This corresponds to a rotational speed of the WE of n=360 rpm, while at n=883 rpm, the equivalent of a double impact corresponds to a drop height of h_s=700 mm. In this case, the sphere destroys the ice almost without reaching the road surface, i.e., the experiment confirmed the possibility of breaking and removing the SIF from the road surface without damaging the pavement by means of the inertial striker of the ice-scaling machine.

11. A double impact of the inertial striker into the previous crater, achieved by reducing the speed of the base vehicle or increasing the rotation speed of the drive shaft, results in a 1.3-fold decrease in the striker's impact velocity (or the rotational frequency of the WE drive shaft). This allows for adjustment and reduction of the overall energy consumption for SIF removal.

12. Snow-ice formations, including thin ice films up to 3 mm thick formed as a result of the freezing of meltwater or rainwater, are effectively destroyed by the mounted chain-type working equipment with spherical strikers. This design enables efficient removal of snow-ice buildup up to 15 mm thick from the road surface in a single pass of the base vehicle operating at a standard drive shaft rotation speed.

13. A significant influence on the ice destruction process is exerted by the radius of the working spherical surface of the striker: as this radius increases, the efficiency of ice destruction decreases. With a flexible linkage (chain) length of 0.2 m, the radius of the striker sphere is recommended to be within the range of 0.05-0.03 m.

14. At a striker mass of m=0,3 kg, kg and a diameter of the spherical working surface r=0,03m, an ice layer of up to h_i=0,08m thick at an ambient temperature of $t^o{}_a$=–20ºC, was completely destroyed without the falling sphere reaching the concrete surface. This experimentally confirms the possibility of avoiding road surface damage when using a striker with a spherical working surface.

15. An ice layer up to 15 mm thick is shattered in a single pass by a striker of m = 0.5 kg, with the swing amplitude of the strikers corresponding to the standard external dimensions of a road brush bristle and the maximum rotational speed of the tractor's power take-off shaft. If this condition is not met, it becomes necessary to increase the mass of the spherical striker and, accordingly, its radius. For the removal of snow-ice formations, as opposed to solid ice coatings, the links of the working shaft with spherical strikers may be alternated with empty segments (without spheres). This arrangement increases the machine's productivity while reducing energy consumption.

16. The destruction of the SIF is not determined by the applied static force but by the kinetic energy delivered to it, and specifically by the portion of that energy converted into useful work of SIF fragmentation - that is, into the potential energy

of stresses arising within the SIF during deformation, which then leads to fracture or crushing. For an ice thickness of 15 mm or more, a striker mass of m = 0.5 kg, rotating at the standard speed of the MTZ-80 tractor's drive shaft, is insufficient for effective destruction. Therefore, to achieve efficient SIF crushing, it is preferable to increase the rotation speed of the drive shaft; if this is not possible, it becomes necessary to increase the mass of the strikers or reduce the tractor's travel speed, though this may increase the overall energy consumption.

17. During the operation of the ice-scaling machine equipped with spherical strikers for cleaning road surfaces from snow-ice formations, the required physical condition of strength is fulfilled: the maximum calculated stresses (stresses at the critical point in the finite element model) arising in the asphalt concrete after the impact of the spherical striker on the overlying ice are lower than the ultimate strength of asphalt concrete. Consequently, the pavement remains intact and durable, whereas the ice layer is destroyed, since the same maximum operational stresses after the striker's impact exceed the ultimate strength of the ice.

18. Using the derived theoretical-empirical formula, calculations of the striker mass were carried out for the same ice-layer thicknesses as in the experiments where the SIF were destroyed by a single impact. The discrepancy between the theoretical calculations and the experimental results proved to be very small (maximum peak error - 15.6%).

19. By modifying the well-known classical Boussinesq model, a closed-form solution was obtained for a new contact problem in elasticity theory: the pressure of a spherical striker on a two-layer foundation (ice over asphalt-concrete pavement) of finite thickness rigidly bonded to a non-deformable infinite medium.

20. The obtained empirical-theoretical relationships and the proposed calculation method make it possible to solve various problems for determining the parameters of impact-type working elements with spherical strikers, both at the design stage and during operation.

Direction of further research. Further work to continue development of the promising low-energy-consumption design of the rotary ice-scaler's working equipment should proceed along the following directions:

- Identification of new, most promising ways to improve the working equipment of the rotary ice-scaler in order to reduce energy intensity and traction resistance by 30-40% and increase productivity by 20-30%, including:
- changes in the shape and fastening of spherical or alternative impact elements (strikers):
- design and manufacture of new experimental and prototype samples and models;
- development of experimental procedures and execution of experimental works;
- development of analytical calculation methods for the structures, their optimization, and determination of effectiveness.

Development of a preliminary (conceptual) design for an innovative working equipment for the rotary ice-scaler, with the prospect of commercializing the results within the Republic of Kazakhstan.