Green principles of ecological safety of transport construction

Ekaterina Shestakova[1*] and *Pavel* Shestakov[1]

[1]Emperor Alexander I Petersburg State Transport University, 9, Moskovsky ave., Saint Petersburg, 190031, Russian Federation

Abstract. The current trend toward the use of 3D concrete printing represents a vector for green financing of innovative transportation projects and a shift from traditional construction to additive manufacturing and a closed-loop economy. The potential impact of additive technology in the field of transport infrastructure is expected to be greater than in any other, due to the scale of construction printing and its environmental potential to ensure the environmental safety of transport construction at the global, regional and local levels, which appears to be a relevant interdisciplinary research area. The article analyzes the transition to a "green economy," including the introduction of additive technologies and the rational use of construction resources. The article gives proposals for energy-efficient and ecological green construction of high-speed railways and provides a rationale for the use of additive technologies using 3D-printed noise protection walls made of eco-concrete (green concrete, geo-concrete). The main recommendations on the choice of structures, optimal for the implementation of active noise protection measures on high-speed railways and artificial constructions are given. Presented the work of PSTU students of the Faculty of Transport Construction on the subject of 3D printing of noise protection panels with different acoustic performance. Modern architectural solutions were made with the preparation of a feasibility study on the implementation of innovations and the development of green design competencies. **Keywords:** environmental safety, environmental education, additive technologies, additive building production, "green" competences, 3D printing, 3D printer, geobeton, noise screens.

1 Introduction

Over the past decades, most developed and developing countries have prioritized sustainable economic growth, expanding opportunities in resource use, and reducing harmful environmental impacts. The circular economy is the key to overcoming the global waste crisis and climate crisis, which are the focus of advanced countries. Russia has significant potential for renewable energy and the introduction of additive green building technologies that set the vector for sustainable economic development.

Russia has the potential to produce "green" hydrogen and develop off-grid wind power plants and may even become a world market leader. In the Energy Strategy of the Russian

* Corresponding author: ekaterinamost6@gmail.com

Federation approved in 2020 for the period up to 2035 (PPRF dated June 9, 2020 № 1523-r) the task is to develop renewable energy with the achievement of innovation by 2024 - 14%, and by 2035 - 20%.

Currently, the transport construction requires quantitative and qualitative changes that contribute to a more effective solution of the problems of increasing the volume of construction, the implementation of large-scale infrastructure projects, opening up opportunities for the development of industrial and economic potential of the Russian Federation.

The implementation of the road map for the realization of the Strategy for development of the construction industry and housing and communal services of the Russian Federation until 2030 with the forecast for the period up to 2035, allows a step-by-step transition to a new, improved system that takes into account new technologies, innovations and implementation of additive technologies (3D-printing) in construction. The Russian Government Decree № 1913-p dated 14.07.2021 "On approval of the Strategy for development of additive technologies in the Russian Federation until 2030" indicates the volume of Russian market of additive technologies (additive equipment and components, materials for additive printing, services and software), the target scenario would increase from 3560 million rubles in 2020 to 13204 million rubles by 2030. The annual growth rate of the domestic market of additive technologies will be 14% (the average variant between conservative and innovative).

A few decades ago, it was hard to imagine that 3D printing would be used in the construction of buildings and transportation facilities, but today it is becoming a reality: the introduction of 3D printing innovations can dramatically reduce the cost of facilities and the pace of construction.

Innovative construction technologies and materials for 3D additive technologies include several major areas and areas of research and development:

- nanomaterials and nanotechnologies;
- effective building materials for green construction;
- resource- and energy-saving technologies for building materials production.

The main objectives of green building is to reduce resource consumption throughout the life cycle and improve the quality of construction, this is also possible with 3D printing materials (e.g., geoblock concrete or the use of self-repairing concrete).

Resource-saving 3D printing is not yet capable of replacing traditional construction on a mass scale, but it can already demonstrate a more efficient use of resources, waste reduction, and has extended recycling practices (recycling of waste).

2 Materials and methods

Today's increasing pressure on the environment from human activities requires a change in attitude toward the way the construction industry currently operates. Construction production organizations around the world are now aware of the need for waste reduction, more reliable product usage patterns, predictive monitoring of production processes and life-cycle accounting of products, with particular attention to the recycling and recovery of discarded materials and products. Many European countries are moving away from recycling and landfill disposal and are gradually increasing the amount of waste recycled by upgrading technology and updating the regulatory framework.

The main hypothesis of the innovative project technological innovation in the field of 3D printing geobeton (in the creation of innovative buildings, artificial structures, noise protection and retaining walls) for ultra-noise-free movement, ensuring compliance with the level of acoustic impact on the environment, including the definition and use of the most effective noise protection technologies to the highest eco requirements and regulatory standards.

Fig. 1 shows 3D printing data on the cost of $1m^2$ from the world practice of additive technologies by realized objects:

1. House in Riverhead, USA, 2020
2. Chicon House, USA, 2018
3. House in Stupino, Russia, 2017
4. Ecohut in Gaia, USA, 2018
5. Office Building, Dubai, 2014
6. Administration Building, Dubai, 2019
7. Villa Winsun, China, 2015

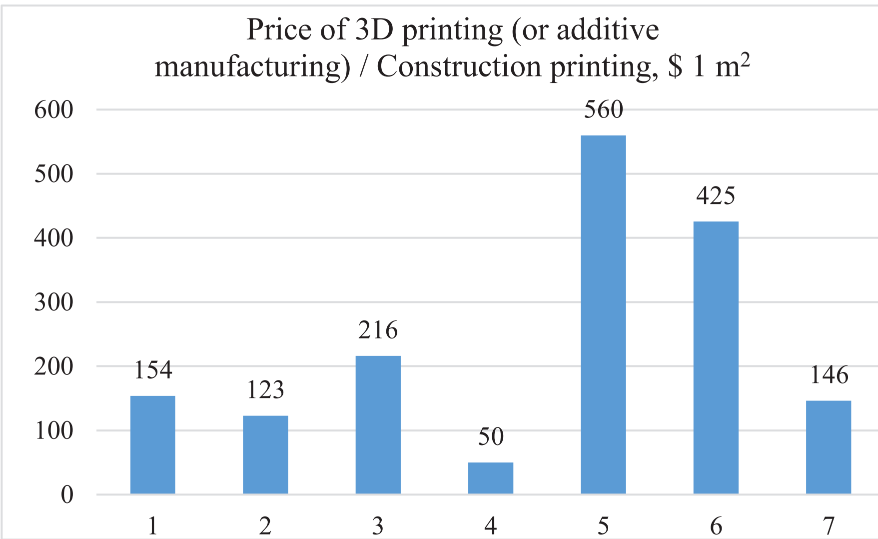

Fig. 1. Data from the global practice of additive technologies on the cost of building construction, $ $1m^2$.

To meet the growing global demands, construction needs a qualitative change and a digital transition to energy-efficient "green technology". The use of renewable energy sources, decentralization of generation, widespread implementation of "smart cities," and the use of innovative technologies and materials will lead to a radical reduction in the cost and timing of construction.

Nowadays building materials made with the use of environmentally friendly natural components are becoming more and more popular. One such building material is geopolymer concrete, which is becoming increasingly common around the world and in Russia thanks to the enormous advantages of the concept of green building. The material is not prone to corrosion, cracking and does not succumb to the destructive effects of the environment. The main advantages of geopolymer concrete: high strength material, low permeability like granite, resistant to high temperatures - non-combustible material, the high curing rate is many times faster than conventional, cost-effective production of ash, high resistance to low temperatures, freezing and thawing. "Green concrete", refers to a young class of cementitious materials, its composition includes ash dust - one of the most common industrial byproducts. It acts as a substitute for Portland cement, which is the most widely produced man-made material on earth.

The use of geocomposite concrete in construction is widely used in Australia, Ireland, USA and other countries. For example, for the first time in 2014 in Brisbane (Australia) an airport was built from concrete based on geopolymer binders, tubes for the subway and elements of the bearing structures of buildings are produced. In the U.S., back in the 1980s, special high-strength geopolymer concretes were used to repair runways and road surfaces. In 2016, in St. Petersburg a new space for public events "New Holland" was opened, where architectural geocrete (géoslab panels) was also used. Geoconcrete is very popular among designers, as it is used for facades, window sills, countertops and other various elements. Dubai Future Accelerators plans that by 2030 at least 25% of every new building will be built with geoconcrete.

In the last few years in Russia there has been a sharp increase in interest in energy-efficient and ecological construction. In Europe there is a special system of certification in the field of design of energy efficient and ecological construction (LEED certification or "carbon credits"). The technical and economic indicators of projects emphasize the importance of waste reduction and that structures using additive manufacturing polymers and concrete, and especially geopolymer cements and concretes based on them (geopolymer concretes, Russian engineers suggested using the term geobeton) are cost-effective solution in comparison with traditional construction.

Thus, geoconcrete not only improves the overall environmental situation, reducing carbon dioxide emissions into the atmosphere by up to 90% and recycling by-products of industrial plants, but also allows for their application in 3D printing in the field of buildings and transport construction, such as the mobile construction printer from Apis Cor (3D géobéton from GEOBETON and RENKA RUS).

STAIRRS project example: noise screens, especially high ones, have a low cost-effectiveness. The combination of low noise screens with a diffractor for sound diffraction and the replacement of cast iron brake pads with composite ones increases the overall profitability and yields a savings of 25% (€700 m). Most noise barriers near railway lines in Europe are 1 to 4 meters high, high barriers (up to 10 meters) are erected in exceptional situations. The use of noise screens printed on a 3D printer will provide a higher degree of protection, as well as higher cost-effectiveness than alternative screens.

Particular importance of the topic of this study is due to the need to solve a new problem that solves the problem of analyzing the evaluation and justification of the effectiveness of investment of infrastructure transportation projects 3D printing. One or another task to justify the effectiveness of additive technologies in building construction is presented in the works of many authors, such as the Massachusetts Institute of Technology, Lappeenranta University of Technology, LTU, LUT University and developments of leading companies Sika and Peri. However, these studies do not consider the possibilities of innovative solutions in terms of expanding the practice and application in the field of transport infrastructure facilities. In this regard, there is a need to solve the new problem of assessing the feasibility of additive technologies for transport infrastructure facilities as part of measures to neutralize the negative noise impact on the basis of generally accepted methods for assessing the effectiveness of investment and innovation.

The feasibility of solving the problem of the application of additive technologies to ensure noise safety of transport infrastructure facilities determines the relevance of the topic of the research.

The object of the research: objects of transport infrastructure of railroads, the noise encapsulation of which by means of 3D-printing provides a quick and cost-effective solution to ensure noise safety.

The purpose of the study is to justify the cost-effectiveness of new 3D-printing technologies and structures for noise safety of high-speed railways.

Objectives:

- Justify the effectiveness of acquiring a 3D-printer to print noise shields in comparison with alternatives in the example of the construction of the high-speed railroad;

- Determine the payback period of the 3D-printer;
- To determine the basic recommendations for the choice of constructions, optimal for the execution of the active noise protection measures at the high-speed railroad and the noise protection of the artificial constructions (tunnels, bridges, etc.); To determine the basic recommendations for the choice of the most effective noise protection measures and the construction of the noise protection screens on the artificial constructions.).

Methodology of justification:

1. Development of a model to justify the effectiveness of 3D printing on the example of the GSR.
2. Calculation of indicators of effectiveness of the innovative project of noise shields made by 3D printing with geobeton for high-speed railways.

Considered objects of railway transport:

Construction of HSR-1 Moscow - St. Petersburg (HSR Moscow - Kazan). Operational length - 679 (790) km. Approximate length of noise screens - 260 (300) km, height 3 - 6 m.

Models for the new construction of the HSR:

1. Metal noise screens by type: three-layer structure of aluminum profile with filler or acrylic glass**.**
2. Composite noise protection screens by type: pultrusion hollow two-chamber closed profiles.
3. 3D-printed screens of the following type: walls made of eco-concrete (ge-concrete) with a textured surface and a sound wave diffuser.

The main characteristics and indicators included in the description of models of noise screens are shown in Fig. 2. In general, it is necessary to consider the model as a structural element of the transport structure, which does not carry a reinforcing function, but affects the structural features and strength characteristics of the artificial structure.

When selecting the optimal noise protection structure, the following indicators are assessed: the value of acoustic efficiency, taking into account all the passive measures used; the possibility and variability of the device and installation of a particular structure in the prevailing conditions; the optimality of the device, determined on the basis of analysis of technical and economic parameters.

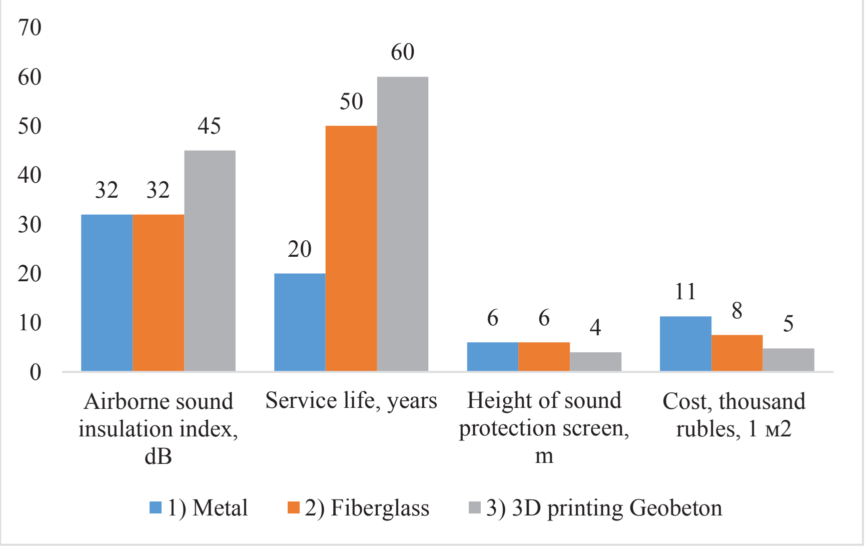

Fig. 2. Main characteristics of noise screen models.

3D-printed noise screens compared to typical metal and composite ones have a clear advantage in terms of air noise isolation, as evidenced by the acoustic index of the panels (air noise isolation index, dB). When choosing soundproofing panels for the screen is recommended to consider not only the acoustic performance, but also the properties responsible for the acoustic efficiency of the screen for the lifetime, the absence of the negative contribution of sound reverberation and environmental friendliness.

3D-printed screens have a number of advantages: architectural expressiveness and aesthetics, the possibility of digital construction using BIM-technologies of information modeling. Such screens provide the possibility of effective sound diffraction, as they have a special structural wave-shaped surface and superstructure of the top of the supporting wall, containing structural recesses, as well as individual resonators, made in recesses along the entire length of the structure, and this further makes it possible to lower the height of the screen.

Solution of problem 1:

1. Determine the cost, service life and warranty of the construction of the screen per m2 (request for proposals from companies that have been involved in major transportation infrastructure projects) for both technologies: ApAtek; KraftSpan.
2. A preliminary analysis of the world examples of 3D-printed buildings has shown that the use of additive technologies will be 30 - 40% cheaper than the purchase at the factory, delivery and installation of soundproof walls-screens. By the example of large objects in the installation of NS (noise screens) by Kraft on the highway Krasnodar - Crimean bridge, a preliminary analysis of the effectiveness of – 33 %:
3. The cost effectiveness of geopolymer noise protection walls is expected to be 2.4 times higher than purchasing from leading manufacturers Kraft and Apatek, etc. as an example of research 2021 (Lappeenranta University of Technology, LTU, LUT University).

- The conjuncture analysis is made on the example of 3 manufacturers' price lists:

$$\frac{(4200 + 7500 + 11287)}{3} = 7662 \text{ rub.}$$

- The cost of geopolymer 3D printed walls per 1 m^2 – 58 €, which converts at the exchange rate of the currency to 05.11.2021:

$$58 \text{ x } 82{,}81 = 4803 \text{ rub}$$

Consequently, the efficiency will be on the order of:

$$\frac{7662 - 4803}{7662} \text{ x } 100\% = 37\%$$

4. Consideration of additional socio-economic effects of noise absorption: reduction in demand depending on the level of noise on the property and the level of health costs depending on the level of noise. Feasibility study of effective wall construction (profile and textures), identification of noise reduction.

Solution of the 2nd problem:

1. Determine the cost of purchasing a 3D printer: $132 \text{ k € x } 82{,}6 = 10903 \text{ k rub}$
2. Determination of production volume per year, payback.

Phase 1: Construction of 260 km of noise protection walls on new railroad tracks, then - printing blocks for existing (reconstructed) tracks, then - support walls: 5 years, 250 hours per year (21 h x 12 m)

The printing speed will roughly be: 1 m2 = 36 h / 154 m2 = 0.234 hours (14 minutes). Maximum print volume per year: 1068 m^2.

Saving on third-party services:

$$1068\ \text{m}^2 \text{x}\ 4803\ \text{rub per}\ 1\text{m}^2 =\ 5129{,}604\ \text{k rub}$$

Payback on the purchase of a basic 3D printing project will occur in 10903 / 5129,604 = 2 years.

In the future, it is proposed to introduce a robot (analog of the startup company's 3D printer COBOD BOD 2 and PERI) into the base system of the printer, which analyzes the progress of work production and compares the obtained technical and economic indicators with the planned ones in the 3D model. Special programs for 3D printing allow you to create concepts and designs, as well as optimize models for release using existing production technologies.

The Institute for Advanced Architecture of Catalonia (IAAC), through the use of computer-aided design and an algorithm to find the best solution through topological optimization, already has experience in creating new structural forms in the field of man-made structures through additive technology, minimizing waste and maximizing structural characteristics through optimization of material distribution.

Solution of the 3d problem: Basic recommendations for the selection of structures optimal for the implementation of active noise protection measures on high-speed railways and the construction of noise screens on artificial structures (tunnels).

Aerodynamic shocks of air waves generated by trains rushing by at high speed affect the safety and acoustic comfort of passengers and urban residents. The main risks of the HSL for man-made structures are the transition section before the tunnel and the impact of lateral wind when driving on the embankment or bridge [1,2].

An increase in the speed of a passing train leads to an increase in pressure inside the tunnel and an increase in the shock wave at the entrance to the tunnel portal, as well as an increase in the noise level from passing trains. Structural and technological parameters of the tunnel design play an important role: the smaller the tunnel cross section, the larger and steeper the pressure wave at the entrance. To reduce the level of aerodynamic noise it is proposed to create by 3D-printing a transitional section between the open section of the railroad and the tunnel.

In the world practice of high-speed railways (Japan, Austria, China, Indonesia) the system of noise and aerodynamic impact encapsulation is used. To reduce the noise level and attenuate micro-pressure waves in the tunnel, the tunnel entrance is made in the form of a socket, inclined and vertical channels for air drainage are installed. The most effective measures are installation of a noise shield and encapsulation of the transition section in front of the railroad tunnel portal, performed in the form of two elements of arch structures, printed by 3D-printing and closed in the designed position.

Successful world projects on noise encapsulation, as analogues, can be implemented in the works of PGUPS students at the Faculty of "Transport Construction". At the end of 2021 there was a competitive work of the students (as a team: gr. BRR-704 Varfolomeeva E. S. and Komarova E.M. gr. T-110 Shestakov P.D.) and released a video clip on the subject of 3D-printing of noise protection on the principle of mounting blocks "Lego" and noise encapsulation in the tunnels on the high-speed rail.

A small part of the sketches and variants of design solutions of noise screens with the use of 3D-printed geo-concrete are shown in Fig. 3, including a clearly textured architectural wave-shaped surface, which is a noise wave dissipator. The author's original presentation is implemented in the architectural and spatial presentation and various color and texture combinations of external surfaces of the walls, as well as using the planting of climbing green plants, covering the "flowering" wall. The optimal design consists of a combination of low noise screens up to 4 m and elements of a special triangular-shaped superstructure for sound diffraction.

In practice, the most effective proved to be teaching students "green" competencies in a competitive team work with visual implementation of examples of 3D printing, which show the unlimited range and variability of designs, architectural styles, and publication of the album of noise protection structures solutions in social networks.

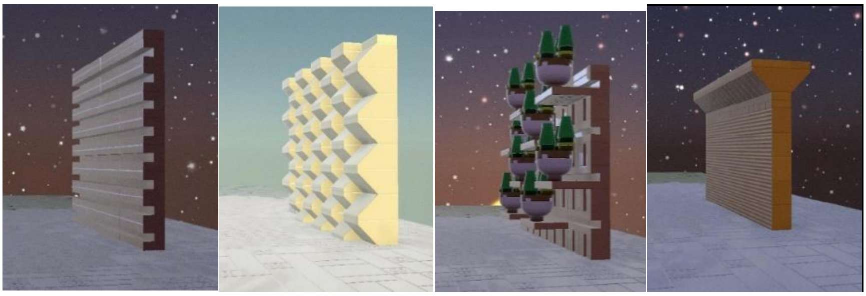

Fig. 3. Sketches of panel designs for 3D printing with geobeton developed by PGUPS students.

As an individual work, the initial stage to determine the level of patent purity, competitiveness, which is the basis for the introduction of an innovative solution to the construction market was carried out. The Espacenet patent database summarizes the experience on innovative solutions in the field of noise protection, but not related to 3D-printing of railways, there is only one patent relating to the field of roads (NS with V-shaped superstructure, patent CN 112976223 A). As a result of the patent search on 19.02.2022 for identification of analogues from the current level, no documents were found in the database of Espacenet Worldwide and USPTO Patent on the request: railway 3D-printing (walls / or / barriers) noise - 0 applications.

3 Results

3D printing is a fairly economical method when considering such aspects as money, construction time and manpower, and in the long run it can complement existing methods and green construction methods. The greatest benefit can be gained by using additive technology to produce out-of-the-box designs with unique geometric shapes and textures.

The cost of construction with the help of additive technologies is lower than the cost of traditional construction by about 30-40%, the cost of materials is reduced by 25-30%, which gives a quick payback of any project at an early date.

As a result of the research, the effectiveness of new 3D-printing technologies and structures for soundproofing of high-speed railways was proved. The study showed that the creation of noise protection screens with the use of 3D-printed geoconcrete allows to significantly reduce the cost, hang the efficiency of construction.

The analysis conducted in this work has shown:

1. The cost of construction of noise screens with the help of additive technologies is 37% lower than the cost of traditional construction, the cost of materials is reduced by 25%, which gives a payback period of 2 years for a 3D printer on the example of the high-speed rail project.
2. It is advisable to introduce additive technologies in the construction of railroads, whereby 3D printer models can be used both with the placement of models on the rails for new tracks, and printing individual elements on a stationary printer, mounted in the design position along the existing (reconstructed) tracks on the principle of Lego blocks.

Based on the results obtained by the author, these recommendations have been formulated:

3. Noise protection screens, especially tall ones, have a low cost-effectiveness. The optimal design consists of a combination of low noise screens up to 4 m and elements with a special top surface superstructure for sound diffraction.
4. Concrete panels (walls) of noise shields are made with the use of 3D-printed geo-concrete and textured architectural wave-shaped surface, which is the noise wave dissipator.
5. To reduce the noise level and attenuate micro-pressure waves, noise encapsulation in the form of a 25 m long bell, created using 3D printing technology, is proposed for the construction of tunnel portals.For the optimal choice of volume-planning and structural-technological solutions of tunnel construction on high-speed railroads, the method of aerodynamics calculation with consideration of wind meteorology, terrain relief and temperature factors should be applied.
6. It is also recommended to consider heteromodular materials for 3D printing based on cryogels for work in the Arctic climate for further development.

4 Analysis of results

To meet the growing global demands, construction needs a qualitative change and a digital shift to energy-efficient “green technology”. The use of renewable energy sources, the widespread introduction of “smart cities”, the use of innovative technologies and the recycling of building materials will lead to a radical reduction in the cost and timing of construction.

In the near future 3D printers will learn to print products of more complex shapes and designs - and additive technologies in some industries may well completely displace traditional production, but the greatest prospects are seen in a reasonable combination of robotic complexes with traditional construction technologies.

The main advantages of the introduction of additive 3D-printing technologies are: flexibility in design; reduction of production cycle time; less influence of human factor in ensuring accident-free construction; reduction of construction time; low level of waste (reduction of possibility of unmarketable product); reduction of number of components (assembly); reduction of life cycle cost.

The feasibility of using 3D printing and structures for high-speed railways in urban development satisfies not only the regulatory conditions, but is also based on ensuring the economic efficiency of such innovative projects, including the main trends: "green technologies", information modeling technologies (BIM), digital construction, printing with clay, geoconcrete, self-repairing concrete [3-13].

Future trends and technologies in training and professional development for digital construction are aimed at creating specialized training centers, transferring knowledge and training of engineers in the field of green technologies, 3D printing with concrete; increasing the scope and areas of implementation of additive technologies with universal interdisciplinary software applications within BIM, development of new environmentally friendly materials with higher technical and operational properties throughout the life cycle [14-20].

5 Conclusion

In Russia the competence of eco-building is just beginning to be mastered, while in the West it is already actively applied. This field of knowledge involves innovation, optimization, analysis of environmental databases and can be considered as a promising new scientific engineering direction.

The level of application of 3D printing with concrete in the field of transport construction and man-made structures in the foreseeable future will only increase due to architectural and artistic expression, geometry of freedom and optimization of material properties, given the versatile design of complex structures and elements of engineering structures, including noise barriers.

The author hopes that the implementation of these studies will increase interest in the introduction of innovative eco-technologies, attracting investment in "environmentally friendly, "green" and sustainable" transportation projects, wide integration of 3D-printing in construction, which will allow to achieve high predictability of the quality construction and commissioning terms of new and reconstructed environmentally artificial structures in the future.

Application of these researches in practice of transport construction will give an opportunity to increase quality, speed of construction and efficiency of noise protection screens on railroads; to optimize expenses for realization of noise encapsulation by selection of optimal noise protection structures.

Reference

1. A. Ledyaev, V. Kavkazskiy, Y. Vatulim, V. Svitin, *Mathematical modeling of aerodynamic processes in railway tunnels on high-speed railways* DOI: https://www.researchgate.net/publication/340053187_Mathematical_modeling_of_aerodynamic_processes_in_railway_tunnels_on_high-speed_railways
2. E. Shestakova, N. Malshchukova, S. Chizhov, E3S Web of Conferences **157**, 06019 (2020) DOI: 10.1051/e3sconf/202015706019
3. E. Shestakova, A. Novikov, A. Antonyuk, P. Kurchanov, Sakhalin Island Lecture Notes in Civil Engineering **49**, 249-263 (2020) DOI: 10.1007/978-981-15-0450-1_26
4. A.P. Lediaev, A.N. Konkov, A.L. Novikov, D.A. Soloviev, Procedia Engineering **189**, 492-499 (2017) DOI: 10.1016/j.proeng.2017.05.079
5. A. Benin, O. Nesterova, A. Uzdin, et al., E3S Web of Conferences **157**, 06012 (2020) DOI: 10.1051/e3sconf/202015706012
6. A. Ledyaev, V. Kavkazskiy, D. Grafov, D. Soloviev, A. Benin, E3S Web of Conferences **157**, 02008 (2020) DOI: 10.1051/e3sconf/202015702008
7. S. Chizhov, A. Pismak, A. Antonyuk, E3S Web of Conferences **157**, 06014 (2020) DOI: 10.1051/e3sconf/202015706014
8. L. Selyutina, E. Pesotskaya, E. Rybnov, S. Sitdikov, E3S Web of Conferences **217**, 11010 (2020) DOI: 10.1051/e3sconf/202021711010
9. E.B. Shestakova, A.V. Ermilova, Occupational safety in industry **(8)**, 86-93 (2020) DOI: 10.24000/0409-2961-2020-8-86-93
10. V. Ulitsky, S. Bogov, *Restoration engineering of historic structures: Case study of building 12 on new Holland Island in Saint-Petersburg Geotechnics Fundamentals and Applications in Construction* (New Materials, Structures, 2019)
11. *Technologies and Calculations - Proceedings of the International Conference on Geotechnics Fundamentals and Applications in Construction* (New Materials, Structures, Technologies and Calculations, GFAC, 2019) DOI: 10.1201/9780429058882-75

12. A. Belyi, D. Shestovitskii, E. Karapetov, D. Sedykh, V. Linkov, EWDTS, 8884435 (2019) DOI: 10.1109/EWDTS.2019.8884435
13. A. Belyi, G. Osadchy, D. Efanov, D. Shestovitskiy, EWDTS, 8524680 (2018) DOI: 10.1109/EWDTS.2018.8524680
14. V.N. Smirnov, E.B. Shestakova, S.V. Chizhov, A.A. Antonyuk, L.A. Lediaev, et al., Magazine of Civil Engineering **76(8)**, 115-129 (2017) DOI: 10.18720/MCE.76.11
15. K.V. Vorob'eva, A.M. Uzdin, M.V. Freze, et al., Soil Mechanics and Foundation Engineering **53(5)**, 336-343 (2016) DOI: 10.1007/s11204-016-9408-2
16. L. Diachenko, A. Benin, E3S Web of Conferences **135**, 03065 (2019) DOI: 10.1051/e3sconf/201913503065
17. N.V. Kanashin, A.A. Nikitchin, E.S. Svintsov, Procedia Engineering **189**, 393-397 (2017) DOI: 10.1016/j.proeng.2017.05.062
18. A. Benin, A. Konkov, V. Kavkazskiy, et al., Procedia Engineering **165**, 1483-1489 (2016) DOI: 10.1016/j.proeng.2016.11.883
19. R.V. Vvedenskij, S.G. Gendler, T.S. Titova, Magazine of Civil Engineering **79(3)**, 140-149 (2018) DOI: 10.18720/MCE.79.15
20. D. Serebryakov, A. Konon, E. Zaitsev, Procedia Engineering **189**, 893-897 (2017) DOI: 10.1016/j.proeng.2017.05.139
21. E.V. Kazaku, E.V. Zvereva, J.V. Tsarionova, IOP Conference Series: Materials Science and Engineering **913(5)**, 052006 (2020) DOI: 10.1088/1757-899X/913/5/052006
22. N.V. Chepachenko, A.A. Leontiev, G.A. Uraev, N.A. Polovnikova, IOP Conference Series: Materials Science and Engineering **913(4)**, 042075 (2020) DOI: 10.1088/1757-899X/913/4/042075