

## Development of High-Performance Sand-Polymer Composites from Regenerated Thermoplastics for Structural Applications under Dynamic Loads

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**Abstract.** This study is devoted to the development and scientific and practical substantiation of a technology for producing highly effective sand-polymer composites (SPC) for structural purposes from recycled thermoplastics. The relevance of the work is determined by the need for extensive recycling of polymer waste and a reduction in the carbon footprint in the construction industry by replacing traditional Portland cement. A polymer matrix of a mixture of recycled low-density polyethylene and polypropylene (v-LDPE/v-PP in a ratio of 70:30) was used as a binder. The dispersed filler is quartz sand ( $\text{SiO}_2 \geq 98.5\%$ ), the fractional composition of which is optimized according to the Andreasen-Fuller model to reduce the voidage of the framework from 38% to 22%. To eliminate interfacial incompatibility and improve adhesion, the compatibilizer HDPE-g-MA (3 wt.%) and the elastomer modifier SEBS were used. The samples were manufactured using extrusion mixing followed by hot pressing under a pressure of 15–20 MPa. The optimal component ratio was found to be 20% by weight of polymer binder and 80% by weight of sand filler. The introduction of HDPE-g-MA promoted the formation of Si-O-CO chemical bonds at the interface, which changed the nature of material failure from adhesive to cohesive and ensured an increase in flexural strength to 39.1 MPa and compressive strength to 96.2 MPa. The developed PPC is recommended for use in vibration-loaded elements of transport and construction infrastructure (railway sleepers, airfield and road slabs, foundations). The use of recycled raw materials reduces the cost of products by 25–30% and decreases CO emissions by 1.8–2.4 tons per ton of polymer.

**Key words:** sand-polymer composite; adhesive failure; cohesive rupture; PND-g-MA modifier; scanning electron microscopy (SEM)

### Introduction

The growing volume of polymer waste represents one of the key environmental and technological challenges of the 21st century [1]. Hundreds of millions of tons of synthetic polymers are generated annually worldwide, a significant portion of which are widely used thermoplastics – high- and low-density polyethylene (LDPE/HDPE), polypropylene (PP), and polyethylene terephthalate (PET) [2]. Low recycling rates and long periods of environmental degradation require the development of new methods for their advanced recycling [3].

At the same time, the construction industry faces a shortage of high-quality raw materials and stringent requirements to reduce the carbon footprint of traditional binders, particularly Portland cement, the production of which is responsible for nearly 8% of global CO<sub>2</sub> emissions [4].

A promising solution to both problems is the development of sand-polymer composites (SPCs) – materials in which a matrix of recycled thermoplastic melts serves as a binder and sand fractions of varying particle sizes serve as a dispersed filler [5, 6]. Traditional sand-polymer products (paving slabs, manhole elements, curbs) have long proven themselves to be corrosion- and moisture-resistant materials. However, their use is still limited to non-structural or lightly loaded components [7].

When attempting to use standard polymer-sand composites in structures subject to severe operational conditions - cyclic bending, impact loads, vibration, and dynamic abrasion (e.g., road bases, railroad ties, vibration-isolating foundation elements), serious drawbacks emerge [8-10]:

1. The lack of chemical interaction between the non-polar polyolefin matrix and the polar hydrophilic surface of silicon dioxide (sand) leads to rapid delamination of the material under load;
2. Unmodified regenerated polymers accumulate microcracks under repeated alternating stress;
3. High creep of the thermoplastic matrix at temperatures above 40°C reduces the load-bearing capacity of structures.

This study aims to scientifically substantiate, develop the composition, and manufacture technology for high-performance sand-polymer composites based on recycled thermoplastics that exhibit increased crack resistance, damping capacity, and strength under dynamic loads.

### 1. Research methods

#### 1.1 Components of sand-polymer composites

The following components were used to synthesize sand-polymer composites:

- 1) Polymer matrix:

- recycled low-density polyethylene (r-HDPE), which is made from crushed waste containers and pipes. MFI = 0.8 g/10 min (190 °C, 2.16 kg), density = 0.952 g/cm<sup>3</sup>;
- recycled polypropylene (r-PP), which is made from crushed bumper and household plastic. MFI = 3.5 g/10 min (230 °C, 2.16 kg), density = 0.905 g/cm<sup>3</sup>.

The polymer matrix was formed from a r-HDPE/r-PP blend in a 70:30 (wt.%) ratio, which ensures an optimal balance between impact strength (HDPE) and stiffness (PP).

Modifiers and compatibilizers:

- HDPE-g-MA (polyethylene grafted with maleic anhydride) with a grafting degree of 0.9 wt.% was used as a finishing agent to improve adhesion to sand.
- slope styrene-ethylene-butylene-styrene rubber (SEBS), impregnated into the matrix to increase impact strength at sub-zero temperatures [11].

3) Mineral filler: quartz sand with a SiO<sub>2</sub> content of ≥ 98.5%. Three sand fractions were formed: coarse (1.25–2.5 mm), medium (0.315–0.63 mm), and pulverized quartz flour/filler flour (d<sub>50</sub> = 15 μm).

To minimize the volume of polymer melt filling the voids between sand grains, the granulometry was optimized using the Andreasen–Fuller model (the equation for optimal particle packing) [12]:

$$P(d) = \left(\frac{d}{d_{max}}\right)^q \cdot 100 \quad (1)$$

where  $P(d)$  - total percentage of particles smaller than  $d$ ;

$d_{max}$  - maximum particle diameter (2.5 mm);

$q$  - packing index (taken equal to 0.35 to ensure maximum packing density of dispersed systems).

### 1.2 Technological process for obtaining SPC

The experimentally established ratio of fractions was 50:30:20 by weight (coarse:medium:dust), which made it possible to reduce the void content of the sand framework from 38% to 22%. The technological process for obtaining the SPC is shown in Figure 1.

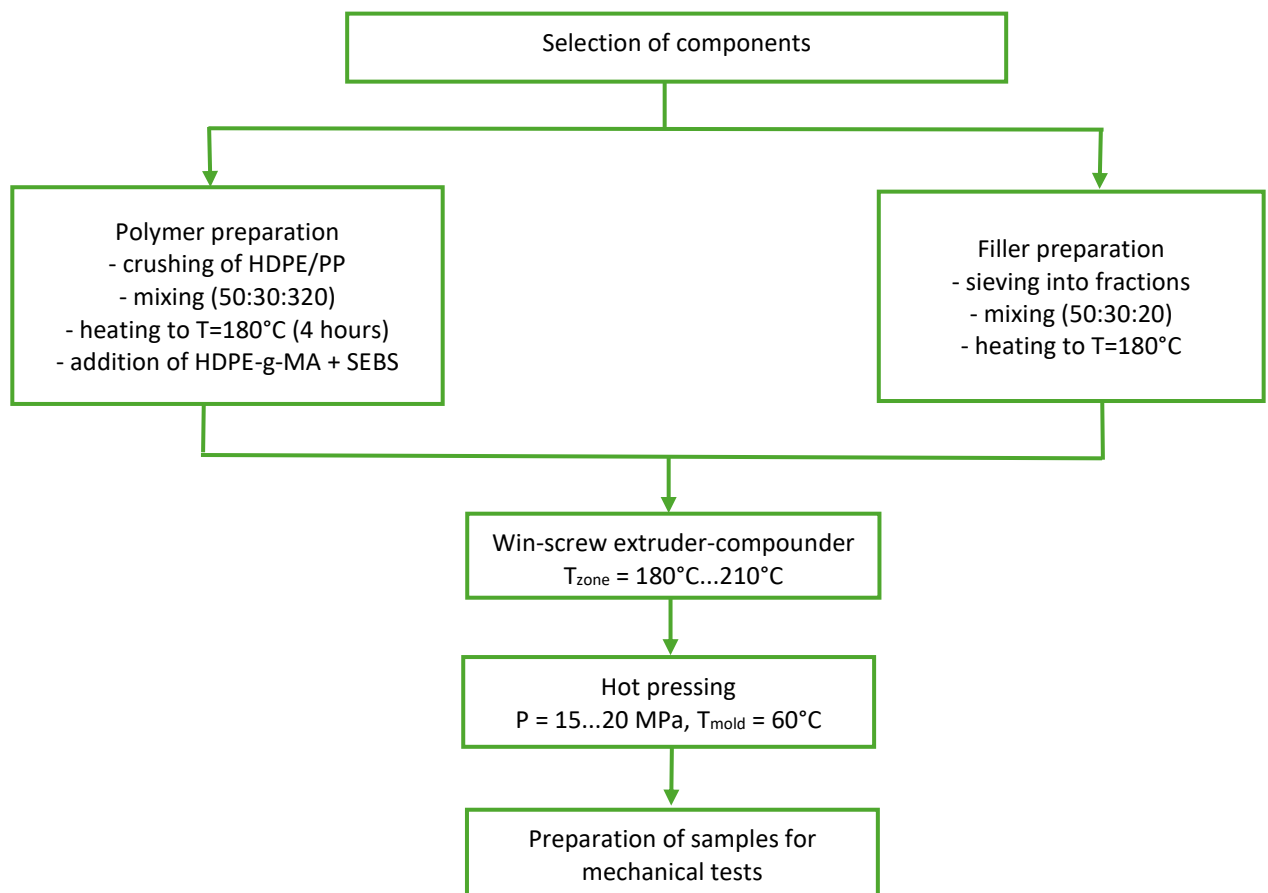


Fig. 1. - Technological process for obtaining SPC

### 1.3 Preparation of specimens for mechanical tests

Polymer pellets were dried in a vacuum oven at 80°C for 4 hours. The sand was calcined at 150°C to a constant weight. The components were dosed and fed into a co-directional twin-screw extruder ( $L/D = 40$ ) with a controlled temperature profile in zones from 180°C to 210°C.

The resulting homogenized melt was fed into a heated mold. Compression was performed in a hydraulic press at a pressure of 15–20 MPa, followed by cooling under pressure at a rate of 10°C/min to a temperature of 60°C to prevent shrinkage cavities.

Four series of samples were produced with varying polymer binder content (from 15% to 30% by weight) and modifying system type.

### 1.4 Test methods

Compressive and flexural strength were determined on a Zwick/Roell Z100 universal testing machine in accordance with GOST 4651-2014 and GOST 4648-2014 at a crosshead speed of 2 mm/min.

Charpy impact strength (unnotched and V-notched) was evaluated on an Instron 9050 pendulum impact tester at temperatures of -40°C, +23°C, and +60°C.

Cyclic bending fatigue testing was performed on a Servopulser servohydraulic testing machine at a frequency of 10 Hz with a cycle asymmetry of  $R = 0.1$ . Temperature dependences of the elastic modulus ( $E'$ ) and loss tangent ( $\tan\delta$ ) were measured on a DMA 242 E Artemis instrument in three-point bending mode at a frequency of 1 Hz over a temperature range of -80°C to +120°C with a heating rate of 2°C/min.

Surface fracture analysis of the specimens was performed using scanning electron microscopy (SEM) on a TESCAN VEGA3 microscope with microanalysis at an accelerating voltage of 15 kV.

## 2. Results

### 2.1 Optimization of the Polymer:Sand ratio and strength indicators

A series of initial tests showed that mechanical properties depend significantly on the degree of filling of the polymer matrix. Average values of the strength characteristics of polyvinylchloride (SPC) are presented below (Table 1) depending on the mass fraction of the polymer binder (a mixture of v-HDPE/v-PP + 3% HDPE-g-MA).

**Table 1.** Strength characteristics of polyvinylchloride depending on the mass fraction of the polymer binder

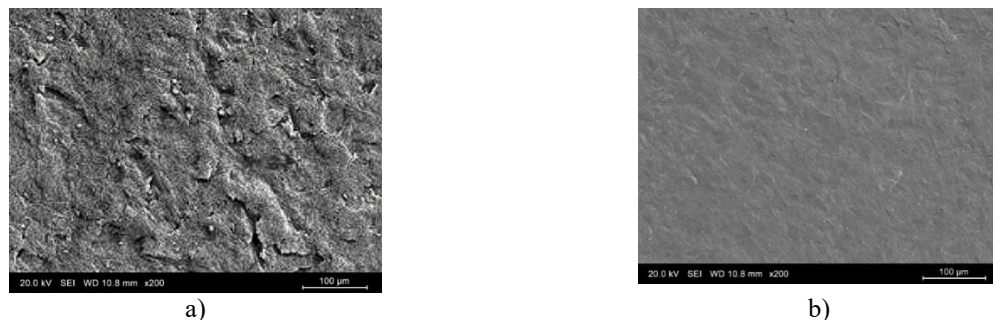
| Polymer content (wt.%) | Density ( $\rho$ , g/cm <sup>3</sup> ) | Compressive strength ( $\sigma_c$ , MPa) | Bending strength ( $\sigma_f$ , MPa) | Flexural modulus of elasticity ( $E_f$ , GPa) |
|------------------------|----------------------------------------|------------------------------------------|--------------------------------------|-----------------------------------------------|
| 12                     | 1.82                                   | 42.5                                     | 14.2                                 | 5.8                                           |
| 16                     | 1.98                                   | 78.4                                     | 28.6                                 | 7.2                                           |
| 20                     | 2.05                                   | 96.2                                     | 39.1                                 | 8.1                                           |
| 25                     | 1.96                                   | 82.1                                     | 35.4                                 | 6.4                                           |
| 30                     | 1.85                                   | 67.3                                     | 29.0                                 | 4.9                                           |

At a polymer content of 12%, a binder deficiency is observed: high intergranular porosity remains in the structure, resulting in low strength values.

Maximum strength properties are achieved at 20% polymer by weight (corresponding to 80% optimized sand filler by weight). Increasing the polymer binder content above 25% leads to a decrease in stiffness and compressive strength due to an increase in the volume fraction of the relatively soft polymer phase.

### 2.2 Effect of interfacial modification on adhesion and failure

The use of the PND-g-MA finishing additive had a decisive impact on the performance of the composites. SEM micrographs of fracture fractures demonstrated a dramatic change in the nature of interaction at the sand-polymer interface.



**Fig. 2.** - Structure of sand-polymer composites: a) without modifier, b) with the addition of HDPE-g-MA

In unmodified systems, cleavage occurs strictly along the interface: the surfaces of the sand grains remain clean, with traces of complete detachment from the matrix (adhesive failure).

In the modified composite (3% HDPE-g-MA), micrographs reveal the presence of polymer films and plastically deformed filaments remaining on the surface of the sand grains (cohesive failure along the matrix). The anhydride groups of HDPE-g-MA chemically react with silanol groups (Si-OH) on the quartz surface, forming strong Si-O-C(O) bonds.

### 2.3 Dynamic properties and resistance to cyclic fatigue

The results of cyclic fatigue tests (bending at a frequency of 10 Hz) showed the advantage of the optimized PPC compared to traditional B30 class concrete and unmodified sand-polymer analogues (Figure 3).

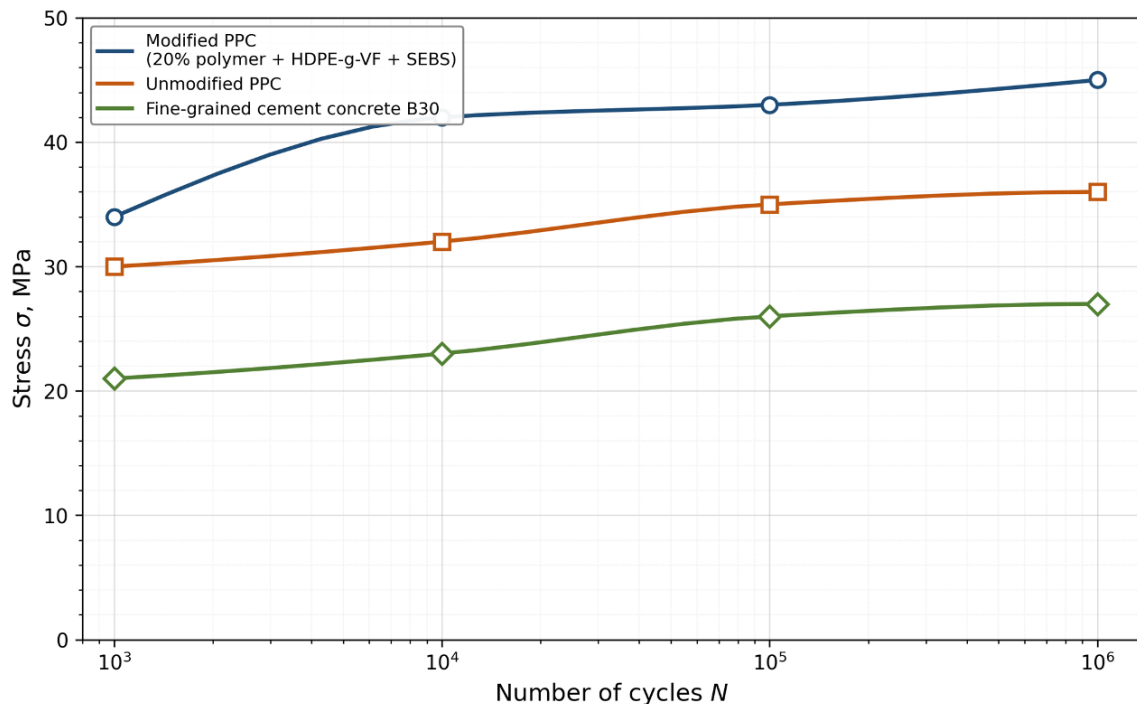


Fig. 3. - Cyclic fatigue of sand-polymer composites

The fatigue strength ( $N = 10^6$  cycles) for the modified PPC was 18.5 MPa, which is almost 47% of its static flexural strength. For the unmodified composite, this value did not exceed 8.2 MPa due to the intensive accumulation of microcracks at the phase boundary.

Cement concrete exhibits rapid strength loss under high-amplitude dynamic loads due to the brittleness of the mineral matrix, whereas the sand-polymer composite dissipates energy more effectively due to the viscoelasticity of the polymer.

### 2.4 Dynamic mechanical analysis (DMA)

DMA demonstrated the temperature stability range of the developed material.

At  $-40^\circ\text{C}$ , the modulus is 11.2 GPa, decreasing to 7.5 GPa at  $+23^\circ\text{C}$  and maintaining a reasonable level of 3.8 GPa at  $+60^\circ\text{C}$ . Peak damping is observed in the glass transition region of the polymer matrix (approximately  $-15^\circ\text{C}$  for the elastomeric modifier and  $+50^\circ\text{C}$  for the amorphous phase of PP). The  $\tan\delta$  value for the modified PPX over the operating temperature range ( $-20^\circ\text{C}$  to  $+40^\circ\text{C}$ ) is between 0.045 and 0.078, which is 3–5 times higher than that of cement and asphalt concrete. This confirms the material's high vibration absorption.

## 3. Discussion

The developed composite's high resistance to dynamic and impact loads is due to the synergistic effect of two factors:

1. Multi-level energy dissipation structure:
  - at the microlevel, plastic deformation of rubber inclusions (SEBS) initiates localized microsilvering (crazing) of the polymer matrix, preventing crack propagation;
  - at the mesolevel, rigid quartz grains force the crack front to deviate from its original direction, increasing the total fracture surface area and the fracture work;

## 2. Formation of an interfacial trans-crystalline layer:

Sand surface finishing promotes nucleation of the polymer phase on the filler surface during crystallization. This results in the formation of a highly ordered layer with an increased elastic modulus, which transfers mechanical stress from the flexible matrix to the durable filler without stress concentration. To assess the feasibility of using the developed sand-polymer composite in load-bearing and vibration-loaded structures, a comparison of its key characteristics with traditional materials is given (Table 2).

**Table 2.** Physical characteristics of vibration-loaded structures and PPC and traditional materials

| Indicator                           | Developed by SPC | Cement concrete B30 | Asphalt concrete (dense) |
|-------------------------------------|------------------|---------------------|--------------------------|
| Density, kg/m <sup>3</sup>          | 2050             | 2350                | 2300                     |
| Compressive strength, MPa           | 96.2             | 40.0                | 4.5 (at 20 °C)           |
| Bending strength, MPa               | 39.1             | 4.5                 | 2.1                      |
| Impact strength, kJ/m <sup>2</sup>  | 18.4             | 1.2                 | -                        |
| Water absorption in 28 days, %      | 0.004            | 4.5                 | 1.5                      |
| Damping coefficient (tan $\delta$ ) | 0.065            | 0.012               | 0.035                    |
| Frost resistance, cycles            | > F500           | F200                | -                        |

A comparative analysis shows that this development surpasses cement concrete in flexural strength by more than 8 times, and in impact toughness by more than 15 times. Nearly zero water absorption (0.04%) ensures exceptional frost resistance (more than 500 freeze-thaw cycles without loss of mass or strength), as the composite structure lacks the capillary porosity typical of hydrated cement systems.

The use of recycled thermoplastics (HDPE and PP) significantly reduces the cost of finished products. Replacing one ton of traditional polymer raw materials with recycled ones reduces greenhouse gas emissions in CO<sub>2</sub> equivalent by 1.8–2.4 tons. Considering that the composite is 80% made up of readily available mineral filler, the final cost of PPC products is 25–30% lower than that of their primary polymer counterparts and is comparable to high-strength specialized concretes with significantly higher durability in aggressive and dynamic environments.

## Conclusions

1. An optimal composition for a structural-grade sand-polymer composite based on a blend of recycled polyolefins (v-HDPE/v-PP 70:30) and particle-balanced quartz sand has been developed. A polymer binder content of 20 wt.% was found to be optimal in terms of physical and mechanical properties.

2. The addition of 3 wt.% of the compatibilizer HDPE-g-MA ensures the formation of stable chemical bonds at the polymer-sand interface. This changes the composite's failure mode from adhesive to cohesive and increases flexural strength by 145% (to 39.1 MPa).

3. Due to matrix modification with an elastomer (SEBS) and high phase adhesion, the cyclic bending fatigue limit based on 10<sup>6</sup> cycles reached 18.5 MPa. The Charpy impact strength was 18.4 kJ/m<sup>2</sup>, allowing the material to be used under intense shock and vibration loads.

4. According to the DMA, the damping coefficient (tan $\delta$ ) of the developed polymer-sand composite exceeds that of traditional cement concrete by more than five times, making the material effective in reducing vibroacoustic effects.

5. These results open up opportunities for the widespread use of sand-polymer composites made from plastic waste in the production of transport infrastructure components (railway sleepers, interrail decking, airfield and road pavement slabs, and drainage channels) operating under harsh climatic and dynamic conditions.

## References

- [1] Vanaraj R., Suresh Kumar S.M., Kim S.C., Santhamoorthy M. A Review on Sustainable Upcycling of Plastic Waste Through Depolymerization into High-Value Monomer //Processes 2025, 13, 2431. <https://doi.org/10.3390/pr13082431>
- [2] Dey H, Sheikh Md.R.K, Shuvo A.N. Recent polymer modification strategies for reducing plastic waste and enhancing recyclability //Polymers and Polymer Composites, 2026, 34. doi:10.1177/09673911261441896
- [3] Kim H. Advances in Plastic Waste Recycling: Technologies, Environmental Impact, Research Trends, and Policy Perspectives 2025 //International Journal of Environmental Sustainability and Protection, 5(3), 9-19 DOI:10.35745/ijesp2025v05.03.0002
- [4] Barbhuiya S., Kanavaris F., Das B.B., Idrees M. Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development //Journal of Building Engineering, Volume 86, 2024, 108861, <https://doi.org/10.1016/j.jobe.2024.108861>.
- [5] Yurchenko V., Haiduk V., Skaskevich A., Zharkevich O., Zhetessova G., Reshetnikova O., Smagulov A., Mussayev M. Study of Deformation and Strength Characteristics of Highly Filled Sand–Polymer Composites Based on Regenerated Thermoplastics //J. Compos. Sci. 2025, 9, 206. <https://doi.org/10.3390/jcs9050206>
- [6] Avdeychik S.V., Antonov A.S., Struk V.A., Prokopchuk N.R., Zhang R. Nanostate Factor in Materials Science of Functional Nanocomposite Materials //Material and Mechanical Engineering Technology, №3, 2024, P.69-75
- [7] Barros J.A.O., Soltanzadeh F., de Sousa C., Vera M.O. Development of Sustainable and Innovative Manhole Covers in Fibre-Reinforced Concrete and GFRP Grating // Appl. Sci. 2024, 14, 6903. <https://doi.org/10.3390/>

app14166903

- [8] Liu J., Bai Y., Li D., Wang Q., Qian W., Wang Y., Kanungo D.P., Wei J. An Experimental Study on the Shear Behaviors of Polymer-Sand Composite Materials after Immersion //Polymers 2018, 10, 924; doi:10.3390/polym10080924
- [9] Zhetessova G., Nikonova T., Gierz Ł., Berg A., Yurchenko V., Zharkevich O., Alexey K. A Comparative Analysis of the Dynamic Strength Properties of the Long Guides of Intelligent Machines for a New Method of the Thermal Spraying of Polymer Concrete //Appl. Sci. 2022, 12, 10376. [https://doi.org/ 10.3390/app122010376](https://doi.org/10.3390/app122010376)
- [10] Milewski H., Leeuw L., Dietz M.S., Diambra A. Shearing resistance of rough polymer-sand interfaces // Conference: ISFOG 2020: 4th International Symposium on Frontiers in Offshore Geotechnics, P.1716-1725
- [11] Mashkin N.A., Esirkepova A.B., Sherov K., Rakhimova G.M., Zharkevich O.M., Mussayev M.M. Activation of Cement Binder in Heavy Concrete Technology //Material and mechanical engineering technology, №3, 2020, 8-17
- [12] Kravanja G., Mumtaz A.R., Kravanja S. A Comprehensive Review of the Advances, Manufacturing, Properties, Innovations, Environmental Impact and Applications of Ultra-HighPerformance Concrete (UHPC) // Buildings 2024, 14, 382
- [13] Zhang T., He J., Xu N., Yin W., Liu D., Liu C., Lang M. Glass fiber-reinforced modified PDPCD composites with improving mode I and mode II interlaminar fracture toughness and impact resistance: Effects of matrix properties //Composites Part B: Engineering 2025, Volume 296, 112225

**Funding.** The Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan IRN AP 27510559 “Modernization of machine tool equipment of mechanical engineering enterprises using composite materials based on additive technologies”.

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