Ensuring environmental safety when using polymer waste in technologies for obtaining building materials

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Abstract. The production of building materials uses large amounts of primary natural resources. Mineral and organic components of the natural environment are used as raw materials, which leads to degradation and disruption of the habitat of living organisms. One of the possible methods to reduce the consumption of natural resources is the use of industrial and consumer wastes as raw materials, which include polymer waste. The high resource potential of polymer waste as a fuel is shown. Waste can replace coal coke, which is used in ferrous metallurgy technologies. The analysis of several technologies for the use of polymer waste as an inert filler and as a bituminous binder in the production of asphalt concrete and building mixtures has been carried out. The classification of various groups of polymer waste by melting temperature and chemical composition is presented. The analysis of technological processes for the use of polymer waste made it possible to conclude that considerable attention is paid to the extraction of economic benefits without environmental assessment of the safety of the technologies used. An environmental assessment of polymer waste disposal technologies has been proposed, which will allow at the stage of technology development to assess the environmental risks arising from the production and operation of the resulting product. It is proposed to select the temperature range in the technological processes for obtaining secondary products as indicators of the formation of environmental risks when using polymer waste.

1. Introduction
The production of building materials requires large amounts of primary natural resources. Mineral and organic components of the natural environment are used as raw materials, which leads to degradation and disruption of the habitat of living organisms. One of the possible methods to reduce the consumption of natural resources is the use of industrial and consumer wastes as raw materials, which include polymer waste. Currently, the volume of polymer waste generation in the world is about 300 million tons per year, most of which is polyethylene (about 19% - LDPE, 13% - HDPE), about 18% - polypropylene, 11% - PET packaging, 14% - various fibers (of which most are polyester). According to various sources, only 15 to 25% of this waste is recycled. [1-4] Polymers are highly resistant to the environment and aggressive chemical environments, which makes them an attractive raw material for the production of building materials and products with a long service life. Large volumes of accumulation and formation of polymer waste make it possible to involve their material and energy potential in the resource cycle of obtaining building materials.
2. Materials and methods

For the initial assessment of technologies for using the resource potential of waste, technologies of various authors were analyzed. First of all, the technological modes to which the raw materials are subjected were analyzed. Currently, a large number of technologies have been developed that use polymer waste as a valuable raw material.[5-8]

A group of scientists from Romania proposes to use polymer waste, in particular, polyvinyl chloride, as an additive in the manufacture of mortars. [9] A recipe was developed for the preparation of mortars by replacing sand with plastic waste in various proportions. Plastic waste was pre-crushed to a size of no more than 8 mm, and then mixed with cement and sand, resulting in a building material with a relatively low density (about 500 kg/m³). The use of plastic waste in the composition of the mortar leads to a significant decrease in the coefficient of its thermal conductivity, which improves the thermal insulation properties of this mortar. In the case of replacing 25% of sand with plastic waste, the thermal conductivity of the solution is reduced by 65% compared to the standard composition of the solution.

The negative effect when using plastic in the composition of the mortar is an increase in the water absorption coefficient, a decrease in adhesion by 50% and a bending strength. A significant disadvantage of this technology is the flammability of the materials obtained, with a large content of plastic waste in the composition of the mortar. The issue of disposal of products obtained using this technology remains unresolved. At the end of the life cycle of such products, secondary pollution with plastic waste is possible due to the fact that being in the composition of the material, they are not subject to destruction. [10].

At present, technologies have been developed that make it possible to use jointly the material and energy potential of polymer waste. An example is the use of polymer waste as a replacement for coal coke, which is used as a reducing agent and fuel in the production of pig iron in blast furnaces. [11] This is because plastics contain 3 times more hydrogen than coal. Hydrogen released from plastics acts as a reducing agent along with carbon monoxide. The reduction of iron ore with hydrogen using plastic increases the reaction rate due to the higher diffusion of H₂ compared to CO. In addition, replacing coal with plastic lowers the temperature of the steelmaking process by at least 100–200 °C due to reducing gases, in this case hydrogen, which increase the energy efficiency of the process.

In countries such as Japan, Austria and Germany, in the production of iron and steel, polymer wastes account for up to 40% of the total mass of coal coke [12]. The use of this technology does not form secondary pollution at the end of the life cycle, but pollutants can be formed that pose a serious threat to the atmosphere.

A group of scientists from India proposes to use polymer waste as a replacement for bituminous binder in the production of asphalt concrete mix. This recycling technology will not only significantly reduce the amount of plastic waste, but also improve the quality of roads: asphalt becomes more plastic and less exposed to mechanical damage. [13-15] Polymer waste of different groups is mixed with heated bitumen in the temperature range from 150 °C to 165 °C. The bitumen binds to the mineral aggregate using plastic, which acts as a binder. The optimal content of plastic waste in the asphalt mix is in the range from 5% to 10%. The modified asphalt concrete mix during laying and subsequent operation shows quite good results in comparison with the standard mix. The use of this technology is limited by the physical properties of various groups of plastics.

3. Results and discussion

The above examples of using the resource potential of polymer waste show that the achieved effects of saving primary resources and reducing accumulated polymer waste do not correlate with the possible secondary pollution of the environment during the implementation of recycling technology. [16-18]. When using these technologies, physical and chemical effects on waste, the use of high temperatures are possible. At the same time, new chemical compounds can be formed that can harm the environment.
Various groups of polymers contain chemicals or additives that give it certain properties. The most unfavorable for the environment and human health are bisphenol A, phthalates and brominated flame retardants.

In this regard, it is necessary to establish criteria that will ensure the safe use of the resource potential of polymer waste in technologies for obtaining target products in demand on the market.

The analysis of scientific research by foreign scientists and the Russian Federation showed that in order to ensure environmental safety and when implementing the technology, it is necessary to take into account such properties of polymers as the melting point, chemical composition, as well as the ability to form chemical compounds that are hazardous to the environment during technological disposal operations. The main groups of polymers used in construction and housing and communal services and their physicochemical properties are presented in table 1.

**Table 1.** Physical and chemical properties of various groups of polymers.

| Polymer groups | PET  | HDPE | PVC  | LDPE | PP   | PS   |
|---------------|------|------|------|------|------|------|
| Chemical formula | (C_{10}H_{8}O_{4})_n | (C_{12}H_{20})_n | (C_{2}H_{5}Cl)_n | (C_{2}H_{4})_n | (C_{3}H_{6})_n | (C_{8}H_{8})_n |
| The melting temperature, °C | 260  | 129-135 | 150-220 | 125-132 | 160-170 | 240  |
| Density, g/cm³ | 1.33-1.42 | 0.93-0.97 | 1.31-1.34 | 0.90-0.93 | 0.90-0.92 | 1.05  |
| Tensile strength, MPa | 172  | 18-32 | 40-60 | 7-16 | 245-392 | 39-44 |
| Danger to the environment | Releases phthalate and heavy metals | not toxic | Very toxic | not toxic | not toxic | Releases styrene |

For the successful implementation of the technology for the disposal of polymer waste, it is proposed to use: organizational and technological, environmental, economic criteria. The criteria assess the technological feasibility of using polymer waste, the risks of the formation of chemical compounds hazardous to the environment and humans, and the economic attractiveness of the technology.

The organizational and technological criterion assesses: the possibility of collecting and the need for sorting polymer waste; the volume of waste generation and the volume of previously accumulated; the need and possibility of preliminary processing of polymer waste (the need for crushing, washing, sorting); physical parameters of the recycling process. Environmental friendliness makes it possible to assess the risks of negative impact on the environment during technological processes of disposal of polymer waste, which are determined by the presence of hazardous chemical compounds in the composition of polymers, the ability to penetrate into the links of the food chain of living organisms. Efficiency determines the financial availability and material benefits when implementing the technology for the recycling of polymer waste.

In order to test the performance of the above criteria at the Department of Environmental Protection, studies were carried out on the possibility of using waste polymers used in construction and housing and communal services in the production of building materials. One of the promising areas for the disposal of polymers is their use in asphalt concrete, since bitumen and polymers have the same raw material base in their primary production.

The asphalt concrete production technology has a number of critical technological limitations. In particular, the maximum heating of the mixture should be no more than 190-200 °C, this is due to the rapid aging of bitumen with increasing temperature. For polymers, a critical indicator is the presence of high temperatures in the recycling process chain, since it is the temperature increase that promotes the formation of new chemically hazardous compounds.

Evaluation of the possibility of using waste polymers in the composition of asphalt concrete using the proposed evaluation criteria is presented in table 2.
Table 2. Estimation of waste polymers for use in asphalt concrete.

| Evaluation criteria                  | PET | HDPE | PVC | LDPE | PP | PS |
|-------------------------------------|-----|------|-----|------|----|----|
| Organizational and technological    | no  | yes  |     | yes  | yes/no | no |
| Environmental friendliness          | no  | yes  | no  | yes  | yes | no |
| Profitability                       | no  | yes  | yes/no | yes | yes | no |
| General recommendation for use as a raw material for asphalt concrete | no  | yes  | no  | yes  | yes | no |

According to the proposed method for assessing polymer waste for their inclusion in the technological schemes for the production of asphalt concrete, HDPE and LDPE wastes are the most suitable. The chemical composition does not contain hazardous chemical compounds. The used temperature regimes for the preparation of asphalt concrete make it possible to transfer the waste into a liquid phase, which is necessary for uniform mixing with the bitumen and the mineral base of the asphalt concrete mixture. The temperature range for the preparation of asphalt concrete will not provoke the formation of new chemical compounds hazardous to the environment and humans. The ability to replace part of the bitumen, to obtain asphalt concrete with increased performance indicators, increased service life shows the cost-effectiveness of using these groups of polymer waste in asphalt concrete production technologies. To confirm the efficiency of using LDPE waste, laboratory studies of asphalt concrete compositions were carried out using LDPE waste.

Fine-grained asphalt concrete of type B, grade I was used as reference samples. In appearance, the samples with the addition of HDPE and LDPE do not differ from the samples obtained by the traditional technology, Fig. 1.

![Figure 1](image_url) Appearance of asphalt concrete samples with the addition of LDPE.

The study of the physical and mechanical properties of asphalt concrete samples was carried out in an accredited road laboratory according to the methods established in GOST 9128-2013. The physical and mechanical characteristics of the control samples and samples with the addition of LDPE are presented in Table 2. Mixture 1 - asphalt concrete mixture of standard composition (crushed stone of fraction 5-20 mm - 46%, sand - 12%, sand from crushing screenings - 39%, mineral powder - 3%, bitumen BND 60/90 - 5%) mixture 2 - asphalt concrete mixture with the addition of 4% LDPE, mixture 3 - asphalt concrete mixture with the addition of 6% LDPE.
Table 3. The test results of asphalt type B grade I according to GOST 9128-2013.

| Indicators                        | Requirement GOST 9128-2013 | Mixture 1 | Mixture 2 | Mixture 3 |
|----------------------------------|----------------------------|-----------|-----------|-----------|
| Average density, g/cm³           | -                         | 2.43      | 2.41      | 2.40      |
| Water saturation, %              | 1.5-4.0                    | 1.88      | 1.74      | 1.80      |
| Residual porosity, %             | 2.5-4.0                    | 3.50      | 3.37      | 3.29      |
| Limit compressive strength, MPa: |                            |           |           |           |
| 20 ºC, not less                  | 2.5                       | 4.60      | 5.90      | 5.80      |
| 50 ºC, not less                  | 1.2                       | 1.47      | 1.60      | 1.59      |
| 0 ºC, not more                   | 11.0                      | 9.50      | 9.88      | 9.75      |

They showed that when using LDPE it is possible to obtain asphalt concrete in its characteristics that are not inferior to asphalt concrete based on natural raw materials.

4. Summary
The technology of recycling polymer waste in asphalt concrete production technologies makes it possible to use the material resource of waste, does not require expensive equipment for preliminary waste preparation, and makes it possible to involve large volumes of waste. The proposed use of the criteria for the assessment of polymer waste allows at an early stage of the development of recycling technology to determine the boundary conditions of technological impact, which make it possible to use the material resource of waste without the formation of a technogenic impact on the environment during its implementation. HDPE and LDPE are the most suitable for the use of polymer waste in technologies for the production of asphalt concrete with ensuring environmental safety. They do not contain environmentally hazardous chemical compounds and the temperature of asphalt concrete preparation allows to completely transferring the polymer into a plastic state sufficient for technological processes.

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