Development of innovative phosphogypsum processing technologies as a factor of import substitution in the rare-earth metal market

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Abstract. An innovative method for the differentiated processing of the phosphogypsum chemical production is proposed. It consists in the simultaneous paving materials production in the form of paving slabs and a concentrate of non-radioactive rare earth metals. Russia currently does not perform large-scale mining of rare-earth metals; its share in the world market is a little over 1%. Today, China is the undisputed world leader in rare earth metals trading. Therefore, production of these necessary for high-tech industries elements of phosphogypsum waste allows the most important current tasks solution, the problem of import phaseout. The experimental studies have shown that the profitability index of the proposed innovative technology production will be more than 50%, which suggests its high economic efficiency. All manufacturers using new technologies and materials in their activities are concerned about the risks. In the studied case, the technology is so low-cost and highly profitable that the impact of risks is almost completely leveled. The technology developed by the authors is based on the formation of the regulation and self-organization principles in the phosphoric acid and mineral fertilizers production. This scientific research contributes to the efficiency improvement of the corporate mechanism used in the innovative technology for phosphogypsum waste processing.

Key words: innovative technologies, life cycle, diffusion, transfer, import substitution, income.

1 Introduction

The problem of innovative technologies introduction in construction is one of the most relevant at the present stage of industrial development [1].

Despite the fact that scientists have developed many fundamentally new technologies and materials that differ not only in the creativity of solutions, but also in the nature of breakthrough manufacturing capabilities, their use in the real production sector takes place, at best, with great caution.

Many ideas and developments remain at the level of theoretical research without due recognition by commercial manufacturers.

Nowadays, there are various ways of phosphogypsum processing. For example, compositions based on gypsum materials, including phosphogypsum [2-5], cement, slag [6], ash [7] and other active additives, are widely used [8]. Mixed binders are being studied, involving the creation of composite materials and including those modified by chemical additives, based on gypsum, phosphogypsum and cement clinker [9-14]. There are many innovative directions for the production of construction materials [15-18]. One of them is the production of cement-free non-fired artificial composites [19-24].
The authors propose a unique and one-of-a-kind technology for the production of a full-fledged product. It is obtained after the waste production cycle, namely, resulting from the phosphogypsum waste processing. It is especially important that the presented technological process has a minimum cost level, which is practically incomparable with the expected profit [25, 26].

It is about creating an effective innovative technology for the recycling of phosphogypsum, increasing its life cycle, and allowing significant reduction of Russia's import dependence on foreign supplies of rare earth metals.

According to expert estimates, phosphogypsum is the largest anthropogenic waste in terms of its volume. About 300 million tons of phosphogypsum has been accumulated in the Russian Federation (Voskresensk, Tambov, Cherepovets, Veliky Novgorod, Kingisepp; Kirovo-Chepetsk; Balakovo; Belorechensk; Meleuz). Phosphogypsum recycling is, according to experts, a transnational problem of enormous environmental and social importance. At the same time, the disposal of phosphogypsum is one of the stages of its life cycle. The ways of phosphogypsum usage in the road construction is known, where the roads can be made better, with longer service life, and much cheaper than traditional asphalt ones. Phosphogypsum contains rare earth metals that can be used after processing into bulk concentrate of rare-earth metal oxides and individual oxides applied in the most knowledge intensive modern technologies, such as the production of nanocrystals, heavy-duty magnets, batteries for electric vehicles, solid-state lasers, special ceramics and coatings, in nuclear energy, aerospace industry, telecommunications. Russia is currently an import-dependent country in the segment of rare-earth metals, since it does not have the capacity to separate concentrates of rare-earth metals.

The scientific novelty of this research is an innovative approach that allows extending the life cycle of phosphogypsum, combining the technology of manufacturing the construction products and the concentrate of non-radioactive rare earth metals from phosphogypsum; importing phaseout in the rare earth metals market; attracting investment to generate income.

2 Materials and methods

For this research, we used dump phosphogypsum from the Uvarovo Chemical Plant, which was liquidated in 2000 due to its bankruptcy. The dump area is 6.4 km$^2$, the volume reaches about 35 million tons; phosphogypsum is from the Voskresensk Chemical Plant. The amount of accumulated phosphogypsum in Russia is presented in figure 1.

![Figure 1](image.png)

**Figure 1.** The amount of accumulated phosphogypsum in Russia.

The developed innovative technology for the construction materials from the phosphogypsum production with the simultaneous of a rare-earth metal concentrate production contains the following stages, shown in figure 2.
Figure 2. Stages of the innovative technology of phosphogypsum processing.

To calculate the investment performance indicators, a discount rate of 6% was used. The net present value (NPV) was calculated according to the formula Eq. (1), profitability index (PI) – according to the formula Eq. (2), the internal rate of return (IRR) – according to the formula Eq. (3):

\[ NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \]  

\[ PI = \frac{\sum_{t=0}^{T} (CF_t)}{\sum_{t=0}^{T} (Co)^t} \]  

\[ \sum_{t=0}^{T} \frac{(CF)_t}{(1+r)^t} + \sum_{t=0}^{T} \frac{(Co)_t}{(1+r)^t} = 0 \]

where \( r \) – key interest rate set by Central Bank, \( CF \) – cash flow (current income – current expenditures), \( Co \) – capital investment at the start of the project.

As our project focuses on short periods (months), the \( CF \) in our model is the net profit from sales of finished goods (sales revenue - labor costs, raw materials, rent). \( Co \) in our model is the cost of equipment.

### 3 Results

The research is based on the formulation of the effective regulation and self-organization principles in the production of phosphoric acid and mineral fertilizers, which contribute to the efficiency increase of the corporate mechanism applied for the phosphogypsum waste processing. The transfer of the developed breakthrough phosphogypsum processing technology will allow producing two additional new products at the current phosphoric acid production plant, which will extend the life cycle and increase additional profit. Thus, the new breakthrough technology will complement the old one due to the diffusion of innovations, as presented in figure 3.

According to the developed experimental technology, it is proposed to manufacture two additional types of products:

1) bulk concentrate of rare earth oxides. Production of rare earth metals from industrial wastes in the Russian Federation will make our country not import-dependent. In the Russian Federation, the production of rare-earth metals at Acon Industrial Group in Veliky Novgorod has been launched. However, the concentrate obtained at the outlet is of high cost due to the re-generated large-capacity waste of phosphogypsum, which makes it less competitive in the world market (China);

2) construction products: gypsum partition block and paving slabs, which will be manufactured using non-fired technology. They are 3-5 times cheaper than similar materials produced using traditional technologies.
Figure 3. Transfer of the innovative breakthrough technology with income generation.

The figure shows the diffusion model of the innovative breakthrough technology for the production of phosphoric acid transfer, which has a number of features:

- in the existing phosphoric acid production technology, phosphogypsum forming waste is stored in dumps, only small amount of which is processed. At the same time, the waste dumps occupy hectares of fertile land, affecting the region’s ecology;
- the innovative technology allows manufacturing two most important products from the phosphogypsum waste within the territory of the plant, one of which (paving slabs) is a cheap construction material, and the other (non-radioactive rare-earth metal concentrate) can replace marketable products imported from abroad;
- as a result of the transfer of phosphoric acid production technology, the plant will receive additional income from the sale of the manufactured products using new technologies, which will significantly increase the investment attractiveness of both the plant itself and the region as a whole;
- the processing of phosphogypsum waste, which has an extremely negative impact on the state of the environment, will significantly improve the environmental situation in a number of regions.

The economic results of the developed technology are shown in the table 1.

Table 1. The economic results of the innovative breakthrough technology of phosphogypsum processing.

| Payoff period, months | 15.7 |
|-----------------------|------|
| NPV (net present value), rubles | 3 125 283 |
| PI (profitability index), % | 53.33% |
| IRR (internal rate of return), % (calculated manually) | 53.10% |
| Breakeven point, items (minimum production volume per month) | 41 463 |
| Financial safety margin, rubles (by what % the sales volume may be reduced without actually sustaining loss) | 57% |
| Studied project duration, months | 24 |

In the transferring technology, design, environmental, and investment risks the following factors should be taken into account: insufficient life cycle assessment during long-term operation, the possibility of changing the quality characteristics of materials, design errors, insufficient equipment, work in aggressive environments, increased operating costs, and lack of consumer demand for the manufactured products. Moreover, based on the level of the production profitability using the
proposed technology, it can be confidently stated that this production is characterized by a minimum level of risk compared to other innovative projects.

4 Discussions
The innovative technology presented in this work allows to: (I) reduce the cost of road construction by 30% or more and of production of wall construction products by 3-5 times; (II) to substitute import goods in the market of non-radioactive rare-earth metals; (III) significantly reduce the negative impact of industrial waste on the environmental situation in several regions of Russia. As a result of the phosphoric acid production technology transfer, the company generates additional income, the region’s profitability increases and its environmental situation improves.

Transfer of innovative breakthrough technology for the phosphoric acid production with the manufacture of additional products will increase production profitability, obtain waste-free technologies, utilize waste dumps of phosphogypsum, reduce Russia’s import dependence on rare-earth metals, and improve the environmental situation in certain regions.

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