Energy-saving technology and equipment for the production of composite binder using local raw materials

A A Romanovich\textsuperscript{1,}\textsuperscript{*}, E Amini\textsuperscript{2}, D M Annenko\textsuperscript{1} and E I Chekhovskoy\textsuperscript{1}

\textsuperscript{1}BSTU named after V.G. Shukhov, 46 Kostyukova Street, Belgorod, 308012, Russian Federation
\textsuperscript{2}K. N. Toosi University of Technology, Tehran, Iran

\textsuperscript{*}E-mail: AlexejRom@yandex.ru

Abstract. The article presents the technology and energy-saving equipment for producing a composite binder with a reduction in the energy cost reduction of the process up to 50%, due to the synergistic effect of mechanical activation of the raw material mixture with the replacement of the clinker component with a mineral hydroactive additive. The energy efficiency of the line is achieved by the joint work of the press-roll unit, and the rotor-vortex mill of superfine, which allow the grinding of raw materials to a dispersion with a specific surface area of 4000...4500 cm\textsuperscript{2}/g. The resulting equation for calculating the effort of grinding materials, which is implemented between the conical rollers in the press-roll unit (PRU). It has been established that the power spent on grinding the material and overcoming the friction in the axles of the pivots rolls and proposed the equation for calculating its variable.

1. Introduction
The rational use of mineral resources in the construction industry is one of the main issues in solving the tasks of energy and resource saving. At the same time, the building materials industry can be a unique waste disposal of other industries to produce new composite binders and a wide range of high-performance materials based on them. Every year in the world about 26 billion tons of rock mass is extracted from the bowels of the planet, about 4.5 billion tons of various minerals are processed, of which only from 2 to 10\% becomes a useful product, 2.7 billion tons pass into the category of industrial waste of the field of use, which, as a rule, are not determined \cite{1-3}. Mining is accompanied by the accumulation of billions of cubic meters of waste rock, which occupy hundreds of thousands of hectares of land. As a result of the accumulation on the surface of our planet of powerful man-made formations, environmental pressure occurs. By the beginning of the XXI century mankind has accumulated such amount of man-made waste that they can be called new deposits. Therefore, the problem of their use with minimal processing costs is acute.

Today, the problem of waste reduction is closely related to the issues of sustainable economic development: in conditions of ever-growing demand for raw materials, while reducing the available reserves and the ultimate exhaustion of natural resources.
2. Main part.
The solution to the problem of industrial waste depends on several factors, but the most effective solution is the acceptance of wasteless technology. With the integrated use of raw materials, industrial waste from some industries can be the raw materials of others. Rational integrated use of mineral natural resources, involvement in the production of man-made waste and secondary products of various industries for the production of building materials will significantly reduce the burden on the environment and lead to resource and energy saving. One of the locomotives of construction, ready for processing and use of man-made waste is the cement industry.

In our country, according to production capacity of cement enterprises, there has been observed an acute shortage of binders. According to the forecasts of the Ministry of regional development, which developed a strategy for the development of the building materials industry until 2020, the need for the construction industry in cement in ten years will almost double (to 98 million tons). One way to quickly increase the volume of mineral binders is to obtain composite binders (OCB) using local raw materials and man-made waste. The use of OCB with the use of industrial waste will not only reduce the consumption of clinker component in the binder, but also to obtain high-performance building materials based on them. It is known that the reserves of waste in the form of slag of electric steel furnaces of the Oskolsky electrometallurgical works are more than 4 million tons, with an annual replenishment of about 500 thousand tons. Currently, there are a number of developments on the use of slag in the production of building materials, construction, repair and reconstruction of roads [4-7]. It has been established that the use of slag materials in the foundations of roads and components of asphaltic concrete road, as sand aggregate and mineral powder, reduces the cost of construction and improves the quality and reliability of the road surface.

Also known technology for producing mineral binders using slag waste from blast furnaces of metallurgical production, one of the main components of which is the fine grinding of its components, including slags.

However, the initial product, slag, is a fairly hard material with a grain strength of P = 300-320 kg/cm², it has abrasive properties and has larger dimensions than the granule size of the mineral additive, which requires grinding and comminution. At this time, there is a wide variety of grinding units and systems used for grinding materials and industrial wastes, which have different strength characteristics. The analysis of technical and economic efficiency from the use of existing and developed grinding systems [9-12] made it possible to identify as the most effective those systems that implement the principle of stepwise grinding of materials with the removal of the coarse grinding stage into a separate unit that performs a more economical method of destruction charge (volume- shearing deformation), than, for example, impact and abrasion. Scientists of BSTU named after V.G. Shukhov developed industrial technology and energy-saving equipment to obtain a composite binder with a decrease in the energy intensity of the process up to 50% due to the synergistic effect during the mechanical activation of the raw mix with the replacement of the clinker component of the mineral hydroactive additive (Figure 1). The technological process (Figure 1) is based on the sequential input of components in dispersed phases into the raw material mixture in the grinding path and at the stage of product separation with certain dispersed characteristics.

The increase in the energy efficiency of the line is achieved by the joint operation of the press-roller unit, which is the development of scientists of the BSTU named after V.G. Shukhov, and the rotary vortex mill superfine comminution new design. In this case, a synergistic effect is achieved. The technology of obtaining a composite binder implies the grinding of raw materials to dispersion with a specific surface area of 4000 ... 4500 cm²/g.
Figure 1. The process flowsheet of the production of composite materials: 1,2,3 – hoppers for raw materials; 2 – press roller unit; 3,5,8,10,12 – feed screw; 4 – dryer drum; 6 – storage bin; 9 – additive bin; 11 – mixing machine; 13 – packing machine; 14 – finished-products storage area.

Reducing the specific energy consumption is achieved, including through the use of a press-roll unit (PRU) at the stage of preliminary grinding with working bodies implementing volume - shearing deformation of materials (Figure 2).

At this technological line is set down the press-roll unit, having the following technical characteristics. (Table 1)

However, the application of energy-saving technology using various regional raw materials and industrial wastes requires scientifically-based recommendations for calculating and designing the energy parameters of the main grinding units of the line. One of the important parameters for the application of the press-roller unit is the power consumption of the engine, which directly depends on the grinding force of the materials realized in the cone-shaped rollers.
Table 1. The technical characteristics of press-roll unit.

| №  | Technical characteristics                  | Parameter value   |
|----|-------------------------------------------|-------------------|
| 1  | Geometrical dimension of rolls            | 0.4×0.3 m         |
| 2  | Dimension tapering of rolls              | 0.3               |
| 3  | Roll opening                              | (3-8)×10⁻³ m      |
| 4  | Circumferential speed roll rotation       | 0.8 m/sec         |
| 5  | Generating capacity of drive rolls        | 2×7.5 kW          |
| 6  | Maximum backward force                    | 90×10⁴ N          |
| 7  | Unit capacity                             | 5-7 tons per hour |

To determine the force arising between the conical rollers in the process of grinding materials, assume that from a certain angle \( \gamma_1 \), which corresponds to the coating thickness \( H_1 \), deformation of the crushed charge is proportional to the specific pressure \( P_1 \) (Figure 3). Then instantaneous value of angle \( \gamma_T \) corresponds to the specific pressure \( P_T \). On the basis of the above it can be inferred that:

\[
\gamma_T H_1 = \gamma_1 H_T \quad \text{or} \quad P_T H_2 = P_2 H_T ,
\]

where \( P_2 \) - centerline pressure, MPa.

![Figure 3. Schematic illustration to determine the grinding force of materials.](image)

Considering the fact that \( H_1 - H_2 = 2R_{av} (1 - \cos \gamma_1) \), where \( R_{av} \) - midradius of rolls; \( H_2 \) thickness of the layer of material on the center line, m.

Using the ratio (1), deduce:

\[
H_2 = \frac{2R_{av} (1 - \cos \gamma_1)}{\gamma_1 - \gamma_2} .
\]

From figure 3 exist, that the thickness of the current material layer is equal to:

\[
H_T = 2R_{av} \cos \gamma_T - 2R_{av} \cos \gamma_1 .
\]

Then variable expression (1) with regard for (2) and (3) will take the following form:

\[
\frac{P_T}{P_2} = \frac{2R_{av} \cos \gamma_T - 2R_{av} \cos \gamma_1}{2R_{av} (1 - \cos \gamma_1) / (\gamma_1 - \gamma_2)} .
\]
Perform shortcut in recognition that measure of the angle $\gamma_2$ on line centers equal to $0^\circ$, than formula (4) be written as:

$$P_T = P_2 \frac{\cos \gamma_T - \cos \gamma_1}{1 - \cos \gamma_1}.$$  \hspace{1cm} (5)

Let us introduce axis of reference «$x$» and «$y$», and project the elementary force $dP$ on axis «$x$», its projection equals:

$$dP_x = dP_T \cos \gamma_T \cos \alpha,$$  \hspace{1cm} (6)

where $\alpha$ - angle of inclination forming the working surface of the rolls.

On the entire width of the working surface of the roll, taking into account (5) having:

$$x = \frac{P_2 BR_{av} \cos \alpha}{1 - \cos \gamma_1} \left( \int_0^{\gamma_1} \cos \gamma_T d\gamma - \cos \gamma_1 \int_0^{\gamma_1} d\gamma \right) \int_0^{\gamma_1} \cos \gamma_T d\gamma.$$  \hspace{1cm} (7)

1) Upon integrating:

$$P_x = \frac{P_2 BR_{av} \cos \alpha}{1 - \cos \gamma_1} \left( \sin \gamma_T - \gamma_1 \cos \gamma_1 \right) \sin \gamma_1.$$  \hspace{1cm} (8)

For the sake of simplicity next computation makes use Maclaurin formula and distribute the sine and cosine in row, in which we restrict ourselves to the first two variables, and discard the rest as small values. Then the variable expression takes (8) the following form:

$$P_x = \frac{2 P_2 BR_{av} \cos \alpha}{\gamma_1^2} \left[ \gamma_1 - \frac{\gamma_1^3}{6} - \gamma_1 \left( 1 - \left( \frac{\gamma_1}{2} \right)^2 \right) \right].$$  \hspace{1cm} (9)

After the appropriate transformation, we obtain an equation for calculating the effort of grinding materials between the PRU tapered rollers.

$$P_x = P_2 BR_{av} \gamma_1 \cos \alpha.$$  \hspace{1cm} (10)

Determine the motor capacity, spent on grinding materials in PRU with conical rollers, according to the following equation:

$$N_{dv} = \frac{N_1 + N_2}{\eta},$$  \hspace{1cm} (11)

where $N_1$ and $N_2$ - supplied power for grinding material and overcoming friction in the roll axles, respectively, W; $\eta$ - coefficient drive efficiency.

The supplied power for grinding material in the tapered rolls can be determined by the equation:

$$N_1 = M \rho \omega,$$  \hspace{1cm} (12)

where $M$, $\rho$, $\omega$ - resulting moment, arising from PRU in process a tapered roll profile when grinding material, Nwm; $\omega$ - angular velocity roll rotation, radian per second.

Determine the value resulting moment that is necessary apply to rolls to ensure their rotation during the grinding process. According to analytical model, presented in the figure 4, we find that:
where \( \frac{F}{2} \) - circumferential force, have an effect on the average radius of the roll.

The circumferential force can be determined by the following equation:

\[
F = 2P_\Sigma \sin \gamma_H ,
\]

where \( P_\Sigma \) - summarized thrust force, N; \( \gamma_H \) - neutral angle degree.

\[ M_p = 2 \frac{F}{2} R_{av} = FR_{av} , \]  

Figure 4. Scheme for determining the resulting moment.

\[
P_x = 0.7 P_2 BR_{av} \gamma_1 \cos \alpha ,
\]

where \( P_2 \) - unit pressure of grinding, N/m\(^2\); \( B \) - width of rolls, m.

Then make an assumption, that \( \sin \gamma_H \approx \gamma_1 \), since it is very small, we get:

\[
N_1 = 1.4 P_2 \omega BR_{av}^2 \gamma_i^2 \cos \alpha .
\]

The supplied power on the overcome friction in roll axles, equal to:

\[
N_2 = 2 \pi d_c \theta_p \eta f_k n ,
\]

where \( d_c \) - roll axle diameter, m; \( \theta_p \) - resultant force from the total spacer effort and the force of gravity of the roll, is equal to:

\[
\theta_p = \sqrt{P_\Sigma^2 + G_B^2} ,
\]

where \( f_k \) - coefficient of rolling friction.

As a case in point determine the intake power of drive PRU with the following source data:

\[
D_{av} = 0.4 \text{ m}, \quad B = 0.1 \text{ m}, \quad P_2 = 100 \cdot 10^6 \text{ N/m}^2 , \quad n = 0.25 \text{ s}^{-1}, \quad \delta = 4 \cdot 10^{-3} \text{ m}, \quad \gamma_H = 4^0, \quad d_c = 0.01 \text{ m}, \quad f = 0.001; \eta = 0.85; \quad G_v = 979.68 \text{ N};
\]

To construct the graphical dependence of power on the size of rolls taper and the specific grinding pressure. The calculated data are presented in table 2.[6-8]
Table 2. The effect of rolls taper on the supplied power on grinding at different pressures.

| Coefficient | \( P_2 = 100 \cdot 10^6 \), N/m² | \( P_2 = 150 \cdot 10^6 \), N/m² | \( P_2 = 200 \cdot 10^6 \), N/m² | \( P_2 = 250 \cdot 10^6 \), N/m² |
|-------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| 0           | 4271.2                           | 6406.8                           | 8542.4                           | 10678.0                          |
| 0.15        | 4257.9                           | 6386.97                          | 8515.96                          | 10645.0                          |
| 0.3         | 4218.7                           | 6328.1                           | 8437.4                           | 10547.0                          |
| 0.5         | 4125.6                           | 6188.4                           | 8251.3                           | 10314.1                          |
| 1.25        | 3698.9                           | 5548.4                           | 7397.8                           | 9247.3                           |
| 2           | 3020.2                           | 4530.3                           | 6040.4                           | 7550.6                           |

The graphical dependence of the effect of the taper value on the supplied power on grinding the clinker at different specific pressures, obtained experimentally, is shown in Figure 5.

Figure 5. The dependence of the effect of the taper value on the supplied power on grinding the clinker at different specific pressures, obtained experimentally.

Thus, the obtained analytical expressions with sufficient adequately reflect the real process, the discrepancies between the calculated values at \( P_a = 100 \) MPa with rolls taper equal to 0.3 (\( N_{dv} = 4.218 \cdot 10^3 \) W) and experimentally obtained values (\( N_{dv} = 3.755 \) W) less than 10%, which fairly adequately reflects the actual process.

The use of these materials in a finely divided state will create conditions not only for the disposal of industrial waste, but also for the development of promising technologies and processes for obtaining cheaper building, thermal insulation and other materials.

3. Summary

It is hereby recommended that an industrial technology and energy-saving equipment for obtaining a composite binder with a reduction in the energy intensity of the process up to 50% due to the synergistic effect during the mechanical activation of the raw mix with the replacement of the clinker component of the mineral hydroactive additive is proposed. The energy efficiency of the line is achieved by the joint operation of the press-roller unit and the rotary-vortex mill of superfine grinding, which allow the grinding of raw materials to dispersion with specific surface area of 4000 ... 4500 cm²/g.
We obtained the equation for calculating the effort of grinding materials, realized between the conical rolls of PRU, is obtained. It was established that the power expended on grinding the material and overcoming friction in the roll axles and derived an equation for calculating its value, which reflects the actual process with sufficient accuracy.

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