Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-48591
www.engineeringscience.rs

Journal of Applied Engineering Science
Vol. 22, No. 2, 2024
Original Scientific Paper
Paper number: 22(2024)2, 1209, 446-457

BASES OF THE METHOD OF PHYSICAL MODELING OF THE PROCESS OF CRUSHING OF MUNICIPAL SOLID WASTE

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A large number of studies are aimed at increasing the energy efficiency of grinding processes of various solid materials, while maintaining the values of other important indicators, such as material consumption, productivity, etc. Based on this trend, a new method for physically modeling the process of grinding municipal solid waste (MSW) was proposed for the first time. Existing physical modeling techniques are designed for homogeneous and isotropic materials (for example, soil, crushed stone, snow, coal, etc.). The strength properties of solid waste vary widely due to the significant heterogeneity of their components. Consequently, when crushing solid waste, traditional crusher designs have low efficiency in terms of energy intensity, material intensity and product quality. The purpose of this work is to develop a new technique for physical modeling of the grinding process, based on the main principles of similarity theory and modeling, considering the properties of waste heterogeneity. As a result of the research, a block diagram of the physical modeling methodology for the interaction of the working bodies of impact crushing machines with solid waste was developed. A list of tasks for the modeling process and similarity criteria have been determined based on the development of rheological models of the "working body - municipal solid waste" system and the laws of mechanics that characterize the waste grinding process. Based on the developed similarity criteria, scale equations for the grinding process are substantiated and formulas are derived for determining the expected parameters of the original based on the parameters measured on the model. The developed methodology makes it possible to create a crusher design with improved energy efficiency indicators with the least material and labor costs.

Keywords: physical modelling, crusher, municipal solid waste, similarity criteria, model

1 INTRODUCTION

Improving the quality of life of people and the growth of the urban population, as well as the pursuit of additional profit on the part of manufacturers through small packaging of goods, have led to a significant increase in the volume of municipal solid waste (MSW), because of which their negative impact on the environment has increased. Currently, to reduce the negative impact of municipal solid waste on the environment, issues related to the collection, transportation, crushing and sorting, disposal of waste in landfills, as well as their use in the form of secondary raw materials remain relevant. It is known that the crushing operation is a key link in the system of integrated waste processing, and, in this regard, many companies pay special attention to the creation and production of energy-efficient crushing machines [1, 2, 3].

Existing universal technologies for grinding solid materials designed for grinding homogeneous solid materials (for example, soil, snow, crushed stone, coal, etc.) are ineffective for grinding solid waste because they have a significantly heterogeneous environment.

The development of a method for physical modeling of the process of crushing solid waste, taking into account the heterogeneity of its components, will make it possible to create an energy-efficient crusher with the least material and labor costs.

The method of physical modeling of various processes, based on the theory of similarity and modeling, allows not only to set up experiments correctly, but also to take into account those factors that at first glance seem unimportant, as well as to effectively process the results of experiments. In addition, physical modeling of the solid waste grinding process to search for rational values of the main parameters serves as a link between theoretical and experimental research [4].

Many works are devoted to the development of methods for physical modeling of the processes of cutting, digging, compacting and transporting soil [5, 6,7,8], which will be the starting point for developing a method for physical modeling of the solid waste grinding process.

To develop the fundamentals of a methodology for physical modeling of the solid waste grinding process, it is necessary to solve the following problems:

- develop a block diagram of an algorithm for the method of physical modeling of the solid waste grinding process
- develop a rheological model of the solid waste grinding process
- develop a criterion equation for the waste grinding process
- develop analytical dependencies for determining the main parameters of the crusher based on the data obtained on the models.

2 LITERATURE REVIEW

A large number of studies are being conducted aimed at increasing the energy efficiency of the grinding process of various solid materials. Existing methods of physical modeling and calculation of the main parameters of crushers are designed for homogeneous and isotropic materials (for example, soil, crushed stone, snow, coal, etc.). The strength properties of solid waste vary widely due to the significant heterogeneity of their components. Consequently, when crushing solid waste, they have low efficiency in terms of energy and material consumption.

The values of the power and energy parameters of crushers used for grinding solid materials (for example, solid waste) to specified fractions depend on many parameters: linear dimensions, shape of the source material, strength characteristics, uniform composition of the material, water permeability and condition of the working bodies, etc. Consequently, the establishment mathematical relationships between force and energy parameters, on the one hand, and the properties of crushed materials, on the other, are possible only in general terms.

The studies in [9,10,11] describe the hypothesis put forward by P. Rittinger about the proportionality of energy costs and the parameters of newly formed areas. F. Kick proposed that the energy costs of grinding geometrically similar materials are equivalent to the volumes of materials. This statement was called the second hypothesis or the law of volumes. Later, it was stated that V. Kirpichev was the first to propose such a formula (much earlier than F. Kick). He developed this dependence based on the provisions of the theory of similarity. Therefore, the second hypothesis is currently called the Kirpichev-Kick law [11].

In 1949, F. Bond proposed that the work expended in grinding brittle materials is equivalent to the product between volume and area, taken under the square root. An analysis of literary sources suggests that all of the above provisions can be considered hypotheses and not laws since they are not confirmed by practice. When the properties of crushed materials fluctuate over a wide range (e.g., components of municipal solid waste), the values of energy consumption for crushing and the value of energy calculated according to three hypotheses differ significantly from each other [11].

A thorough analysis of the essence of the above hypotheses made it possible to conclude that none of the above hypotheses is adequate in theoretically determining energy consumption, even at small intervals, for example, when crushing pieces of isotropic material of a simple shape in a laboratory. Numerous assumptions and restrictions added to the considered crushing hypotheses only complicated the methods for calculating the energy consumption for grinding, and the reliability of these hypotheses still needed to be improved [11].

V.I. Balovnev proposed a semi-empirical hypothesis to study the design and technological parameters when using various crushing methods; the main essence of this hypothesis is as follows. The character of acting forces determines the power and energy indices of the crushing process, the way they are applied to the crushed material, and their share ratio in the grinding process [12].

In practice, one has to deal primarily with anisotropic materials, for example, when shredding wood waste and the complexity of the process depends on many parameters. Combining all parameters into one analytical dependence is a challenging task.

Methods for physical modelling of the working processes of the contact of the active bodies of road-building machines with non-homogeneous and anisotropic media, such as municipal solid waste, were studied in [13, 14, 15,16,17, 18].

All three hypotheses and the generalized V.I. Balovnev hypothesis are applicable only in a limited area - in elastic deformations; the viscous and plastic properties of natural bodies are not considered (most of the M.S.W. components possess such properties).

In this connection, there is a need to develop simplified, but quite accurately consistent with experiments, methods for physical modeling of the process of grinding solid waste and calculating the main parameters of crushers, which use the original experimental data obtained on physical models.

3 METHODS

The algorithm for constructing a methodology for physical modelling and the stages of modelling "working body-municipal solid waste" systems in relation to M.S.W. is shown in Fig.1.

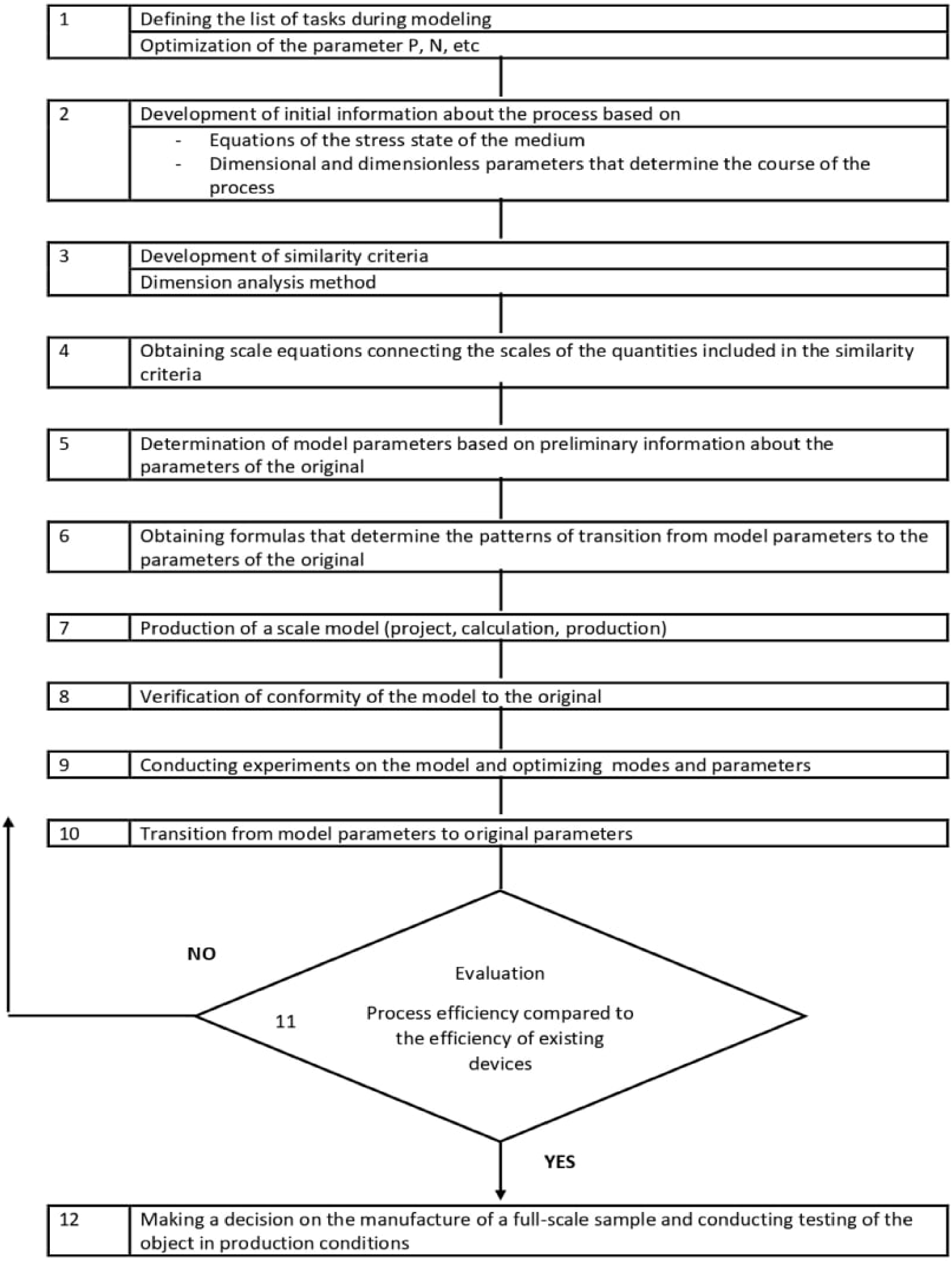
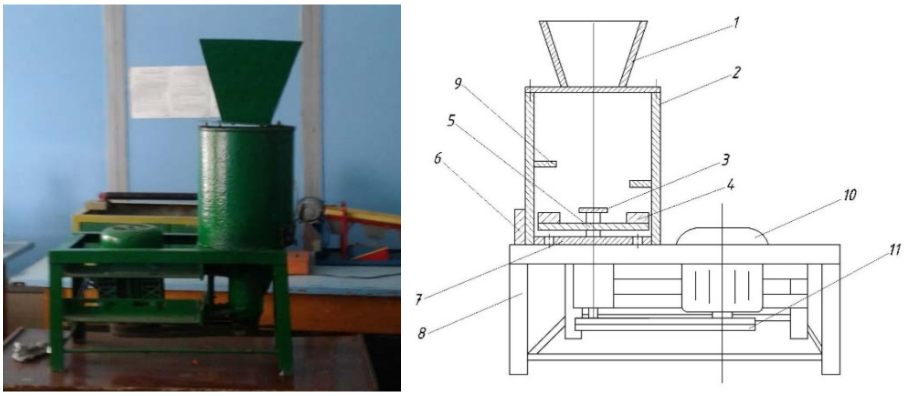


Fig. 1. Block diagram of the technique of physical modeling of the processes of interaction of the working bodies of crushing machines of impact type with municipal solid waste

An algorithm for performing specific tasks for optimizing power and energy parameters was developed using the N. Hertz nonlinear elastoplastic model [19, 20, 21, 22]. As an example of using the developed physical modeling technique, a physical model of a hammer crusher for grinding organic waste components has been developed. The general view and design diagram of the crusher are shown in Fig.2.



a) b)

Fig.2. Hammer crusher: a) general view of the hammer crusher, b) structural diagram of the hammer crusher: 1-bunker; 2-working chamber; 3-knife rotating; 4-hammer; 5-rotor; 6- side grate; 7-lower grate; 8-frame crusher; 9-knife fixed; 10-electric motor; 11- V-belt

The hammer crusher consists of a hopper 1, which consists of steel sheets welded with a thickness of 3.0 mm in the shape of an isosceles trapezoid, the lower ends of which are welded to a disk with a diameter of 300 mm, which in turn serves as a cover for the working chamber 2. The working chamber 2 is made of a cast-iron pipe with a diameter of 300 mm, the lower end of which is welded to the frame 8 of the crusher, and in the upper part of the working chamber four through holes are drilled in a circle, the hopper 1 of the crusher is attached to them with bolts. The electric motor 10 is bolted to frame 8 of the hammer mill. It is positioned so that crusher wash water or liquid waste does not enter the electrical part of the electric motor. To do this, a pulley is installed in the lower part of the working chamber, which is rigidly mounted on the shaft. A pulley is fixed to the output shaft of electric motor 10 by means of a key, which is connected to the pulley of the working chamber 2 by means of a V-belt drive. A cruciform working body is mounted on dowels to the upper part of the shaft of the working chamber. A rotor 5 is welded onto a sleeve with a diameter of 20 mm from the bottom side. On the outer side of which hammers 4 are welded. A rotating knife 3 is also welded to the upper part of the sleeve, the ends of which are pointed for better grinding. To obtain crushed waste to the desired size, a side grate 6 is installed in the lower side part of the working chamber 2. In addition, to improve the efficiency of grinding the organic components of the waste, lower grates 7 are drilled along the periphery. For better grinding of waste on the walls working chamber 2 fixed knives 9 are welded.

Hammer crusher works as follows. The waste arriving for grinding enters the loading hopper 1. Then the waste enters the working chamber 2, where it is accelerated to a rotation speed equal to the nominal rotation speed of the electric motor 10 due to the creation of air pressure by means of a hammer 4. Accelerated waste to the nominal rotation speed of the electric motor 10 is crushed due to the collision of waste with knives 9 rigidly welded to the walls of the working chamber 2. In addition, the waste is crushed by colliding with the grate 5.

A hammer crusher is designed for crushing organic components of MSW in the system of their complex processing. The working body of the crusher consists of horizontal plates and vertical plates welded on them, installed along the rotor axis. Grinding of organic components of the waste is conducted due to the collision with the rotor blade, due to the impact on the knives welded on the wall of the working chamber, and due to the impact of the waste on the walls of the working chamber. In addition, the grinding of waste is conducted due to the impact of the organic components of the waste on the openings of the grates.

The analysis of an a priori information and the search experiments conducted made it possible to determine the list of factors influencing the crushing process: rotor speed - n, s^{-1}; rotor diameter - D, m; the average linear size of the components of waste - d_{av}, m; the linear size of the hammer - l_m, m; setting angle of the hammer - α, degree; crusher power - *N*, kW; the volumetric weight of waste - δ, $\frac{N}{m^3}$; free fall acceleration - $g, \frac{m}{s^2}$; the area of the light surface of the grate - F_l, m^2; waste humidity - ω, % waste supply - Q, $\frac{kg}{h}$.

The technological scheme of waste processing and their properties at the final stage of processing made it possible to reduce the number of factors affecting the crushing process significantly. Optimization of kinematic, geometric, force and power parameters has dramatically reduced the time and material costs for determining the optimal parameters of machines.

4 RESULTS

Analysis of the working process of crushing waste on a hammer crusher equipped with multicomponent working bodies and the predominance of specific contact forces made it possible to study the active process of waste crushing by various crusher working bodies.

The maximum value of the contact force P_{max} (formula 1) was determined when the waste components collided.

$$P_{max} = \left[\frac{2(n+1)k^{n+2}}{m\vartheta_0^2}\right]^{\frac{1}{n+1}} = \left[\frac{(n+1)k^{n+2}}{E_0}\right]^{\frac{1}{n+1}} \quad (1)$$

where E_0 is the reduced kinetic energy of the components of municipal solid waste; ϑ_0 is the initial velocity of collision, $\frac{m}{s}$; m is the mass of waste components, kg; k, n are experimental coefficients. The critical value of the velocity of collision ϑ_{cr} (formula 2) of the waste components with the blades of knives welded on the inner walls of the working chamber and the blades of the rotating crusher rotor is determined.

$$\vartheta_{cr} = \sqrt{\frac{\sigma_{st}^2 V}{mE}} = \sigma_{st}\sqrt{\frac{V}{mE}} = k_1\sigma_{st} \quad (2)$$

where ϑ_{cr} is the critical value of the required speed, $\frac{m}{s}$; V is the volume of waste components, m^3; E is the modulus of elasticity of waste components, $\frac{N}{m^2}$; $k_1 = \sqrt{\frac{V}{mE}}$ is the dimensional coefficient characterizing the physical and mechanical properties of the organic components of waste, $\frac{m^2 s}{kg}$; σ_{st} is the ultimate strength of waste components, $\frac{N}{m^2}$. The dependence of the contact force of the waste components on the main parameters of the process (formula 3) makes it possible to optimize the value of the contact force in the process of collision of the waste components with the internal walls of the crusher.

$$\begin{cases} P = \frac{1.140m(\vartheta_n^*)^2}{x_{max}} sin\frac{1.068\vartheta_n^* t}{x_{max}}, \quad 0 \le t \le \frac{\pi x_{max}}{1.068\vartheta_n^*} \\ P = 0, \;\; t > \frac{\pi x_{max}}{1.068\vartheta_n^*} \end{cases} \quad (3)$$

where ϑ_n^* is the standard component of the pre-impact velocity, $\frac{m}{s}$; x_{max} is the maximum value of elastic-plastic strain, m; *t* is the contact duration time, sec.

A visual representation of the pattern of change in stresses and strains in the process of impact of the components of municipal solid waste on the crusher rotor blades, on the walls of the working chamber of the crushing machine, and on the knives welded on the inner walls of the crusher depending on the properties of the waste under the impact is determined by rheological models, which, in turn, make it possible to develop more general similarity criteria for the M.S.W. crushing process. The M.S.W. crushing process scheme and the process's rheological equivalent are shown in Fig. 3.

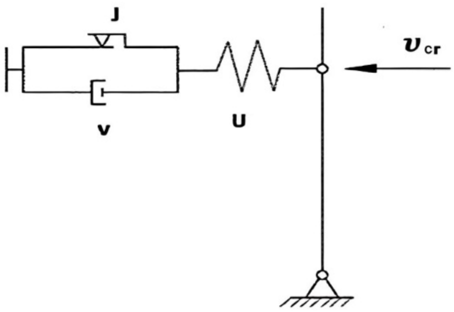


Fig.3. Scheme of the M.S.W. crushing process and the rheological equivalent of the process.

In obtaining general similarity criteria, it is sufficient to represent the grinding process as an elastoviscous-plastic model. The link (u) shows the rapid elastic shape change of the body under force. Links (v) and (j) imitate the manifestation of rigid-plastic and viscous properties of the waste components.

$$\tau_\Sigma = \tau_u = \tau_j + \tau_v \quad (4)$$

where τ_Σ is the total shear stress, MPa; τ_u is the shear stresses arising in the elastic stage of strain development, MPa; τ_j is the rigid-plastic component of shear strain, MPa; τ_v is the viscous component of shear strain, MPa.

The shear stresses that arise during the impact of the rotor blade on the M.S.W. components, based on the rheological model, can be divided into two zones: the zone of elastic deformations, where the shear stress is determined as:

$$\tau = \gamma G \quad (5)$$

where τ is the shear stress in the zone of elastic deformations, MPa; γ is the shear strain; *G* is the shear modulus, MPa.

Shear stress in the zone of plastic deformations is:

$$\tau = \gamma_1 G_1 + \tau_{pl} \quad (6)$$

where γ_1 is the shear strain in the zone of plastic deformation, m; G_1 is the shear modulus in the zone of plastic deformation, MPa; τ_{pl} is the shear stress in the zone of plastic deformation, MPa. M.S.W. is presented as a medium with friction and cohesion between waste components, i.e., a plastic Coulomb-Mohr medium. Based on the physical modeling scheme developed above

1. We determine the resistance force and power of the grinding process and its efficiency. The resistance force to crushing is:

$$P = \tau l_m^2 \tag{7}$$

where l_m^2 is the contact area of the working body of the hammer crusher with waste components, m^2. The power required to perform the crushing process is:

$$N = P\vartheta \tag{8}$$

where ϑ is the speed of rotation of the hammer crusher rotor, $\frac{m}{s}$.

2. The internal forces arising before the working body are calculated according to the Mohr-Coulomb theory.

The initial form of the process is shown in Figure 3. The shear stress equation has the following form:

$$\tau = \sigma tg\rho + C + \frac{\gamma l_m}{g}\frac{d\vartheta}{dt} \tag{9}$$

3. The similarity conditions are determined by the method of integral analogs and using the laws of mechanics, equations (5) - (9):

$$\pi_1 = \frac{\tau}{\gamma G}, \quad \pi_2 = \frac{\tau}{\gamma_1 G_1}, \quad \pi_3 = \frac{\tau}{\tau_{pl}}, \quad \pi_4 = \frac{C}{\gamma l_m}, \pi_5 = tg\rho,$$

$$\pi_6 = \frac{C}{\tau}, \ \pi_7 = \frac{\tau l_m^2}{P}, \ \pi_8 = \frac{P\vartheta}{N}, \ \pi_9 = \frac{\vartheta^2}{g l_m^2} \tag{10}$$

Development of similarity criteria for crushing municipal solid waste based on the dimensional analysis method.

Additional criteria characterizing the working body's parameters and the active process of grinding are determined using the dimensional analysis method.

The analysis of the influence of factors acting on the process of waste grinding and the statement of criterion dependencies was conducted based on the methods of the theory of similarity and dimensions using the π-theorem [23]. Crushing performance depends on many parameters, the most important of which are power, degree of crushing, and type of material being processed. In our case, the type of material is known, and the degree of required crushing $i = \frac{D_{av}}{d_{av}}$, is also known. According to the analysis of the initial information, $i \approx 3$ allows one-stage grinding technology to be conducted. Accepting certain assumptions and restrictions, the performance of crushing the organic components of M.S.W. using hammer crushers (depending on their design and technological parameters) can be characterized by the following functional dependence:

$$Q = \varphi(D, n, N, d_{av,} F_l, l_m, \alpha, \delta, g) \tag{11}$$

where N is the power of a crusher, W; D is the rotor diameter, m; n is the rotor speed, s^{-1}; Q is the crusher productivity, m^3/hour; F_l is the light surface area of the grate, m^2; l is the linear size of the hammer, m; α is the hammer setting angle, degree; δ is the volumetric weight, $\frac{N}{m^3}$; g is free-fall acceleration, m/s^2; d_{av} is the average linear size of the components of waste, m.

Let us define the similarity criteria for this process. In our case, there are 10 physical quantities characterizing the process (n=10).

It follows from consideration of these quantities that one of them, i.e., α is automatically a similarity criterion [24].

The dimensions of the remaining 10-1=9 physical quantities can be expressed in terms of three basic units of measurement - force *P*, length *L*, and time *T*.

We write out the formula for the dimensions of these quantities:

$[d_{av}] = [D] = [l_m] = L$, $[Q] = L^3T^{-1}$, $[\delta] = PL^{-3}$, $[g] = LT^{-2}$, $[n] = T^{-1}$,$[F_l]$=L^2, $[N]$=PLT^{-1} ,

To find an additional number of similarity criteria, we should choose base quantities with independent dimensions, which would include all the main units of measurement. We take three quantities with independent dimensions: δ, D, g ($m = 3$).

Then, it remains to find 9-3=6 similarity criteria. To find criterion π_{10}, we take, for example, the dimension of parameter *Q* and write it into the numerator, and the product of the dimensions of the quantities δ, D, g with unknown exponents a_1, a_2, a_3, we write into the denominator.

$$\pi_{10} = \frac{(L^3T^{-1})'}{(PL^{-3})^{a_1}(L)^{a_2}(LT^{-2})^{a_3}},$$

The exponents are determined by equating the dimensions of the numerator and denominator to each other to obtain a dimensionless complex. So, for $a_1 = 0$, $a_2 = 2{,}5$, $a_3 = 0{,}5$, we obtain:

$$\pi_{10} = \frac{(L^3T^{-1})'}{(L)^{2,5}(LT^{-2})^{0,5}},$$

Let us substitute symbols of physical quantities instead of dimensions. Then, raising these quantities to the indicated powers, we finally obtain:

$$\pi_{10} = \frac{Q}{D^{2,5}\sqrt{g}}, \tag{12}$$

In the same way, we obtain the remaining similarity criteria. Finally, we obtain the following system of criteria:

$$\pi_{11} = \frac{Dn^2}{g}, \ \pi_{12} = \frac{d_{av}}{D}, \pi_{13} = \frac{N}{\delta D^{3,5} g^{0,5}}, \quad \pi_{14} = \alpha, \quad \pi_{15} = \frac{F_l}{D^2}, \quad \pi_{16} = \frac{l_m}{D} \tag{13}$$

If we divide criterion π_{10} by π_{15}, then we obtain new criterion

$$\pi_{17} = \pi_{10}/\pi_{15} = \frac{Q}{D^{2,5}\sqrt{g}} \cdot \frac{D^2}{F_l} = \frac{Q}{F_l\sqrt{Dg}} \tag{14}$$

If we multiply criterion π_{11} by π_{12}, then we obtain criterion π_{18}

$$\pi_{18} = \pi_{11} \cdot \pi_{12} = \frac{Dn^2}{g} \cdot \frac{d_{av}}{D} = \frac{d_{av}n^2}{g} \tag{15}$$

If we divide criterion π_{10} by π_{13}, then we obtain new criterion π_{19}

$$\pi_{19} = \pi_{10}/\pi_{13} = \frac{Q}{D^{2.5}g^{0.5}} \cdot \frac{\delta D^{3.5}g^{0.5}}{N} = \frac{QD\delta}{N} \tag{16}$$

If we divide criterion π_{12} by π_{16}, then we obtain new criterion π_{20}

$$\pi_{20} = \pi_{16}/\pi_{12} = \frac{l_m}{D} \cdot \frac{D}{d_{av}} = \frac{l_m}{d_{av}} \tag{17}$$

The experiments were conducted under conditions of approximate physical modeling when the properties of the medium are not changed, when such parameters as the cohesion force between the components of waste, the angles of external and internal friction between the components of waste, and the shear forces of elastic and plastic zones of the crushing process are the same.

Under these conditions, the criterion dependencies obtained by analyzing the dimensions are particularly interesting. The criterion equation has the following form:

$$\frac{Q}{F_l D^{0.5} g^{0.5}} = \varphi(\frac{d_{av}n^2}{g}, \alpha, \frac{N}{\delta D^{3.5} g^{0.5}}, \frac{d_{av}}{D}) \tag{18}$$

Development of scaled equations for crushing organic components of municipal solid waste.

To find the value of the similarity indices, we should determine the ratio of the similarity feature of a life-size machine to the similarity feature of the model.

From π_1, it is possible to calculate scale dependencies

$$k_\tau = k_\gamma k_G \tag{19}$$

From π_2 $\quad k_{\tau_1} = k_{\gamma_1} k_{G_1}$ (20)

From π_3 $\quad k_\tau = k_{\tau_{pl}}$ (21)

From π_4 $\quad k_c = k_\gamma k_l = k_\gamma k_D$ (22)

From π_5 $\quad k_{tg\rho} = 1$ (23)

From π_6 $\quad k_c = k_\tau$ (24)

From π_7 $\quad k_P = k_\tau k_l^2 = k_\tau k_D^2$ (25)

From π_8 $\quad k_N = k_P k_\vartheta$ (26)

From π_9 $\quad k_\vartheta = \sqrt{k_g k_l} = \sqrt{k_g k_D}$ (27)

From π_{10} $\quad k_Q = k_D^{2.5}\sqrt{k_g}$ (28)

From π_{11} $\quad k_n = \sqrt{\frac{k_g}{k_D}}$ (29)

From π_{12} $\quad k_{d_{av}} = k_D$ (30)

From π_{13} $\quad k_N = k_\delta k_D^{3.5}\sqrt{k_g}$ (31)

From π_{14} $\quad k_\alpha = 1$ (32)

From π_{15} $\quad k_{F_l} = k_D^2$ (33)

From π_{16} $\quad k_{l_m} = k_D$ (34)

From π_{17} $\quad k_Q = k_{F_l} k_D^{0.5} k_g^{0.5}$ (35)

From π_{18} $\quad k_n = \sqrt{\frac{k_g}{k_{d_{av}}}}$ (36)

From π_{19} $\quad k_N = k_Q k_D k_\delta$ (37)

From π_{20} $\quad k_{l_m} = k_{d_{av}}$ (38)

From scaled equations (23), (25), (26), and (28)
for $k_\gamma = 1$ and $k_{\gamma_1} = 1$, it follows that

$$k_\tau = k_{\tau_{pl}} = k_C = k_G = k_D \text{ and } k_{\tau_1} = k_{G_1} \tag{39}$$

From scaled equations (23) and (32)

$$k_{tg\rho} = k_\alpha = 1, \tag{40}$$

Since the experiments were conducted on the ground, k_g=1, it follows from (23) that

$$k_\vartheta = \sqrt{k_D} \tag{41}$$

Therefore, the scale of forces of resistance to grinding from (29) is

$$k_P = k_D^3\,, \tag{42}$$

The performance scale from (28) is

$$k_Q = k_D^{2.5}, \tag{43}$$

The scale of rotor shaft speed from (33) is

$$k_n = \frac{1}{\sqrt{k_D}}\,, \tag{44}$$

The scale of linear dimensions from (34) is

$$k_{d_{av}} = k_D, \tag{45}$$

The power scale from (37) is

$$k_N = k_D^{3.5}, \tag{46}$$

The scale of the area of the grate from (29) is

$$k_{F_l} = k_D^2, \tag{47}$$

The performance scale from (31) is

$$k_Q = k_{F_l} k_D^{0.5} = k_D^{2.5} \tag{48}$$

The speed scale from (32) is

$$k_n = \sqrt{\frac{1}{k_{d_{av}}}} = \sqrt{\frac{1}{k_D}} \tag{49}$$

The power scale from (33) is

$$k_N = k_Q k_D = k_D^{3.5} \tag{50}$$

The scale of the linear size of the hammer from (34) is

$$k_{l_m} = k_{d_{av}} = k_D \tag{51}$$

Determination of the crusher model parameters used for crushing organic waste components.

We determine the dimensional values of the parameters for the model. If the indices of similarity of volumetric weight for the original and the model are equal, the volumetric weights of waste must be similar to each other

$$\gamma_m = \gamma_n \tag{52}$$

The compound of waste components is determined by formula (39)

$$c_m = \frac{C_n}{K_D} \tag{53}$$

The coefficient of internal friction with the M.S.W. components is determined based on (40)

$$tg\rho_m = tg\rho_n \tag{54}$$

The stress in the M.S.W. medium in front of the working body τ_m (a determined value) is found by formula (38)

$$\tau_m = \frac{\tau_n}{k_D} \tag{55}$$

Grinding resistance forces are determined based on (46)

$$P_n = \frac{P_m}{k_D^3}, \tag{56}$$

Crusher capacity is determined based on (39)

$$Q_m = \frac{Q_n}{k_D^{2.5}}, \tag{57}$$

Crusher rotor shaft speed is determined based on (44)

$$n_m = n_n k_D^{0.5}, \tag{58}$$

Based on formula (45), we determine the linear dimensions of the crushing machine

$$l_{m_m} = l_{m_n}/k_D, \tag{59}$$

The power value for model drive is determined based on (46)

$$N_m = \frac{N_{\text{H}}}{k_D^{3.5}}, \tag{60}$$

In formulas (51)-(60), k_D is the set value determined by the simulation scale.

Formulas for determining the expected parameters of the original according to the parameters measured on the model.

Following the inverse relationships, formulas for the transition from the model to the original are established to determine the parameters of the crusher model.

The strength properties of the original medium, during operation in which the working bodies of the machine are subjected to the loads predicted in modeling, are determined by the following formulas:

The relationship between waste components is

$$c_n = c_m k_D \tag{61}$$

the specific gravity of waste components is

$$\gamma_n = \gamma_m \tag{62}$$

friction characteristic (external and internal friction) is

$$tg\rho_n = tg\rho_m \tag{63}$$

shear stresses arising in the mass of waste components in front of the working body of the fill-size machine are:

$$\tau_n = \tau_m k_D \tag{64}$$

loads acting on the hammers of full-size crushing machines are:

$$P_n = P_m k_D^3 \tag{65}$$

Full-size crusher performance is:

$$Q_n = Q_m k_D^{2.5} \tag{66}$$

The rotor shaft speed of the full-size crusher is:

$$n_n = \frac{n_m}{k_D^{0.5}} \tag{67}$$

Linear dimensions of the full-size crusher are:

$$l_{m_n} = l_{m_m} k_D \tag{68}$$

The drive power of the original is:

$$N_n = N_m k_D^{3.5} \tag{69}$$

The results obtained in were used to select a linear scale.

In the above study, the scale factor of the physical model is substantiated; its value depends on two aspects:

- on the properties of waste (composition and structure; the composition of waste depending on the structure; volume density, humidity, compression properties, etc.);
- on the accuracy of the measuring equipment.

Calculations conducted based on the developed methodology and limitations related to the properties of the medium made it possible to determine the value of $k_D = 2.5$. For the original, a single-rotor hammer crusher SMD-112 was chosen.

5 DISCUSSION

Analytical determination of the maximum value of the contact force and the impact speed of the waste components made it possible to determine the dependence of the contact force on the main parameters of the collision process and this, in turn, made it possible to optimize the value of the contact force. The value of which makes it possible to select the optimal values of the main parameters of the crusher, providing a minimum of energy intensity at a constant value of productivity.

The developed algorithm for the physical modeling of the solid waste grinding process made it possible to consistently determine the process similarity criteria, starting with criteria representing unambiguous relationships between stresses. In addition, dependencies were identified that determine the energy and power characteristics of the process.

A comprehensive study of the grinding process made it possible to obtain a full range of criteria characterizing all stages of solid waste grinding.

The results of a comparative analysis of the list of criteria obtained based on the laws of mechanics and rheological models with similarity criteria obtained by dimensional analysis showed that these methods, when used correctly, complement each other on the one hand, and on the other hand make it possible to concentrate efforts on more important criteria.

6 CONCLUSIONS

1. The developed block diagram of the method of physical modeling of the process of crushing organic components made it possible: first, to cover the entire range of tasks performed according to the scheme in strict sequence; second, to determine the entire set of similarity criteria that fully describe the crushing process with the least material and time costs.
2. The rheological equivalent of the process of crushing the organic components of MSW, completes the entire system of criteria that describe the crushing process.
3. Dependencies (64)-(69) made it possible to calculate the power and energy parameters of a full-scale crusher based on the results obtained on the models.

7 LIMITATIONS

The significant heterogeneity of the composition of waste and the variability of its properties do not allow the development of clear mathematical models describing the process of their grinding. These limitations did not allow us to use the method of integral analogues when developing a physical modeling method (the derivation of similarity criteria is carried out through the use of a system of differential equations describing the waste grinding process).

In this regard, we used the method of dimensional analysis when developing a system of similarity criteria. The disadvantage of this method is that in the absence of a sufficient amount of primary information or the lack of necessary experience of the researcher, some parameters and indicators may not be taken into account when drawing up the criterion equation. This in turn can affect the efficiency of the crushing machine.

Further research in this direction can be developed through experimental studies. The use of waste samples of various compositions for their grinding will allow us to outline research directions.

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Paper submitted: 07.01.2024.

Paper accepted: 12.04.2024.