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SELECTED RESULTS OF STUDIES OF BRIQUETTING PROCESS OF FINE-GRAINED MATERIALS IN ROLL PRESS BRIQUETTERS

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Abstract

In the present paper a general outline of methods for consolidation and compaction of fine-grained materials is presented, with a particular focus on the compaction method in roll presses. The state of the art of the theory of the compaction of fine-grained materials in roll press briquetters is evaluated.

A modified, mathematical model is described, based on investigations of the compaction process of fine-grained materials in roll press.

Experimental results of the investigation of the variability of external friction during the briquetting process are also presented in this paper.

For selected materials a process of compaction in a roll press was computer-modelled with the aid of a program based on the above mentioned mathematical model in which experimental results on variability of the external friction were incorporated.

Computer-modelled results have been used to formulate the criteria for the design and construction of roll press briquetters.

Introduction

Existing techniques for the mining, enrichment and processing of raw materials generate large quantities of fine-grained waste of various

kinds, e.g.: fines and subsieve of excavated material, dusts, sludge, chips, etc. For economic purposes, it is necessary to rationalise the majority of that waste by consolidating it into a lump form before processing.
Equally, numerous modern techniques used for the processing of raw materials involve crushing and grinding operations in order to obtain adequate shape, size and size distribution of material particles, followed by consolidation and compaction operations necessary for further treatment, e.g.: ores and metal concentrates, metal powders, and ceramic materials. There are three basic methods of consolidations of fine-grained materials:

- sintering (agglomeration),
- pelletising (cumulative consolidation), and
- compaction and pressing (briquetting) [1-4].

Economically, the cheapest method of consolidation of fine-grain materials is sintering. For this reason it has found wide application, especially in metallurgy. However, there are some exceptions when the sintering process cannot be used. This is the case with coal and carbonaceous materials, materials difficult to sinter, and those materials which change their chemical composition when heated; thus making the smelting process difficult or impossible to carry out in the way required. Polish copper ore is another example of this kind of material, due to a low content of sulphur and high content of bitumen matter.
In such and similar cases, it is only the methods of pelletisation and briquetting that can be used. Pelletisation, however, requires a high degree of pulverisation of consolidated material (particle size between 40 - 80 μm). For this process a binding agent is added and the moisture content of the material to be pelletised needs controlling at a constant level. Moreover, as a rule green pellets, require further processing like drying, heating, partial sintering, which considerably increases the complexity of the whole pelletisation process. Additionally, the size and density of granulates are relatively small and varied. Thus, the only way of consolidating fine-grained materials, especially waste, is the method of briquetting.

The briquetting process can be carried out in various presses (briquetters), such as stamp, roll, and ring-roll presses.
Briquetting is characterised world-wide by the most dynamic development, especially when realised by means of modern roll presses.

This is due to the fact that briguetters (roll presses), as compared to others presses offer numerous advantages, most importantly low energy input (requirement) per unit of the final product, continuous operation mode, high output, and compactness of construction.

The decision undertaken in Poland, in the sixties, regarding the construction of coal fines and semi-coke briquetting plants led to an increase interest in roll press technology.

At first roll press briquetters were bought abroad. Those used later were of Polish design and construction, with emphasis focused on their output and power transmission systems. They were equipped with gravity feeders and roll press tyre pits of the semi-spherical shape. This type of press enables briquetting of fine-grained material susceptible to compaction, after an addition of a binding agent, but does not make it possible to solve the problem of briquetting materials which are difficult to compact, or allow for briquetting without the use of binding agents.

Since many industrial wastes are difficult to compact and the use of binders is often impossible, either because of technological or economical reasons, there was strong demand for developing a briquetting method which would enable the compaction of these materials without binders. As a result of this demand a complex investigation was undertaken at the Department of Technological Equipment and Environmental Protection (formerly Institute of Metallurgical Machines and Automatic Control) of the University of Mining and Metallurgy in Krakow for the development of a general method of selection of roll presses and the improvement of roll press compaction system design. This resulted in the design and construction of prototypes of two roll presses, PW 500 and PW 1000. The feasibility of these presses for binderless briquetting of materials "difficult to compact" such as brown coal, calcium fluoride quicklime, and glass fibre concentrates, were demonstrated on pilot-scale.

It is worth noting that this should contribute to solving the problem of fine-grained industrial waste, which is critical in Poland, whilst at the same time new opportunities were created for many Polish plants to change the production profile, and/or to rationalise the use of fine-grained technological waste.

In the present paper, the results of both conceptual and the utilitarian research contributing to modern roll press design are presented. Some trends in further research, part of which is now in progress, have also been addressed.

Theoretical problems of fine materials compaction

In practice, two kinds of granular media are distinguished:

- cohesion media, for example natural soil, and
- cohesionless media, for example those prepared for compaction such as porous, powdered materials.

Although granular in structure, from the point of view of it strength characteristics natural soil is considered to be a continuous medium with the strength model of elastic-plastic body. However, in practice, it is difficult to make allowance for strain-stress dependence, so for the sake of simplicity, natural soil is treated as a rigid-plastic body.

Conversely, cohensionless, powdered, porous materials undergo compaction during loading, which causes changes in physical properties of these materials. This makes it impossible to treat them as continuous media. As a consequence, the application of continuous media mechanics in the modeling of compaction process of porous, powdered materials (henceforeward fine-grained materials) should not be used indiscriminately. This accounts for some of the deficiencies of the compaction models, especially where roll presses are concerned.

Such shortcomings inspired the author to look for a more exact mathematical description of the real physical situation.

Modelling of fine-grained material compaction process in roll presses

The most commonly used model of fine-grained material briquetting process was developed by Johanson [5] whose theoretical work contains many simplifications. His model is based on his own empirical formula, the so-called the compaction equation. Like many other formulae of that type, it describes briquetting of fine-grained materials in a closed die. Variation in the properties of the material to be briquetted was presented by a constant. Moreover, the manner in which briquetting was replaced by compaction of bulk material between smooth rolls remained controversial, as it was assumed that the width of a compacted band in an equivalent system of fine-grained material was the same as the mean height of the briquette. This means that the existence of the spaces separating the pits within the working area of roll press tyres was omitted from the model.

The shortcomings of Johanson's model inspired the search for a more exact mathematical description of the briquetting process in roll press. Same sources [6,7] suggest that for the case in question, mathematical models of rolling of continuous media can successfully be used. However, they do not show how to solve many of the problems resulting from the substantial differences between the rolling of continuous media and the briquetting of fine-grained materials in a roll press. For this reason the present author has attempted to formulate a new mathematical model of briquetting of fine-grained materials in a roll press with gravity feeding.[1,2,8-11]

The model, developed on the basis of the so-called slab method, and on the theory of rolling of metal powders, is deterministic in character. In theoretical considerations, the briquetting of a fine-grained material was replaced by its compaction between smooth rolls with the diameter, R_0, in an equivalent compaction system. This is schematically presented in Fig. 1.

In this case, the mathematical model gives the following set of equations and empirical formulae:

$$R_0 = \sqrt{R^2 - \frac{kV_b}{2\pi B}} \tag{1}$$

$$\frac{dp_y}{dh_y} + p_y \frac{\mu ctg(\alpha_0/2)}{h_y} = \frac{\vartheta}{h_y} + \frac{d\vartheta}{dh_y} \tag{2}$$

$$\vartheta = Cs^D w^E \tag{3}$$

$$\mu = f(s,w) \tag{4}$$

$$p_y = p_{max}\left[1 - \left(\frac{\beta_y}{\beta}\right)^2\right] \tag{5}$$

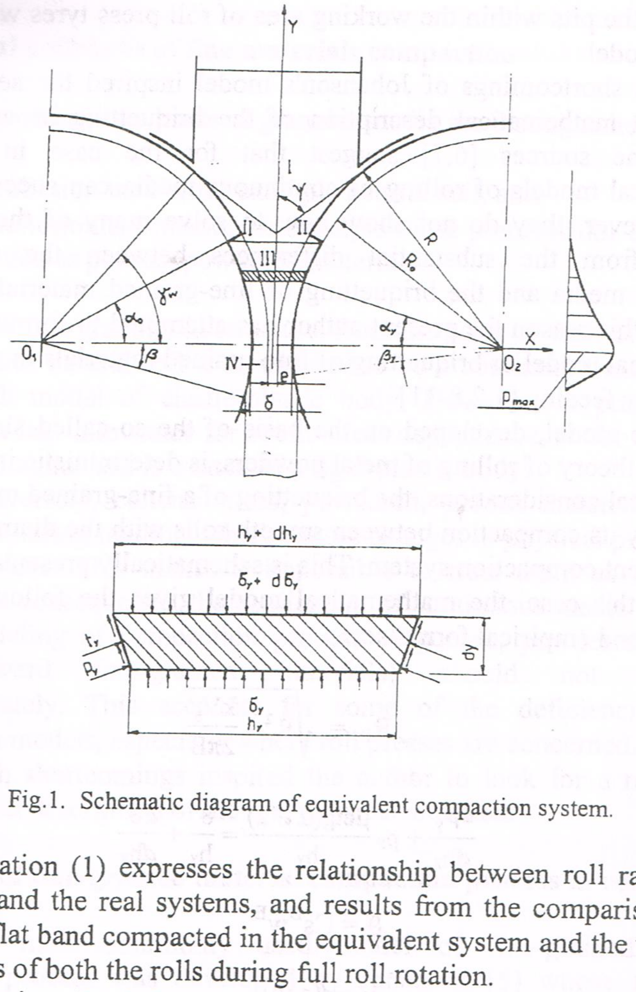


Fig.1. Schematic diagram of equivalent compaction system.

Equation (1) expresses the relationship between roll radii in the equivalent and the real systems, and results from the comparison of the volume of flat band compacted in the equivalent system and the volume of forming pits of both the rolls during full roll rotation.

Equation (2) defines the relationship between the unit pressure, which is exerted on the compacted material within the central part of the forming pit, the geometry of the equivalent compaction system and the properties of briquetted material.

Equation (2) was developed on the basis of the condition of balance of forces acting on the isolated element of briquetted material of the volume limited by the surfaces of the rolls and by two planes perpendicular to the direction of the material flow and separated from each others by infinitesimal distance, dv. In this equation Coulomb's model of the friction

($t_y = \mu p_y$) and condition of plasticity ($p_y - \sigma_y = \vartheta$) were applied, and for the sake of simplicity, the nip of the roll arc was replaced by its chord.

Empirical formula (3) represents the variation of the equivalent of yield stress in the process of compaction, named here unit compaction resistance. The unit compaction resistance is a variable, which is dependent upon the compaction ratio and the moisture content within the compacted medium. It represents the amount of unit pressure necessary to achieve a known compaction ratio of material to be consolidated in a closed cylindrical die, with a maximum limited value of friction, comparable volumes of briquettes, and with comparable ratios of height-to-cross section of briquettes.

Variation in the external friction during the briquetting process is represented by general function, Eq.(4), whose form depends upon the varying properties of the medium to be compacted. This will be discussed in the next section.

Equation (5) allows for the determination of variation of unit pressure during the expansion of briquettes. This equation has a form based on the experimental results for various kinds of fine-grained materials. It is expected that in the future it will be replaced with the deductive formula.

Testing variation in external friction during briquetting

So far all modelling work done on the compaction of fine-grained materials in roll and stamp presses have been based upon the assumption that the coefficient of external friction has a constant value. This is not in conformity with the real physical state which is one of the causes for discrepancy between theory and practice. To eliminate this, an investigation on variation in external friction during briquetting was undertaken [12-14]. Namely, the goal of that study was to determine the qualitative and quantitative character of variations in static and kinetic external friction coefficients for selected systems: steel - selected fine-grained materials under compaction.

The following fine-grained materials were selected for investigation:

- technological waste from a rolling bearing factory,
- brown coal fines,
- deposits of iron-bearing sludge,
- calcium fluoride.

Experimental work was carried out on universal, purpose-built laboratory rig STZ-1 M, shown schematically in Fig. 2.

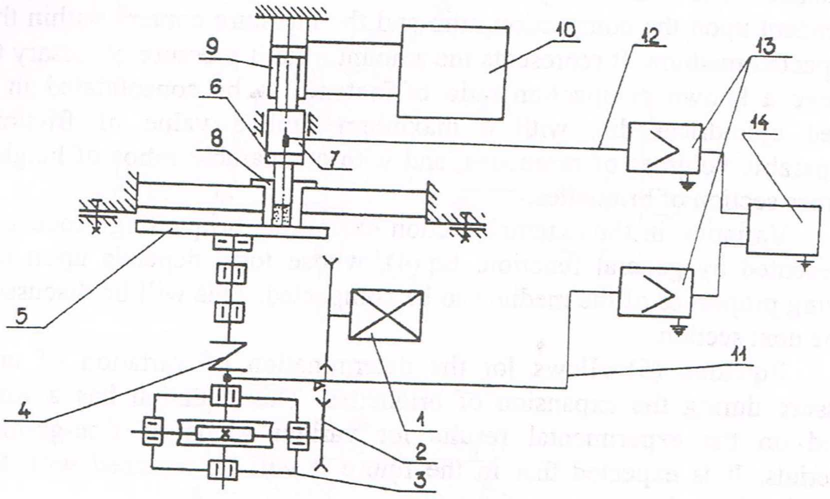


Fig. 2. Schematic diagram of STZ-1 M laboratory rig. 1-DC motor, 2-belt, 3-worm gear, 4-flexible clutch, steel plate, 6-punch, 7-leading punch, 8-die, 9-hydraulic servo-motor, 10-hydraulic system, 11-torque measuring path, 12-pressure force measuring path, 13-strain gauge amplifier, 14-recorder.

The rig consists of the counter-specimen supporting steel plate /5/ driven via belt /2/ and worm gears /3/ by a DC motor /1/. The die /8/ and the punch /6/ are used to compact fine-grained materials. Selected load is applied by a hydraulic servo-motor /9/.

The rig provides three measuring paths, two of which are shown on Fig. 2. The third measuring path is arranged when the steel plate /5/ is stopped, the leading punch /7/ is dismantled and the die /8/ is lifted up. This enables a load transducer to be placed under the die in order to measure a real load on the surface of contact: specimen - counter-specimen. All experiments were carried out in conditions similar to a real physical situation.

During the investigation, the range of variation in unit pressure of 18-136 MPa was assumed to conform to the conditions of commercial briquetting in roll presses.

The assumed relative speed of the steel plate against a specimen of compacted material was 0.02 m/s. A ring made with the thermally treated NC4 steel of the hardness of 55 HRC was used as the counter-specimen.

Specimens of fine-grained materials compacted in a closed die have a cylinder shape with 20 mm diameter. Their volumes were experimentally selected to achieve the height-to-diameter ratio of 2/3 for the highest degree of compaction.

As an example the qualitative and quantitative character of variations in the coefficient of kinetic external friction for a set of wearing pairs: steel – selected fine-grained materials with given content of moisture are shown in Fig. 3 - 4.

As can be seen from Fig. 3 - 4, in the case of technological waste from the rolling bearing factory and brown coal fines the coefficients of kinetic and static external friction decrease with the unit load increase. In the pressure range of 30 - 100 MPa a slight variation is observed in the coefficients of friction while compacting deposits of iron-bearing sludge. However, the opposite was observed for calcium fluoride, whereby the coefficients of static and kinetic friction were found to increase with increase in the unit load. This means that calcium fluoride represents a group of materials difficult for briquetting.

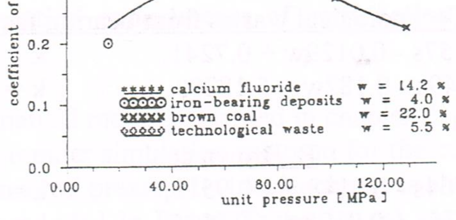


Fig. 3. Relationship between coefficient of static external friction and unit pressure during compaction of selected fine-grained materials.

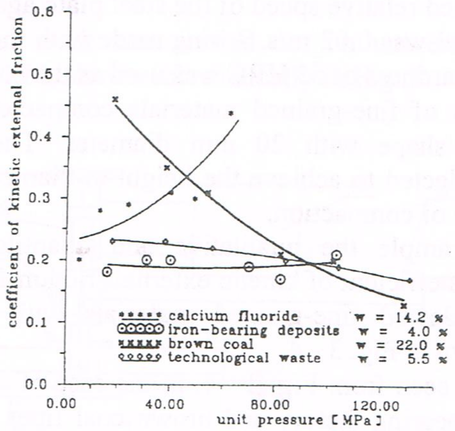


Fig. 4. Relationship between coefficient of kinetic external friction and unit pressure during compaction of selected fine-grained materials.

On the basis of these results an attempt was made to generalise the problem of variation in friction coefficient in briquetting. This was done by expressing the unit load in terms of the degree of compaction of fine-grained materials and by taking into account the moisture as a second independent variable.

As a result of regression analyses it was found that there is no single general empirical formula to describe the relationship between friction coefficient and the independent variables. Specific regression formulae for materials under investigation are presented below.

A. Technological wastes from bearing factory.

$$m_{st} = -0.1157s - 0.0129w + 0.7241, \qquad k = 0.521 \qquad (6)$$

$$m_k = -0.9949s - 0.182w + 5.1829, \qquad k = 0.840 \qquad (7)$$

B. Brown coal.

$$m_{st} = -0.5764s - 0.0148w + 0.9518, \qquad k = 0.927 \qquad (8)$$

$$m_k = -0.6535s + 0.0198w + 0.8938, \qquad k = 0.953 \qquad (9)$$

C. Deposits of iron-bearing sludge.

$$m_{st} = e^{45.0453s + 0.3554w - 14.0380s^2 - 0.0315w^2}, \qquad k = 0.840 \qquad (10)$$

$$m_k = e^{8.4635s + 0.0476w - 2.7307s^2 - 0.0028w^2}, \qquad k = 0.768 \qquad (11)$$

D. Calcium fluoride.

$$m_{st} = e^{5.4394s + 0.1708w - 1.5208s^2}, \qquad k = 0.819 \qquad (12)$$

$$m_k = e^{-6.1925s + 0.8663w + 2.0558s^2 - 0.0299w^2}, \qquad k = 0.769 \qquad (13)$$

where:

m_{st}	- coefficient of static external friction,
m_k	- coefficient of kinetic external friction,
s	- compaction ratio of fine-grained material,
w	- moisture content of fine-grained material,
k	- correlation coefficient.

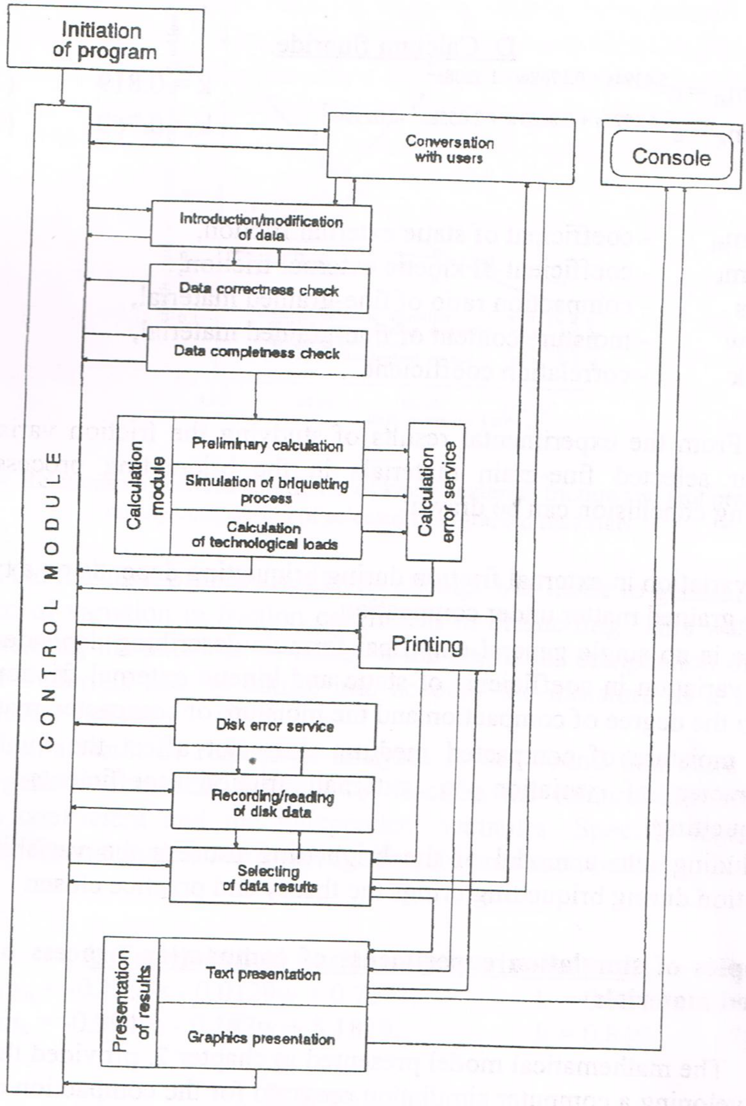
From the experimental results of studying the friction variability for four selected fine-grain materials in the briquetting process, the following conclusion can be drawn:

- the variation in external friction during briquetting depends on a type of fine-grained matter under compaction,
- there is no single general empirical formula describing dependence of the variation in coefficients of static and kinetic external friction with both the degree of compaction and the moisture of compacted material,
- the moisture of compacted medium does not affect the qualitative character of variation in external friction coefficients during briquetting,
- including into a model of the briquetting process the variability of friction during briquetting brings the theory and practice closer.

Examples of simulation experiments of compaction process of fine-grained materials

The mathematical model presented in chapter 2. provided the basis for developing a computer simulation program for the compaction of fine-grained materials in a roll presses. Its block scheme is shown on Fig. 5. The program was encoded in Pascal-Turbo Pascal V4 language dialect, and was run on IBM compatible microcomputer.

The computer program and the special forms of the necessary empirical formulae Eqs.(6) - (13) were used in the present study to



simulate the process of compaction of selected fine-grained materials [3-5,16,17]. The computation results gave some information about the compatibility of these materials and, enabled the prediction of appropriate roll presses. This in turn made it possible to develop the concept of the technological process itself [17-19].

Examples of several computations are presented below. Computed changes of unit pressure during briquetting in a roll press of the fine brown coal fraction of various moisture levels are shown in Fig6. In this case, roll diameter d = 1000 mm and gap width between the rolls, e = 1,5 mm were assumed.

In turn, Fig. 7 shows the effect of gap width between the rolls on the change of unit pressure during briquetting of brown coal of assumed moisture w = 24% [16].

Fig.5. Block scheme of computer program for the process of compaction of fine-grained material in roll press.

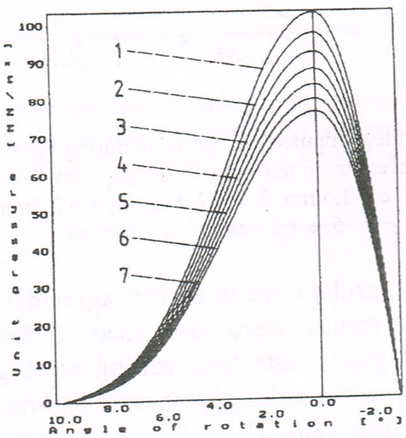


Fig. 6. Dependence of the computed unit pressure during brown coal briquetting in the PW 1000 roll press upon assumed moisture content "w" of brown coal. 1. w = 23.5%, 2. w = 24.0%, 3. w = 24.5%, 4. w = 25.0%, 6. w = 26.0%, 7. w = 26.5%

In both cases, a significant effect of the selected variables on maximum value of the unit pressure was noted. This means that these variables are of crucial importance for the process of briquetting. The computed optimum values of the moisture content and the gap width were tested in industrial conditions.

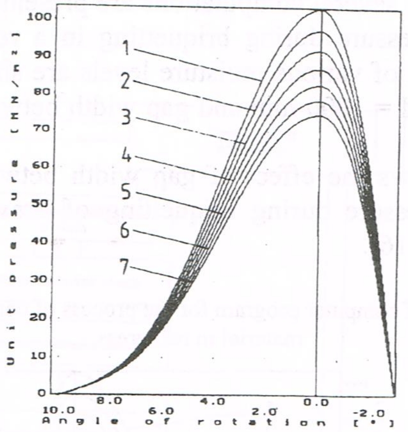


Fig. 7. Dependence of the computed unit pressure during brown coal briquetting in the PW 1000 roll press upon the value of the gap between the rollers, "e".
1. e = 1.0mm, 2. e = 1.5mm, 3. e = 2.0mm, 4. e = 2.5mm, 5. e = 3.0mm, 6. e = 3.5mm, 7. e = 4.0mm.

Industrial test results were in perfect agreement with the computed data. The computed results were also used to solve the problem of utilisation of technological waste from rolling bearing factory. A concept of waste management was developed, which used briquetting and smelting of waste in a blast furnace [20-22].

Figure 8 shows the computation results on the basis of which the adequate volume of briquettes to be produced was chosen. Roll diameter d = 360 mm. and the most advantageous moisture of material w = 6 per cent were assumed. Due to relatively low maximum value of unit pressure it was decided to choose low volume briquettes of 5 cm^3. To check the effect of nip angle value, the computation was repeated with nip angle higher by 7%. This resulted in 18% increase in maximum value of unit pressure, as, shown in Fig. 9. Presently work is in progress on designing a special briquetting machine where these computation data will be tested.

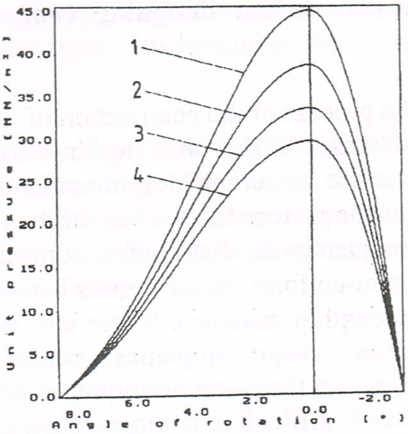


Fig. 8. Dependence of the unit pressure upon briquette volume, V, during briquetting wastes from bearing factory in roll press PW 360 (under construction), with nip angle $\alpha_0 = 8.6°$. 1. $V = 4.5\ cm^3$, 2. $V = 5.0\ cm^3$, 3. $V = 5.5\ cm^3$, 4. $V = 6.0\ cm^3$.

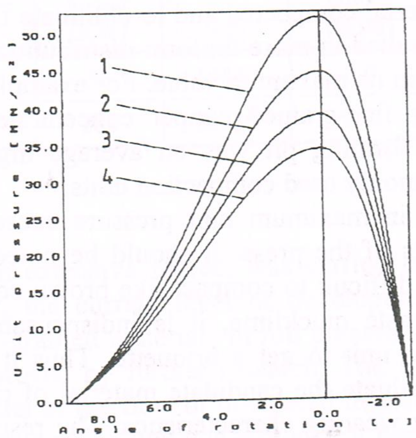


Fig. 9. Dependence of the unit pressure upon briquette volume, V, during briquetting wastes from bearing factory in roll press PW 360 (under construction), with nip angle $\alpha_0 = 9.2°$. 1. $V = 4.5\ cm^3$, 2. $V = 5.0\ cm^3$, 3. $V = 5.5\ cm^3$, 4. $V = 6.0\ cm^3$.

Research into improvement in designing compaction unit in roll presses

Analysis of the process of the compaction of fine-grained materials in pits of roll press tyres revealed that two half-forms situated on the opposite sides of rolls are not completely closed during the briquetting stage. This means that the material flows out, in the direction opposite to roll rotation, and consequently the distribution of pressure on the area of a forming pit becomes non-uniform, which results in non-uniform density of briquettes and poor strength parameters. It was also noted that in the case of the so-called "drop" shape briquettes, which is very common, destruction stress appears on the plane of briquettes division. This stress is specially high in materials difficult to compact, such as brown coal, which shows a high springback after briquetting.[1,2] All these shortcomings of the old system of compaction unit provided an impulse to find a better solution, which ended successfully. A new project of the compaction unit of roll press [23] made it possible to limit, under laboratory conditions, the out-flow of the material compacted and to eliminate the division plane in briquetting. This resulted in more uniform distribution of pressure, with a significant increase in its maximum value. For example, during laboratory tests on briquetting fine-grained copper concentrate this value in the central part of the forming pit was on average higher by 80% when compared with commonly used compaction units.

An increase in maximum unit pressure causes a shorter life of compaction elements of the press. It should be noted however, that for materials which are difficult to compact like brown coal, zinc-lead oxide, ferric oxide, and waste quicklime, it is indispensable to use a newly designed compaction unit to get a briquette. Thus it is crucial in these cases to properly evaluate the candidate material of construction for roll press tyres with low wearing characteristics. The results of this research were published elsewhere [1-2,15,24].

The new compaction unit was tested on an industrial scale: it operated in the Legnica Copper Metallurgical Plant and in the Briquetting Plant of Konin Brown Coal Mine. The results obtained in both plants confirmed the laboratory results. Moreover, other advantages of the new compaction system were noticed:

- simpler construction and assembly of roll press tyres,
- longer duration, or total elimination of wearing-in, of new rings,

- possible significant simplification in power transmission system of the press, in which the parts synchronising the rotation of rolls can be eliminated.

Prototypes of the roll presses PW 500 and PW 1000 were equipped with these new compaction unit. The presses were successfully tested in industrial conditions and can be used to briquette materials of various levels of compatibility. Selected technical characteristics of these briquetters are shown in Table 1.

Table 1. Selected technical characteristic of roll presses constructed in the Department of Technological Equipment and Environmental Protection.

Roll press	Roll diameter [mm]	Driving power [KW]	Mass [kg]	Volumetric output [m3/h]	Overall dimension [mm]
PW 500	500	55	10440	3.0	4450x2650x2320
PW 1000	1000	200	90530	12.5	8400x4200x3640

Conclusions

Although an extensive project was carried out at the conceptual stage of the study, the current level of development of the theory of compaction of fine-grained materials in roll presses is still unsatisfactory, and should be improved by further research. The first step would be to develop both a model of the flow of powdered material through the screw type feeding and compacting unit and a model of phenomena occurring in the zone confined by side surfaces of equivalent working rolls. This should result in a qualitative and quantitative formulation of the effect of geometric feature of screw feeders and of the properties of compacted material on unit pressure in the briquetting process. This formulation will facilitate, first of all, the improvement in the design of screw feeder. It is expected that at a further stage the simplification can be abandoned, with no need to briquetting of bulk media with compaction between smooth rolls. This means that for the first time in theoretical considerations a real compaction system will be taken into account, which should result in a mathematical model that describes the mechanism of briquettes formation in an open die. Such a model will allow for the determination of unit pressure distribution on the forming side of the rolls, which in turn will result in the selection of optimum shape of cavities. It is also expected that it will be possible to arrive at higher conformity between theory and practice as far as calculations of technological loads in compaction system are concerned. In modelling the process of briquetting powdered materials in an open die it is planned to include different ways of feeding and precompaction.

As the design, the construction and the operation of roll presses is very complex, it is crucial to approach in systematic way this problem. A general method of selection of roll presses for compaction of fine-grained materials, including waste materials is under development[3]. The method will provide a tool for selection of the most advantageous roll press out of the set of available machines, for modernisation of such a press, or for an evaluation of the criteria to design a new machine. The results of conceptual research obtained so far were implemented and/or used in practice. Compaction units in industrial roll presses were improved by using a new shape of briquettes and screw feeders. Prototypes of two modern roll presses, which conform to world standards, were designed and constructed. They were equipped with compaction units designed on the basis of laboratory results.

To summarise the paper, it should be noted that only the most important lines in research into the roll press construction have been addressed. Details can be found in an extensive bibliography.

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Notation

R_o- roll radius in the equivalent compaction system,

R- real roll radius,

k- number of forming pits in roll press tyres,

V_b- briquette volume,

B- roll width in real compactionsystem,

p_y - unit pressure,

p_{max}- maximum unit pressure value,

h_y - distance between rolls at d_y,

μ - coefficient of external friction,

α_o - nip angle,

α_y - compaction angle,

ϑ- unit compaction resistance,

s – c ompaction ratio of material,

w - density of briquetting material,

C,D,E- coefficients of regression equation,

β_y - unstressing angle,

β- angle defining a zone of elastic expansion of briquette,

γ_w - charge angle,

ψ- inclination angle of material layer,

δ - gap between the rollers in equivalent system,

e - gap between the real rollers,

t_y - unit force of friction,

σ_y - normal stress,

I - charge zone,

II - feeding zone,

III- compaction zone,

IV- expansion zone