Improving the use of wood waste

D.A. Ilyushenko[1], *V.A.* Markov[1], *V.A.* Sokolova[1,*], and *V.A.* Kalyashov[2]

[1]Saint Petersburg State Forest Technical University named after S.M. Kirov, Russia
[2]Saint Petersburg State University of Architecture and Civil Engineering, Russia

Abstract. On the territory of our country, including St. Petersburg and the Leningrad Region, there are a large number of enterprises engaged in the processing of wood for various purposes, among which, to a large extent, there are enterprises involved in the primary processing of wood in sawmills. The resulting wood waste from bark and sawdust, in most enterprises, lead to rotting processes. The issue of the utilization of these wastes in practice can increase the production culture, increase the amount of recyclable waste from a timber processing enterprise and, thus, increase its efficiency. The article describes a mathematical model for the dynamic compaction of ground wood bark with the aim of producing fuel briquettes of their debarking waste.

The solution to the issue of the integrated use of forest resources involves the widespread processing of numerous types of logging production waste, including wood bark [1, 2]. Given the current wood debarking conditions in the forest and pulp and paper industry of our country, the recyclable bark resources amount to over 6 mln m^3 [3]. However, the share of its industrial use is currently insignificant [4].

One of the main ways to utilize logging and wood processing waste is generating energy, where the calorific value and thermal decomposition products are of primary importance; however, for several reasons, the direct use of such waste as fuel is complicated [5, 6, 7].

It is known [8, 9, 10] that to effectively use the wood raw materials, sawdust, chips, bark, and other waste can be briquetted. The wood waste briquettes may also be used as household and industrial fuel free of drawbacks inherent in loose wood waste. Arranging the production of such briquettes is a potential source of profit for a wood processing enterprise [11]. But herewith, the fuel briquette production process has not been sufficiently studied.

The experience of various industries has shown [12, 13] that the use of dynamic loads, i.e., the impact force is an effective technique of compacting loose materials. Dynamic loads increase the packing density and homogeneity of the finished products and decrease the effective coefficient of friction between the material particles and the surrounding surfaces, which significantly reduces the forces required and leads to a decrease in the press equipment dimensions and manufacturing complexity, as well as reduces its cost compared to static pressing [14].

The solution to the issue of the integrated use of forest resources involves the widespread processing of numerous types of logging production waste, including sawdust and bark. The effective use of wood waste is among the most important issues of the integrated processing

* Corresponding author. sokolova_vika@inbox.ru

of wood raw materials in the national economy. Along with economic problems, the use (utilization) of wood waste small fractions and bark also affects profound ecological issues – environmental protection. The social aspect of utilizing wood waste is that their processing technologies have significant potential for creating new jobs.

Many scientists have studied the issue of effective use of wood waste small fraction, including N.A. Modin, V.V. Nikishov, V.I. Patiakin, A.N. Eroshkin et al. However, as practice shows, this issue has not been completely resolved.

Ways of utilizing waste largely depend on the science and technology development level, and the type and concentration of waste. Herewith, sawdust and chips can be used as fillers in construction when manufacturing various building structures (xylolite, wood concrete, fiberboard, sawdust concrete, wood concrete, and cement-bonded particle boards), piezo-thermoplastics, and whole-pressed products [15, 16, 17, 18]. They are used as raw materials in chemical (e.g., to obtain tannins) and energy-chemical wood processing. However, arranging the listed processes at sawmills and woodworking enterprises is not always possible and expedient, which is especially relevant for small and medium enterprises due to the high cost of the necessary equipment and certain requirements for the qualification of staff [19].

Wood bark as part of biomass may be used in various production fields. However, in most cases, its use is limited to avoid the deterioration of the product quality and technical and economic indices of the enterprise. In particular, this applies to the production of soft and hard fiberboard, where the bark component should not exceed 30 and 15-20 %, respectively. Bark may only be used in the inner layer of particleboard. When manufacturing particleboard and fiberboard, the bark content in wood raw materials should be limited to 15–20 % that has been noted in [20].

According to [21], the mass content of bark (as a percentage of the wood volume) may reach 14 % (Table 1).

Table 1. Mass Content of Bark Depending on Wood Species

Wood Species	Bark Content, %	Bark Yield from 1 m^3 of Dense Timber, kg			Weight of 1 m3 of Oven-Dry Dense Timber, kg
		Oven-Dry	Moisture Content 55 %	Moisture Content 60 %	
Spruce	9.5	27	60	67.5	280
Pine	11.0	37	82	92	334
Larch	12.0	75	166	187	418
Aspen	14.0	60	130	150	420
Birch	13.0	58	130	146	445

Given the current wood debarking conditions in the forest and pulp and paper industry of our country, the recyclable bark resources amount to over 6 mln m^3, including about 2 mln m^3 of that formed at sawmills and woodworking enterprises. However, the share of its industrial use is 12.7 % only.

The bark is considered an undesirable impurity in wood raw materials for hydrolysis. It is directly called "... a harmful impurity, ‘barren rock’ in the hydrolysis raw materials ..." [22]. Other authors have taken the same view [23, 24, 25].

There have been attempts to use bark as raw materials to obtain a nutriculture medium by oxidizing it with atmospheric oxygen at a temperature of 200-220 °C and a pressure of 30-45 atm in a neutral environment. This technique also features the use of wastewater to wet the raw bark that reduces sewage flows and increases the yield of low-molecular substances. Further development in this direction has been a proposal to oxidize bark in alkaline conditions. The disadvantages of these techniques include the rather severe oxidation environment and reduced yield of low molecular compounds digested by yeast. In addition, it becomes necessary to use ion-exchange resins, which complicates the process and raises its cost [26].

In some papers [27, 28, 29], an attempt has been made to assess the possibility of processing bark (debarking waste) based on a systematic approach, i.e., sequential use of its various components. In this regard, when considering the most easily recoverable substances, e.g., tannins in conifers, a departmental impasse should be noted, which occurred at the time. Enterprises processing spruce saw logs did not give spruce bark in the required volume, and the wet spruce debarking waste available in large quantities at the pulp and paper plants did not meet the requirements of GOST 6663-74 in terms of the content of neither tannins nor moisture [27]. Their drying and transportation to extracting plants predetermined the unprofitability of this option.

Thus, considering the totality of information given in the literature, we can assume that the wood bark cannot take a significant place in modern chemical technologies for processing the wood biomass, since it does not contain the required amount of fibers comparable on strength and dimensional characteristics to the wood; bark contains too many labile compounds undergoing various quick transformations, whose properties are difficult to predict; it also contains too little carbohydrates to replace or supplement wood raw materials for hydrolysis, etc. To date, its only ‘advantage’ is waste bark, and it may be assumed that this waste’s cost is low at the wood raw materials processing place.

One of the main ways to utilize logging and wood processing waste is generating energy [28, 29, 30], where the calorific value and thermal decomposition products are of primary importance. Table. 2 represents data on the calorific value of various wood and bark species (for oven-dry wood).

The use of biomass as fuel is one of the few actual possibilities to reduce the greenhouse effect, since plant waste is neutral with respect to the carbon dioxide (CO_2) balance in the atmosphere, i.e., its combustion generates the same amount of this gas with that absorbed during plant growth. The use of oil, coal, and gas to generate energy leads to an increase in the CO_2 concentration in the atmosphere due to burning carbon, which has accumulated in these energy carriers for millions of years. According to the Kyoto Protocol 1997 on joint efforts to reduce greenhouse gas emissions into the atmosphere, industrialized countries should reduce such emissions by an average of 5.2 % compared to 1990. In Europe, the USA, and Japan, such a decrease should reach 8, 7, and 6 %, respectively [31].

Table 2. Calorific Value of Various Wood Species [32]

Wood Species	Calorific value, MJ/kg
Oak	20.35
Birch	20.61
Pine	21.22
Alder	20.44
Spruce	20.35
Aspen	20.02

For comparison, Table 3 provides data on the net calorific value of other fuels.

Table 3. Net Calorific Value of Some Fuels [33]

Fuel	Calorific value, MJ/kg
Brown coal	10.5-15.7
Hard coal	20.9-30.1
Peat (moisture 20 %)	15.1
Diesel	42.7

In recent years, the use of wood waste to generate energy has been considered an alternative to traditional fuels. This is because wood waste as a fuel has the below advantages:

- it is CO_2 neutral,
- it relates to renewable energy sources,
- it virtually does not contain sulfur,
- it has a low cost compared to fossil fuels,
- it has a low ash content.

However, the direct use of wood waste is difficult for the following reasons:

- small wood waste occupies large storage areas due to the low bulk density. Their transportation over considerable distances is unfeasible.
- the boiler room efficiency reduces, since sawdust blocks the flame when combusting in the furnace; only their upper layer burns, and part of the unburned fuel is discharged to the smoke flue and chimney.

Literary sources show that to effectively use wood, sawdust, chips, bark, and other waste can be briquetted. The wood waste briquettes may also be used as household and industrial fuel free of drawbacks related to loose wood waste.

Briquettes are dense pieces obtained from loose wood by compressing it with or without binders (in this case, it is believed that lignin released from wood cells under pressure and temperature acts as a natural binding element in briquetting). The briquetting technique without binders has become more widespread, since in this case, environmentally friendly briquettes are produced [34].

The quality of the briquette obtained depends on many factors, the main of which are the chemical composition, physical state, and moisture content of the material pressed, fractional composition and size of the briquetted particles, heating temperature before compressing, pressing force, and exposure time under pressure. Herewith, it should be noted that the effect of the material moisture content, fractional composition, and heating temperature on pressing has not been fully studied [9].

To properly calculate the crushed wood waste briquetting process, an adequate mathematical model is required, considering the most critical factors affecting the equipment operation and the product quality.

Many scientists have studied the compaction of whole and crushed wood, including P.N. Khukhriansky, N.A. Modin, V.I. Patiakin, S.M. Bazarov, V.I. Ogarkov, A.N. Eroshkin et al.

Most existing techniques to calculate the press equipment operating parameters recommend experimental determining the external force forming the briquette [35]. In addition, these techniques can only be used for pressing under the action of static force.

There are works devoted to the effects of dynamic loads, i.e., the impact force on solid wood. Among them, studies by P.N. Khukhriansky, B.M. Buglay, V.V. Pamfilov, V.A. Bazhenov, V.N. Bykovsky, F.P. Beliankin, V.F. Yatsenko, E.K. Ashkenazi et al. can be noted.

The work by V.V. Pamfilov [36] provides experimental data on the wood strength at high load application rates for the main forest-forming wood species in the European part of Russia.

The works by P.N. Khukhryansky [37, 38] are devoted to the contour compressing of wood under the action of impact loads. The resulting dependences related to solid wood are also unsuitable to describe the crushed wood briquetting process.

In the work by A.V. Korshak [35], briquetting sawdust on impactor press equipment has been considered. The dependencies obtained in the study are rather complicated, which makes their practical application difficult. Apart from a too narrow, in our opinion, briquette mass range (up to 50 g) in which the research has been carried out, the published data cannot be considered valid in the process under consideration due to the significant difference in the sawdust and bark stress-strain properties.

In the scientific and technical literature [39,40], quite many models have been considered that describe the phenomena occurring under the action of impact loads.

The simplest model is the collision of perfectly rigid bodies, which assumes an instantaneous impact; a change in the velocities of colliding bodies is described by Newton's hypothesis. Using this model, solutions have been obtained for some vibropercussion systems [39].

Despite this model is a convenient simplification to determine the kinematic system parameters, it does not consider the compliance of the material processed or allow defining the deformations that occur upon impact and therefore, is unsuitable to describe the briquetting process.

When determining the forces arising from a collision, the impact compliance should be considered as an effect of local deformations of bodies. To do this, solid models with local deformations have been used [40]. Along with elastic models, elastoplastic models of the impact process are also known.

There are nonlinear viscoelastic and nonlinear elastoplastic models, in which, as a rule, the nonlinear elastic dependence is based on the Hertz formula. The interaction of rigid materials, e.g., metals, has been described using such models in penetration problems [40].

The idea of replacing a deformable body with a finite number of masses interconnected by elastic, viscous, and plastic elements is of interest. The static similarity is often used, when masses are determined on the assumption that the sum of all partial masses is equal to the total mass. The elastic element stiffnesses are determined from the condition of equality to the total stiffness. E.g., when simulating a longitudinal impact on a deformable rod, it can be replaced by the scheme shown in Fig. 1.

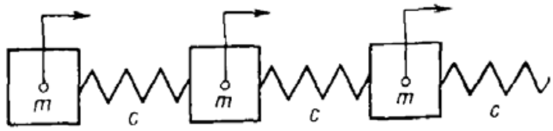

Fig. 1. A Model of a Multi-Mass System for the Case of a Longitudinal Impact on a Deformable Rod.

For the scheme considered, we have:

$$m = \frac{\rho F l}{n} \tag{1}$$

$$c = n\frac{EF}{l}, \tag{2}$$

where n is the number of elements.

Then, the total mass and stiffness are defined as follows:

$$M = nm = \rho F l \tag{3}$$

$$n\frac{1}{c} = \frac{EF}{l} \tag{4}$$

When choosing *m* and *c*, the dynamic similarity is also considered, when the masses and stiffnesses are chosen so that the first *n* eigenfrequencies of the model and medium are the same.

Such models allow determining the distribution of internal stresses in the deformable body and the impact duration. E.g., in [37], the use of a multi-mass system model allows determining the packing homogeneity of sawdust briquette according to the below scheme:

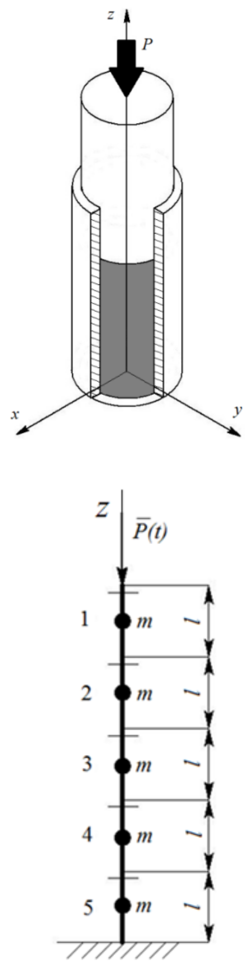

Fig. 2. The Medium Model in the Form of a Rod System

The solution of the system motion equation has been reduced to the solution of the matrix equation:

$$K\bar{v} + \Gamma\dot{\bar{v}} + m\ddot{\bar{v}} = \bar{P}(t), \tag{5}$$

where K is the system stiffness matrix, *Γ* is the dissipative matrix, *m* is the mass matrix, $\bar{P}$ is the vector of external loads, and $\bar{v}$ is the vector of generalized displacements.

The solution (1.5) is found as an expansion:

$$\bar{v}(t) = \Phi\bar{a}(t), \tag{6}$$

where Φ is some square matrix, $\bar{a}(t)$ is the vector of time-dependent coefficients.

After elementary transformations, considering (6), equation (5) is written as follows:

$$\Phi^T m\Phi\ddot{\bar{a}}(t) + \Phi^T \Gamma\Phi\dot{\bar{a}}(\mathrm{t}) + \Phi^T K\Phi a(t) = \Phi^T P(t) \tag{7}$$

and transformed as follows:

$$\ddot{\bar{a}}(t) + \Psi^T \Gamma_m \Psi\dot{\bar{a}}(\mathrm{t}) \;\; + \Psi^T K_m \Psi a(t) = b(t), \tag{8}$$

using the below notations:

$$\begin{gathered} \Psi = m^{0,5}\Phi \\ K_m = ((m^{0,5})^{-1})^T K(m^{0,5})^{-1} \\ \Gamma_m = ((m^{0,5})^{-1})^T \Gamma(m^{0,5})^{-1} \\ b(t) = \Psi^T((m^{0,5})^{-1})^T \bar{P}(t), \end{gathered} \tag{9}$$

where $m^{0,5}$ is the matrix composed of the square roots of the corresponding mass matrix elements.

As matrix Ψ, the matrix of normalized eigenvectors of matrix K_m has been chosen. Then:

$$\Psi^T K_m \Psi = \Lambda, \tag{10}$$

where Λ is the matrix of eigenvalues of matrix K_m.

The eigenmode expansion has been applied to (1.8); considering the inertial, dissipative, and elastic elements, the final system motion matrix equation is as follows:

$$\ddot{\bar{a}}(t) + \gamma p\dot{\bar{a}}(\mathrm{t}) + p^2\bar{a}(t) = \bar{b}(t) \tag{11}$$

Solution (11) is expressed in terms of the Duhamel integral using an impulsive admittance function (IAF) (13):

$$a_j(t) = \int_0^t k_j(t-\tau)b_j(\tau)d\tau \tag{12}$$

$$k_j(t) = \frac{1}{p_{1j}} e^{\frac{-\gamma p_j t}{2}} \sin(p_{1j}t), \tag{13}$$

where $p_{1j} = p_j\sqrt{1-\frac{\gamma^2}{4}}$

Using the $\bar{a}(t)$ coefficient values determined according to (1.6), the generalized displacement $\bar{v}(t)$ values have been found. Internal forces $\bar{S}(t)$ can be determined by the action of elastic forces on each system mass. In matrix form, this equation will be as follows:

$$\bar{S}(t) = L_S K\bar{v}(t), \tag{14}$$

where L_S is the matrix of the influence of internal forces built using one of the known techniques.

Thus, from the solution of equations (8) and (14), time-varying values of internal forces in any element of the model under consideration, as well as displacements of the upper section of each element under the action of an arbitrary external load can be determined.

However, it is obvious that mathematical difficulties occur when practically using such a system model, since large differential system motion equation sets should be solved.

The so-called distributed parameter model is also known [39], which allows revealing the wave nature of impact propagation. However, bringing the solution to the end causes certain mathematical difficulties, therefore, as a rule, this model is not used in practical calculations. Quite simple relations are known only for longitudinal impact with an elastic rod.

Thus, we can conclude that the stress-strain state of wood bark when exposed to impact is not adequately considered in the scientific and technical literature. There are also no comparatively simple dependencies that allow relating the impact load and the geometric parameters of the matrix with the density of the briquette formed.

References

1. Nikishov V.D. Integrated Use of Wood - M.: Forest Industry, 1985. - 264 p.
2. Mikhaylov G.M. Recyclable Material Resources of the Forest and Wood Processing Industry (Education and Use): Reference Book / ed. iss. / Mikhailov G.M. - M.: Economics, 1983, 224 p.
3. Korobov V.V., Rushnov N.P., Processing Low-Quality Wood Raw Materials (Issues of Non-Waste Technology), M.: Ecology, 1991, 288 p.
4. Veretennik D.G. The Use of Wood Bark in the National Economy, M.: Forestry, 1976, 120 p.
5. Veselov A.A. The Use of Wood Dust as a Secondary Raw Material and Fuel: Overview, M.: 1984, 56 p.
6. Wood Waste is a Potential Alternative for Conventional Fuel (Coal, Fuel Oil, Gas): Abstracts / Scientific and Practical Seminar (2002; St. Petersburg), St. Petersburg: 2002, 72 p.
7. Forest Bioenergy: Approved by EMA for Education in the Field of Forestry as a Textbook for Students of Universities / St. Petersburg State Forest Technical Academy, Moscow State Forest University - M.: Publishing House of Moscow State Forest University, 2008, 348 p.
8. Redkokasha D.V. Production of Pressed Materials from the Logging Waste and Off-Spec Wood: Overview, M.: 1970, 78 p.
9. Modin N.A., Eroshkin A.N., Briquetting of Crushed Wood and Wood Bark, M.: Forestry, 1971, 112 p.
10. Veselov A.A. The Use of Plywood and Match Production Wood Waste, M.: Forest industry, 1987, 160 p.
11. Gomonay M.V. Production of Fuel Briquettes. Wood Raw Materials, Equipment, Technologies, Operating Modes, M.: Publishing House of MSFU, 2006, 68 p.
12. Ragulskene V.L. Vibropercussion Systems. Vilnius: Mintis, 1974. - 320 p.
13. Batuev G.S., Golubkov Yu.V., Efremov A.K., Fedosov A.A., Engineering Techniques for Studying Impact Processes, M.: Mechanical Engineering, 1977, 248 p.
14. Vinogradov V.A. The Effect of Vibration when Briquetting Crushed Wood, Technology and Equipment of Wood Processing , pp. 166 - 169.
15. Tsyvin M.M., Kottsov S.G., Shmakov I. V., Production of Wood Powder: Overview, M.: 1977, 37 p.
16. Mikhayilov G.M., Serov N.A, Ways to Improve the Use of Recycled Wood Raw Materials, M.: Forestry, 1988, 224 p.

17. Musikhina L.N. Integrated Use of Spruce Bark. - In the book: Abstracts of the All-Union Conference on the Use of Wood Bark. Sverdlovsk, 1971, p. 51-53.
18. Pindzhoian M.L. Korolit is a New Building Material. M.: Forest Industry. No. 10, 1969. p. 13-14.
19. Bazhanov E.A. Briquetting of Wood Waste, Wood Processing Industry, 1996, No. 4, pp. 16 - 18.
20. Chemistry and Technology for Processing Wood and Bark, Edited by Geles I.S. Petrozavodsk. 1990 pp. 140-155.
21. Boykov S.P. Studying the Wood Debarking by Cutting on Rotary Machines. Thes. Cand. Eng. Sc. - L.: 1970, 178 p.
22. Yudkevich Yu.D., Vasiliev S.N., Yagodin V.I. Obtaining Chemical Products from Wood Waste. SPb.: SPbFTA, 2002. pp. 30-32.
23. Alekseeva E.A. Chemical Composition of Aspen Bark Lipids. Abstract of Thes. Cand. Eng. Sc. SPb.: SPbFTA, 1970. pp. 5-11.
24. Ermakov S.G., Khakimova F.Kh. Development of the Wood Debarking Waste Integrated Utilization Technology, Forest Journal. 2002. No. 5. pp. 11-17.
25. Shamko V.E. State and Prospects of the Sulfite Processes Development, Review. Pulp, Paper and Cardboard. M., 1988. 50 p.
26. Gelfand E.D. The Concept of Creating Environmentally Friendly Hydrolysis Production, Forest Journal. 1995. No. 2-3. pp. 147-150.
27. Gazizov A.M., Grigoriev I.V., Gumerova O.M. Analysis of Technical Solutions to Improve the Quality of by-the-Piece Mechanical Debarking of Round Timber Materials, Manuscripts: Bibliogr. Ind. VINITI, 9/30/08. No. 546 – Iss. 2008, 23 p.
28. Zhitkov A.V. Wood Bark and its Properties. M.: Paper Industry, 1958, No. 2, p. 4.
29. Zhitkov A.V. Utilization of Wood Bark. M.: Forest Industry. 1985, 136 p. (Ser. The Economic Life of the Country)
30. Korobov V.V., Rushnov N.P. Processing Low-Quality Wood Raw Materials. Issues of Non-Waste Technology, M.: Ecology, 1991. pp. 188-208.
31. Geles I.S. Wood Biomass and the Fundamentals of Ecologically Acceptable Technologies for its Chemical and Mechanical Processing. Petrozavodsk, 2001. - 382 p.
32. Nikitin N.I. Chemistry of Wood and Cellulose, M.: Publishing House of the USSR Academy of Sciences, 1962, 712 p.
33. Koshkin N.I., Shirkevich M.G. Handbook of Elementary Physics, Ninth Edition, M.: Science, 1982.
34. Gomonay M.V. Wood Processing Technology: Reference Textbook, M.: Publishing House of MSFU, 2001, 232 p.
35. Korshak A.V. Justification of the Technology for the Wood Briquette Production on Impact Press. Thes. Cand. Eng. Sc. SPb: 2011, 132 p.
36. Pamfilov V.V. Pamfilov V.V.; resp. ed. Rymarenko L.A., Effect of Impact Loads on the Structure and Mechanical Properties of Wood, Bryansk: 1965, 73 p
37. Khukhryansky P.N. Contour Pressing of Wood by Impact, Furniture and Woodworking: Ref. Inf. M.: VNIPIElesprom, 1965. Iss. 25. p.37.
38. Khukhryansky P.N. Pressing and Bending Wood, Khukhryansky P.N, L.: Goslesbumizdat, 1956, 244 p.
39. Vibration in Technology: Handbook. In 6 vol., Ed. Counc: Chelomey V.N. (chairman), M.: Mechanical Engineering, 1979, V. 2. Oscillations of Nonlinear Mechanical Systems, Ed. I.I. Blekhman. 1979. 351 p.