ASPECTS REGARDING THE COMPACTION OF CARDBOARD WASTE IN VERTICAL PRESSES WITH DISCONTINUOUS FLOW
/
ASPECTE PRIVIND COMPACTAREA DEȘEURILOR DIN CARTON ÎN PRESE VERTICALE CU FLUX DISCONTINUU

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***Keywords:** compaction, vertical press, cardboard waste, multiple stages, resisting force, energy consumed*

ABSTRACT
The paper analyses the compaction of cardboard waste in vertically stationary presses, the stages of making the bale of material and the forces resistant to the displacement of the cardboard pressing plate at each stage of compaction, the relationship between the piston stroke and the pressing forces, as well as the partial and total energy consumption of compaction. Some clarifications are made regarding the correlation between the piston stroke and the compaction time, respectively the forces resistant to compaction. A link shall also be established between the volume of pressed material and its mass, so that the final density of the bale of material can be specified.

ABSTRACT
Lucrarea analizează compactarea deșeurilor din carton în prese vertical staționare, etapele realizării balotului de material și forțele rezistente la deplasarea plăcii de presare a cartoanelor în fiecare etapă a compactării, relația dintre cursa pistonului și forțele de presare, precum și consumul de energie partial și total al compactării. Se fac unele precizări legate de corelația dintre cursa pistonului și timpul de compactare, respectiv forțele rezistente la compactare. De asemenea, se stabilește o legătură între volumul de material presat, masa acestuia, astfel încât să se poată preciza densitatea finală a balotului de material.

INTRODUCTION
There are many companies that collect paper and cardboard waste in Romania, but there are few companies that process it for recycling and re-use. Therefore, the integrated process of recovery and recycling of cardboard includes several stages and operations, when we think about using cardboard waste for other purposes than a primary source of heat.

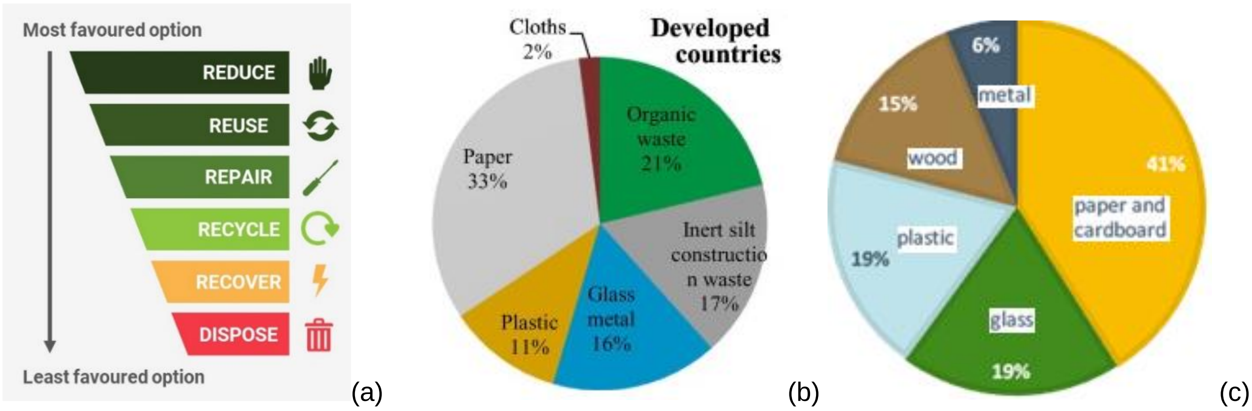
Recycle and reuse of cardboard is a common method of solid waste management which can be easily transformed into other objects, especially for large packaging (*Esmieo, Shaklawon and Ali Shanab, 2018*). Cardboard recycling means the reprocessing and reuse of thick sheets or rigid multi-layered paper primarily for the packaging of large products, including primarily cardboard boxes, but also other categories. First of all, the municipality is responsible for transporting the cardboard to the final disposal site outside the waste site, but the cardboard collectors also have an interest in passing these categories of waste to processors and recyclers (*Esmieo, Shaklawon and Ali Shanab, 2018; Naveen and Sivapullaiah, 2020; Kumar and Agrawal, 2020*).

Recycled cardboard and paper waste, recovered from municipal waste mixtures, can be a good source both for obtaining energy and for treating waste water (from which suitable filters can be made), increasing sustainability and the circular economy in the circuit of recovery and recycling of paper and cardboard (*Peretz et al., 2021*). This waste can also be an important source of cellulosic biomass, used as a substrate for cellulase production, by treatment with sulfuric acid (*Al Azkawi, Sivakuma, Al Bahr, 2018*).

Studies have been carried out to see if cardboard waste can be used as a partial substitute for aggregates to produce lighter, greener and cheaper building bricks in advanced research in the field of innovative sustainable building materials (*Ahmad et al., 2018*).

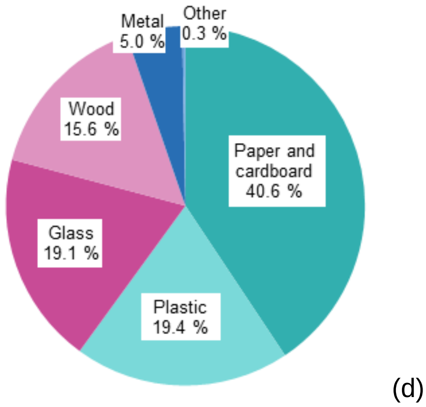
The results showed, however, that using cardboard as a partial substitute for aggregates leads to obtaining bricks with low strength, which can only be used for non-load-bearing interior walls.

In the recovery of cardboard waste, compacting it to form larger bales that can be stored for a longer period and transported more easily is a basic operation. This can be done with the help of presses, vertical or horizontal, stationary or movable, with continuous or discontinuous flow, of different capacities. In this way, the costs of storage, transport and disposal are thus greatly reduced due to the regular shape of the bales and the increased volumetric mass in relation to the volumetric mass of bulk cartons (*Lazea M.B. et al., 2021*).



b) Municipal waste composition

; c) Packaging waste composition (*Collectors, 2020*)



d) Packaging waste generated by packaging material, (*Eurostat, 2019*)

Fig. 1 – Options in waste management (a) and the composition of municipal waste, respectively packaging, according to several sources (b, c, d)

According to Eurostat (2019), in the EU the participation of paper and cardboard waste in the total waste generated by the recovery from the packaging of products and goods of any nature is about 40.6%, while plastic has a participation of only 19.4%. Finally, the pertinent conclusion can be drawn that paper and cardboard waste is an important raw material for a variety of products, in the most diverse fields of activity. The technological processes of recycling those wastes can lead to the production of composite materials, cellulose nanofibers and nanocrystals, light bricks, porous carbon, bioethanol, hydrogen and biofuel. However, the most feasible and economical would be their use in the production of cellulosic nanomaterials (nanofibers and nanocrystals) (*Ozola et al., 2019*).

As part of mitigating the problem of increasing amounts of paper (and cardboard) waste generated that end up being deposited at municipal waste dumps or being burned, in their paper, *Osamwonyi, Okokpujie and Dirisu,* (*2018*), proposed the design of a horizontal waste paper baler. Design parameters included maximum compression force (10 KN), piston rod travel distance, respective piston stroke (609 mm), time of a work cycle (9 minutes) and hydraulic system pressure.

The conclusion was that such compacting presses can be designed and made according to local needs, in different sizes and according to the nature of the waste that should be compacted and baled.

This work aims to present some information regarding the behaviour of packaging cardboard waste in the process of compaction and baling in stationary vertical presses, with fixed volume, with a discontinuous work process, both in terms of bale formation stages, but also of energy consumption in stages.

MATERIALS AND METHODS

Cardboard waste that occurs in various processes, or from the packaging of relatively large products, needs to be compacted before being sent to recycling for reuse. Their compaction can be done in stationary vertical presses with discontinuous flow or in horizontal presses with continuous flow. The compaction process takes place in several stages, because it is necessary to reduce the dimensions of the volume of material introduced into the press and to compact a large amount of waste, the volume of the pressing chamber being fixed. So, by pressing the first volume of material introduced into the press, it is reduced in volume sufficiently to add another volume of material, relatively identical to the first, followed by compaction in the second stage and again the addition of another volume of material, followed by of further compaction until the press chamber can no longer receive material due to the increase in the density of the material introduced sufficiently long and the force resisting compaction over the force made by the hydraulic piston.

In our experiments, we used a vertical press, with discontinuous flow, PP 1207 (Strautman, Germany), which can develop a maximum force of 50 tf, having a pressing chamber fed from the front by means of a sliding door (fig. 2).

Fig. 2 - Baler press PP-1207 for experiments and the tied bale obtained after compaction/baling

The cartons used in the experiments were recovered from the store network and were of various sizes and shapes, in several layers. There was no analysis of their structure and no prior sorting.11.5 kg of cardboard waste was initially introduced into the pressing chamber, the volume being calculated based on the transverse dimensions of the pressing chamber and the height of the chamber at the moment the cartons are touched by the pressure plate, which is about 0.2 m^3. The data of the experiments carried out are shown in Table 1, the bale formation taking place in seven relatively identical stages, in terms of the amount of material added to the baling chamber and the way of working. It should be noted that the maximum working capacity and performance of the machine specified by its technical book have not been reached.

Moreover, no initial processing of the cartons was carried out, they were not shredded and their dimensions were not reduced, so they were placed in the pressing chamber in accordance with the free volume of the chamber which allowed the introduction of equal amounts of cartons.

RESULTS

Having available the data from Table 1 (*Lazea et al, 2021*), the variation curves of the resistant forces were drawn graphically (in Excel) according to the displacement of the compaction plate, for all the 7 samples mentioned before, so that the resulting bale had about 80.5 kg.

It is found that the variation of the resisting force with the displacement of the pressure plate does not follow a predetermined trajectory, even if in principle it is an upward-sloping curve, the resisting force depending on the random placement of the cartons in the press chamber, with gaps unevenly distributed between the inserted cartons in the press.

There are several similar curves, the maximum resistance force registering very close values mainly due to the way the hydraulic circuit of the press is made.

Table 1

Variation of pressure forces with compaction piston displacement for the seven samples *(Lazea et al., 2021)*

Time, (s)	P1		P2		P3		P4		P5		P6		P7	
	V= 0.2 m^3 m = 11.5 kg		V= 0.4 m^3 m = 23 kg		V= 0.6 m^3 m = 34.5 kg		V= 0.8 m^3 m = 46 kg		V= 1.0 m^3 m = 57.5 kg		V= 1.2 m^3 m = 69 kg		V= 1.3 m^3 m = 80.5 kg	
	Displacement (mm)	Force (daN)	Displacement (mm)	Force (daN)	Displacement (mm)	Force (daN)	Displacement (mm)	Force (daN)	Displacement (mm)	Force (daN)	Displacement (mm)	Force (daN)	Displacement (mm)	Force (daN)
1	183	457	233	258	231	153	183	193	236	128	246	148	183	278
2	231	633	271	912	270	914	237	258	267	390	277	410	221	932
3	385	705	347	980	342	982	336	372	336	458	346	478	297	985
4	523	742	432	992	422	992	529	416	418	510	428	530	382	997
5	645	772	523	980	510	981	630	521	479	563	489	583	473	985
6	810	960	595	967	602	962	725	586	555	631	565	602	545	972
7	958	955	671	968	668	961	802	632	626	766	636	646	621	973
8	1099	968	758	966	748	965	868	662	692	802	702	701	708	971
9	1244	980	824	967	817	968	902	706	760	861	770	782	774	972
10	1323	979	896	967	892	968	950	803	838	912	848	893	846	972
11			975	966	991	970	1026	852	905	983	915	978	925	971
12			1035	977	1042	975	1111	876					985	982
13			1234	977	1302	977	1194	921					1184	982
14							1235	961						
15							1278	979						
Energy, J	**673**		**1544**		**1536**		**1292**		**1065**		**1027**		**1554**	

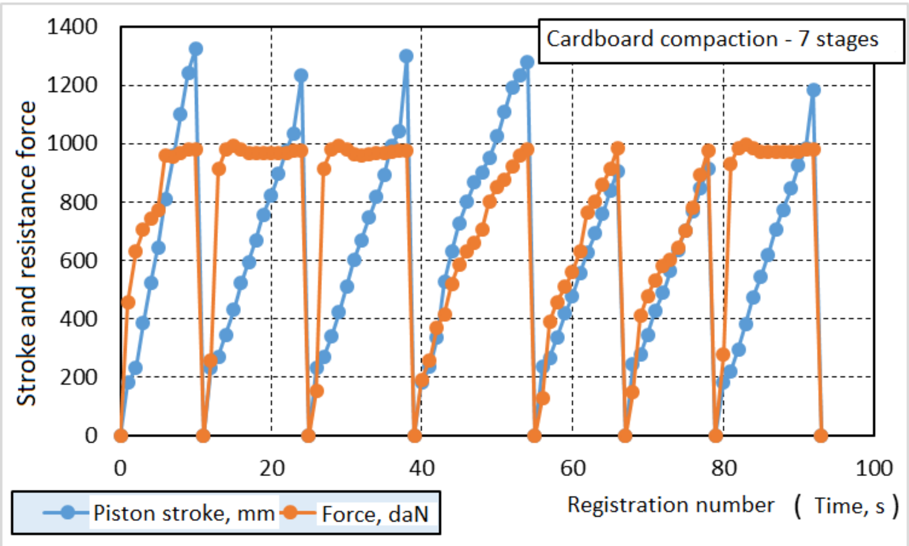


Fig. 3 - Pressure forces and displacement of the pressure plate when compacting cardboards

From the analysis of the data in the table and the graphs in fig.3, it is observed that the displacement of the pressure plate reaches relatively high values not only at the first stages of compaction, but also in the final phase of compaction, even if the highest displacement value has been reached at the first compression (about 1323 mm), the stroke from which the records of the force resistant to compaction begin, having minimum values of about 183-236 mm. The values of the resistance to compaction force are between 977 - 983 daN, which means that at higher values the resistance sensor in the hydraulic circuit is activated and it gives a signal to retract the pressure plate.

Based on the graphs drawn in the MS Office Excel program, the areas under the force-displacement curves (fig. 4) were determined, which represent the energy consumed in each stage of the compaction process, and its values are presented at the bottom of table 1.

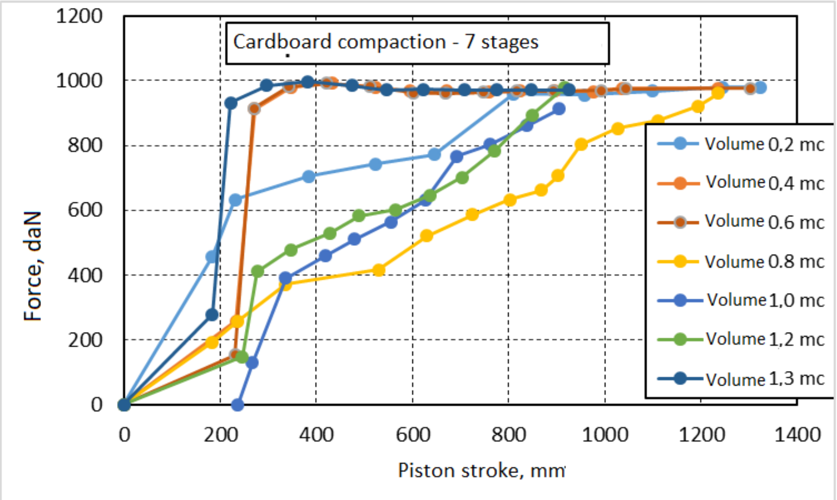


Fig. 4 - Force variation – displacement when loading the press with pressed cardboard in 7 similar stages

It is found that the lowest energy consumption is during the first compaction, when there is a small amount of cartons inside the press, in the following stages the energy consumed increases with the amount of cartons added and with the parameters of the process – force – displacement. However, the placement of the cartons in the press premises also has a determining role, this having a random character.

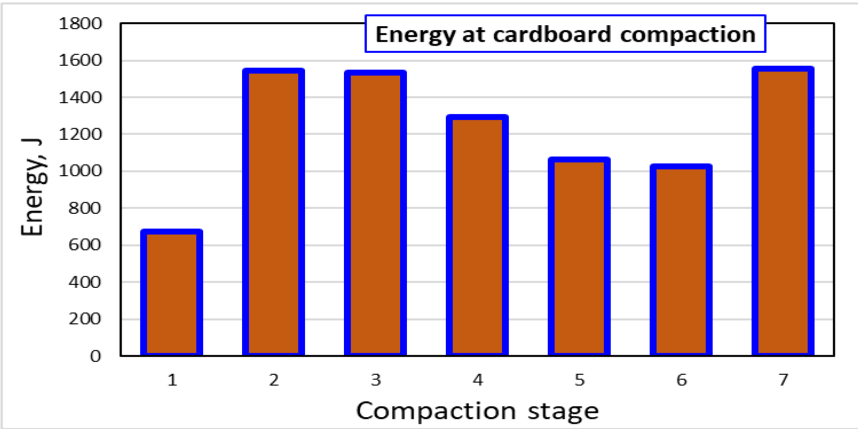


Fig. 5 - Variation of energy when compacting cartons in the 7 stages of compaction

In the separate representation of the stroke of the pressure plate, simultaneously for the 7 stages of compression, the upward slope of the stroke is better observed in correlation with the increment time, which was set to 1 second (fig.5).

At the same time, even if the trend is clearly linear (as shown by the values of the regression coefficient ($R^2 \geq 0.9723$), the plate movement speed is not a constant one, depending on the resistance encountered during compaction and on the random placement of the cartons, and the circuit hydraulically adjusts the speed according to the sensed force. It is found that the speed has values between 69 mm/s (stages 5 and 6) and 135.7 mm/s (at the first stage of compaction). Practically, the actual compaction starts from the moment the material is detected by the pressure plate in its downward stroke.

The data records show the constancy of the volume of cardboard waste introduced/added to the press chamber at each stage of compaction, i.e. the constant increase of the amount introduced.

Based on the volume of material in the press chamber and its bulk volume (placed in the press chamber), the constancy of the density of the material is also observed (fig.8).

In Table 1 and figures 5-7, it can be seen the variation of the pressing force during the seven stages of compacting the cartons until the moment of tying the bale, as well as the variation of the stroke of the piston (pressing plate) and the energy consumed in the process.

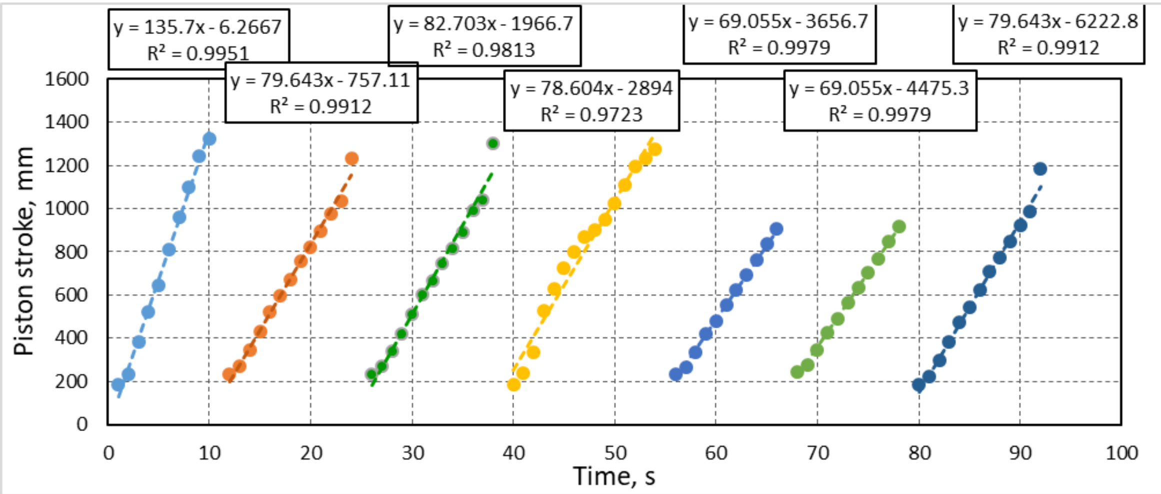


Fig. 6 - The variation of the stroke of the pressure plate when compacting the cartons in the 7 stages

From the regression analysis of the experimental data, respectively of the compaction force with the stroke of the pressure plate, a different variation is found in the seven stages of bale formation, which does not have to be the same every time. This is due to several factors, which are also random: the type and thickness of the cartons, the way they are placed in the pressing chamber, the differentiated arrangement front-back, respectively left-right, the moment the cartons are touched by the pressing plate, etc.

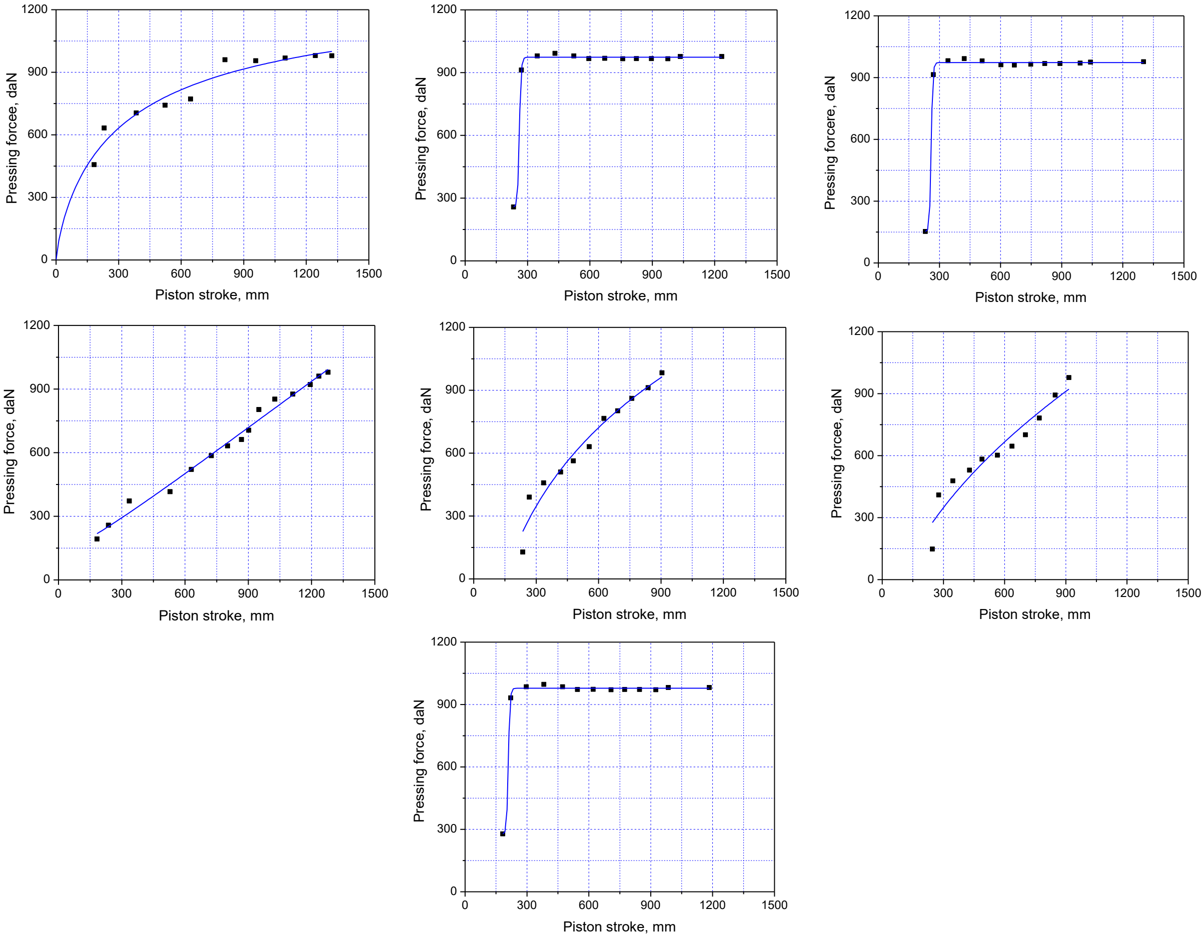


Fig. 7 – The variation of the pressing force with the stroke of the piston, in the 7 stages of compaction

Table 2

Values of the parameters of the logistic regression equation (1) and of the coefficient of determination R^2

	P1	P2	P3	P4	P5	P6	P7
A_1	-0.264	257.218	152.533	122.696	-2107.177	-403.804	277.32
A_2	1347.083	973.364	972.818	7825.699	12500.324	95556.463	978.36
x_0	349.572	260.650	259.457	7202.908	178492.12	$3.7 \cdot 10^6$	209.78
p	0.796	60.794	64.289	1.192	0.250	0.514	50.80
R^2	0.980	0.998	0.999	0.988	0.959	0.920	0.998

$$y = A_2 + \frac{A_1 - A_2}{1+\left(\frac{x}{x_0}\right)^p} \tag{1}$$

The regression analysis carried out shows a logistic correlation, according to the relation (x), between the compaction resistance force and the stroke of the pressing plate. Although the stroke of the pressing plate shows a linear correlation with the pressing time, we could tend to say that the pressing force has a similar correlation. Yes, this is valid for portions, for areas of the press room (on its vertical), but overall the regression shows us a very good logistic correlation, as said before.

This is represented by the high values of the correlation coefficient R^2, which has very high values (between 0.920 and 0.999), even if looking at the graphs we could say that they are not true, but the analysis program used (Microcal OriginPro 8.0) validated the values presented, together with the coefficients and values of the relationship parameters (1) (see Table 2).

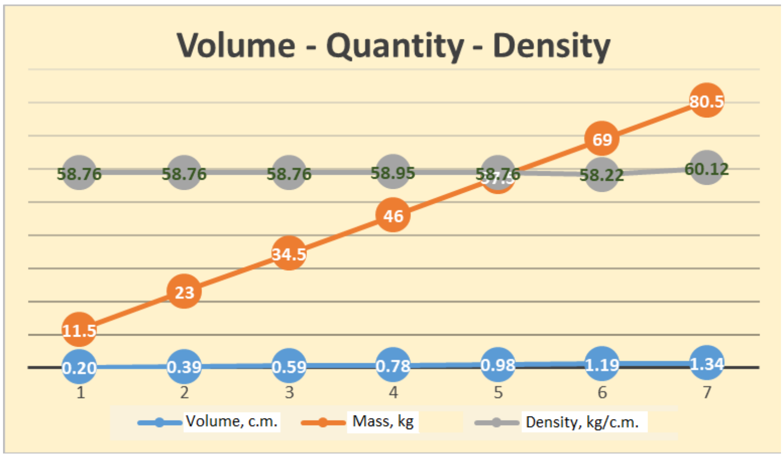


Fig. 8 - The variation of the amount of material, the volume and the density at the initial moments of the compaction stages of cardboard waste

Figure 6 clearly shows the linear variation of piston stroke with press time (having a constant step of 1 second), even though the slope of the line changes depending on the amount of material in the press chamber and the resistive force encountered by it. It should be mentioned here that the characteristics of the cartons in the pressing room and their (random) placement influence both the characteristics of the regression lines and the changes in the pressing resistance force.

A bale is formed in several successive stages (7 stages), in which the machine is successively fed with a relatively close amount of material in terms of volume and mass, in each feeding stage. Therefore, the mass of the final bale is the sum of the masses of the seven consecutively added charges, while the volume of the bale depends on the pressure with which the material is pressed and the resistance of the previously formed bales, and found in the discharge channel. From fig. 8 it is found that the density of the bale increases with each stage of the process, in the end the volumetric mass of the bale can reach values of around 60-70 kg/m^3.

CONCLUSIONS

The elucidation of the movement of the working parts of these mechanisms is necessary for a good understanding of their operation, but especially in order to redesign and improve their functional parameters for an operation without loss of material and with low energy consumption.

From the studies carried out, it was sought to determine the relationship between the pressure applied to the material (waste) in the compaction chamber and the density (densification) of the material.

The dynamic simulation brought results that can be verified in reality, regarding the mechanical behaviour of the studied components.

From the authors' determinations, the maximum compaction/pressing force in each of the seven stages of cardboard waste bale formation has values below 1000 daN, while the total compaction energy is around 8.0-9.0 kJ.

In the future, a complex analysis of the compaction equipment must be made, this being necessary for a system with dynamic data, taking into account the influence of the chassis on the movement of the active parts, referring here to the compaction of waste in the space of municipal waste collection machines, either selected/sorted or unselected.

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