Compaction of grass silage taking vibrating stresses into account

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Abstract: In order to achieve higher compaction rates when storing wilted grass or chopped maize in clamp silos, some farmers use rollers with vibratory rolling elements to compress the material. The study aimed to determine the effect of vibrating tools on the compaction of ensiled material. Taking wilted grass as an example, experiments were conducted with a hydropulse system with quasi-static and vibrating compaction. The results showed that the higher compaction performance observed in practice was due not to the vibratory movement of the rolling element, but instead to the additional vertical force resulting from the imbalance.

Keywords: vibrating compaction, grass silage, hydropulse system

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1 Introduction

Alongside low cost, minimising losses and maintaining quality are key process objectives in silage production. The quality of the silages is determined not only by the material harvested, but above all by the process engineering parameters. Careful storage intake and compaction in the clamp silo plays a particularly significant role here. As a result of the increases in harvested mass flows in recent years, higher demands are being made of the compaction of ensiled material in order to achieve the densities necessary for optimal silage quality. A number of studies conducted on farms, e.g. by Baumgarten (2007), showed that on more than 80% of farms the recommended values were not achieved. In order to increase the compaction performance, more vibratory rollers are being used in practice. However, apart from initial results of practical trials (Häbler et al., 2008), there have not yet been any comprehensive investigation results on the influence of various vibration parameters on the density as a function of the material properties.

In order to achieve the necessary densities in the silo depending on the material to be ensiled, certain conditions need to be observed for intake of the harvested material and initially empirically determined values were available here. In later systematic studies the key parameters registered during compaction with compaction vehicles were correlated with densities measured in the silo. For instance, the compaction effect was examined as a function of the number of tractor passes (Müller, 1969; Edner, 1985). Taking the various parameters into account, differentiated regression equations were derived for calculating the necessary compaction outlay in a horizontal (clamp) silo (Muck and Holms, 2000; Bernier-Roy et al., 2001).

The Humboldt University Berlin was the first to include vibratory rollers such as are used in road building in such studies. Initial results document that in the case of maize ensiling, the necessary compaction time can be roughly halved by comparison with tractor operations (Häbler et al., 2008). The influences on the density of ensiled material in the silo are very complex and interact mutually, so that the recommended values determined in this way can only be generalised to a limited extent. That is why approaches are being developed to measure

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the product density online during compaction for needs-driven steering of the compaction process (Geyer and Hoffmann, 2012). Irrespective of whether and when such solutions for silage reach practical maturity, theoretical and fundamental examinations on a laboratory scale are necessary to describe the functional dependencies between the diverse influencing parameters and be able to develop machinery for silage compaction further.

A number of authors use cylindrical press pots for compaction experiments in the laboratory. In the case of static loads, this makes it possible to express a compaction function for calculating the storage density (Fürll, 1972; Fürll et al., 2006). According to this, the vertical pressure has the greatest influence on the storage density. This is followed by influences due to storage duration, dry mass content and bending stiffness of the haulms. A relation was also derived on the elastic recovery behaviour from retardation experiments for fresh meadow grass at the press pot (Herold, 1970). A press pot with a diameter of 125 mm in conjunction with a material testing machine was used to analyze the influence of material properties, and especially of the chopping length too, on the compactability of silage material by monitoring force-path diagrams (Wagner, 2005; Wagner and Büscher, 2005). In order to map the conditions beneath a tractor wheel, a block-shaped experimental container with a base area of 482 mm × 584 mm was also used. The experiments were conducted with alfalfa, grass and maize silage materials, with layer heights from 0.15 m to 0.6 m, pressing time of 1 s to10 s, and at pressing pressures between 20 and 80 kPa (Muck et al., 2004; Savoie, 2004). Several layers were applied and compacted one after the other. The density could then be displayed as a function of the logarithm of the number of layers. In all cases the density depended significantly on the pressing pressure, but the effect of the pressing time was low.

Bernier-Roy et al. (2001) conducted compaction experiments with a tractor wheel as well as experiments with press pots. For this purpose a tractor wheel was mounted on a frame, pre-loaded with wheel loads of 39 kPa and 64 kPa, and guided over ensiling materials in a compaction channel. Regression equations were drawn up for the press pot experiments and for compaction by the wheel to estimate the achievable end density.

So far no results from laboratory examinations exist for compaction of ensiling material by vibrating loads that provide information about the achievable storage density as a function of the material properties and the vibration parameters. Basic studies exist in literature for compaction of earth materials. With the aid of spring-mass models that map the compaction vehicle and the rheological properties of the soil, it was possible to achieve good agreement between theoretically calculated and experimentally determined results (Van Susante and Mooney, 2008). The vibration excitation also influences the compaction effect. In practical experiments on weathered granite sandy soil, for example, centrifugal vibration was proved to be superior in comparison with vertical vibration as regards the settlement achieved (Muro, 2001). A comparison of static load, the action of shock-type loads, and static loading with vibrations superimposed for compacting cement-stabilised soils revealed that the latter method achieves the greatest increase in density (Kenai et al., 2006).

In systematic basic examinations on a laboratory scale in a press pot with ensiling materials commonly encountered in practice, empirical findings are to be obtained on how the density of the ensiled material depends on the material properties and various compaction algorithms. The focal area of the examinations is oriented to demonstrating the influence of vibrations on the compaction effect for ensiling materials. By vibrations we mean the rising and falling pressing pressures during the compaction operation. The transferability of the results obtained to the conditions in practical silos is to be largely ensured by appropriate peripheral conditions of the laboratory experiments. Finally, the results are expected to yield points of approach for optimising the compaction of ensiling materials in horizontal silos.

2 Materials and methods

2.1 Experimental material

The experiments were conducted with wilted grass from the first and second cut. The range of dry mass (D_M) content at which the best ensiling results are achieved is 30%-45% (Nussbaum, 2001; Fürll et al. 2006). In order to take into account the extreme values that are certainly encountered in practice, dry mass values between 20%-50% were selected for the experiments.

In the selection of cutting length, the experiments were oriented to the now customary practice of shorter cutting lengths. Because of the better compaction possibility, cutting is mainly carried out at lengths which are less than 20 mm. That is why the cutting lengths in the experiment variants were 4, 9 and 17 mm.

The sample material had a crude fibre content of 230-250 g kg^{-1} dry mass.

2.2 Compaction test rig

2.2.1 Experimental set-up

The compaction test rig consists of a 2,400 mm high portal frame, on the upper cross beam of which a hydraulic cylinder belonging to a hydropulse installation is secured. On the piston rod there is a force transducer with the pressing piston (ram). The pressing piston descends into a press pot, the jacket of which stands on a height-adjustable cross-bar and which is filled with the ensiling material to be compacted (Figure 1). The base of the press pot is not connected with the cylinder jacket, but is supported on the cross-bar via a force transducer (Figure 2).

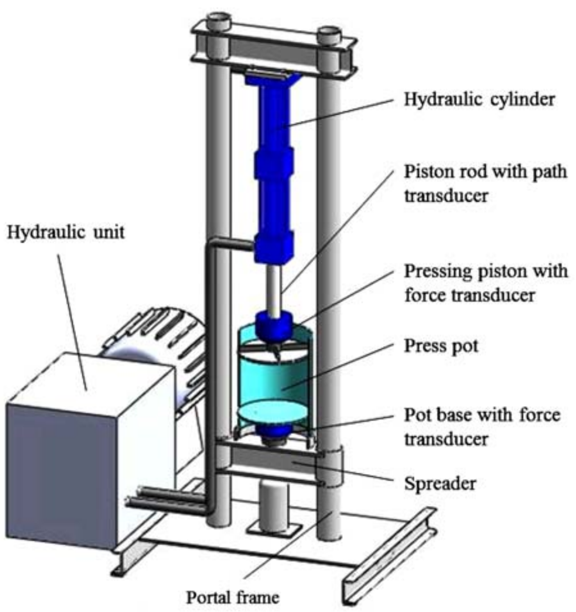


Figure 1 Main assembly groups of the compaction experiment stand

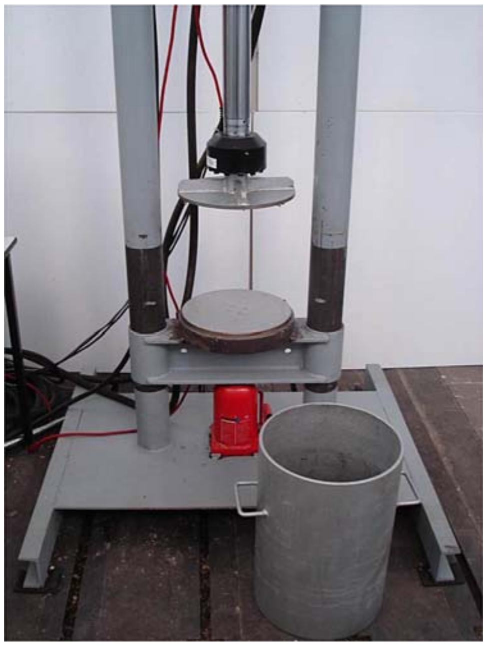


Figure 2 Base plate and press pot

The diameters of the pressure plate and the base plate are each 2 mm smaller than the jacket of the press pot. This allows separate measurement of the compaction force at the pressing piston at the base force on the base of the press pot. The frictional force at the wall can be determined from the difference between the two forces. The cross-bar on which the press pot stands is height-adjustable over 300 mm in order to be able to realise a press pot height of 450 mm plus filling gap of 100 mm despite the given maximum lift of the pressing piston.

The portal frame and base plate are dimensioned in such a way that even in the case of vibrations and the corresponding vertical pressures, sufficient firmness and stiffness are ensured.

The press pot base and compaction plate have a diameter of 310 mm, resulting in a cross section area of the press pot of 0.0755 m². With the maximum force of 50 kN that can be achieved with the piston of the hydraulic cylinder, it is thus possible to achieve a maximum pressing pressure of 650 kPa.

The hydraulic cylinder is connected with a hydraulic unit via a servo valve. The servo valve is controlled via a PC with the aid of created software. The PC also registers the measurements of the two force transducers and the path transducer at the piston. The data are stored and can subsequently be processed (Antoniewicz, 2008; Weiß, 2008).

2.2.2 Performance of the experiment

The servo valve of the hydraulic cylinder and the capture of measurement data are controlled via the hydropulse installation with the aid of the TestStar II Control System-Software. Within the framework of these experiments, the software was used above all to steer the compaction operation.

The ensiling material for the compaction experiments was taken in a sufficiently uniform batch from directly behind a forage harvester and used very soon after this. At the start of each experiment a partial quantity was filled loosely into the press pot up to the required layer height. In subsequent experiments of a test series, the same sample mass was used each time. Then the respective experimental process was started at the PC. With pulse cycles of 0.25 s, the time from the test start, the path travelled by the pressing piston and the forces measured by the load cells at the pressing piston and the press pot base were recorded and transferred to an Excel file for further processing. In each experimental series three samples were withdrawn to determine the dry mass and the actual chopping length.

The quasi-static compaction course (Figure 3) simulates the pass of a two-axle tractor over a silo at a travel speed of 4 km h^{-1}.

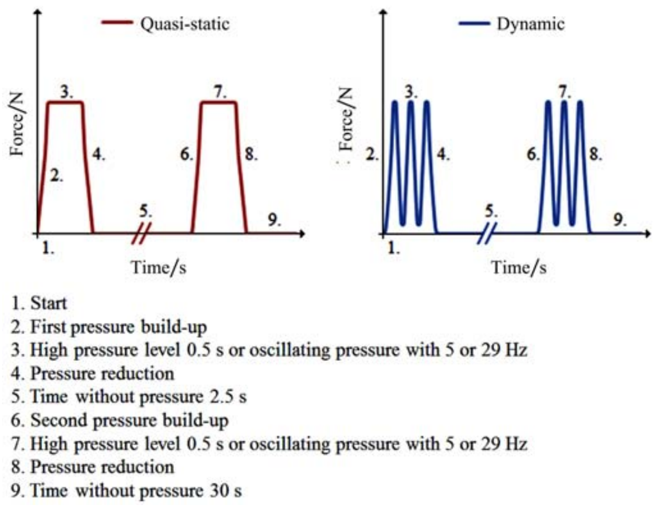


Figure 3 Pressing force-time course for quasi-static and dynamic loads

The dynamic compaction curve represents compaction with a tandem roller with vibration, also at a travel speed of 4 km h^{-1}. The pressure is increased up to a specified value. During the retention time of 0.5 s, a sinusoidal vibration is generated between the specified upper pressure value and the lower value of 100 N with frequencies of 5 Hz and 29 Hz respectively.

The parameters were varied in the experimental program (Table 1).

Table 1 Parameters of the experimental program

Parameters	Values
Material	wilted grass, first and second cut
D_M/%	20 - 50
l_C/mm	4, 9, 11, 17
p_{max}/kPa	50, 100, 200, 400
f/Hz	0, 5, 29
Compaction duration/s	0.5
Time without compaction/s	2.5
Number of compaction cycles	6 (corresponds to the number of passes)

Note: D_M means dry mass; l_C means theoretical cutting length; $p_{\max}$ means compaction pressure; f means frequency.

Altogether 104 compaction experiments were carried out.

As all pressure experiments were conducted with a uniform press pot and pressure die, the maximum force is proportionate to the maximum pressure.

With a quasi-static pressure load and an idealised rectangular course, on average a force corresponding to the maximum force is applied during the loading period. Presupposing the same maximum force, in a sinusoidal application of force, the mean force is only half of the maximum force. For the same mean force to be applied in the dynamic compaction as in the quasi-static compaction, twice the maximum force is necessary in the dynamic compaction. On the basis of this connection, comparison variants with twice the maximum force were also examined in each case (Table 2).

Table 2 Variants of the pressure load

Type	Nature of load	Variant 1 /kPa	Variant 2 /kPa
I	Quasi-static, single maximum pressure	100	200
II	Vibration, single maximum pressure	100	200
III	Vibration, double maximum pressure	200	400

With the aid of a variance analysis, it was examined what factors influence the density value. The target size was the dry mass density. The fixed factors were compaction pressure, cutting length and frequency of vibration. The dry mass content was evaluated as a random quantity. The medium compaction pressure was calculated for all measurement series too. In the quasi-static compaction the medium compaction pressure corresponds to the maximum pressure, and in dynamic compactions to half the maximum pressure.

In view of the fact that the repetitions differ in the individual load variants and because the dry mass represents a random effect, the mixed model (Type III) was selected for the variance analysis. The GLM procedure from the statistical programme package SAS Version 9.3 was used for calculations.

3 Results and discussions

3.1 Trend shown by the density curves

A typical ensiling material density curve in the press pot on compaction of wilted grass during a six-fold double cycle with quasi-static compaction at 50 kPa and 200 kPa maximum pressure shows a degressive increase of the density (Figure 4). The initial layer thickness is 300 mm and D_M is 26%. The density is calculated from the measurement values recorded (1).

$$\rho = \frac{m}{Ah} \tag{1}$$

where, ρ is ensiling material density, g cm^{-3}; m is mass of the ensiling material filling, g; A is press pot basic area, A = 755 cm^2; h is layer height calculated from the piston travel, cm.

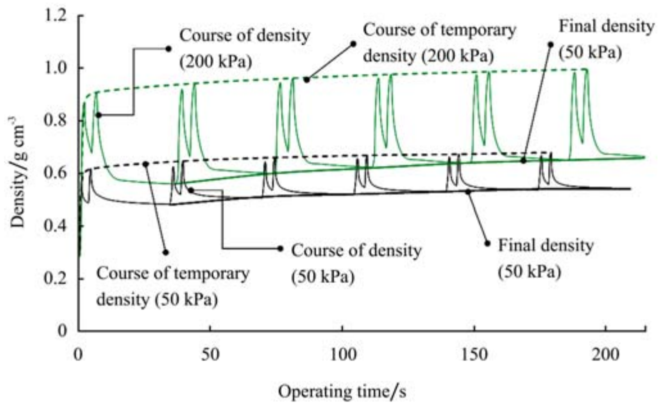


Figure 4 Density curve for quasi-static compaction of welted grass in the press pot

The experimental material is first compacted with a rise in force of the piston of 12 kN s^{-1} until the specified compaction pressure is reached. The subsequent retention time is 0.5 s. When the piston pressure is relieved, the material displays elastic recovers and the density drops. After 2.5 s the second compaction occurs and the rising pressing pressure leads to a renewed increase in density. Despite the same piston force, this is somewhat higher because the ensiling material can now be compressed more strongly. In the following load relief phase of 30 s the ensiling material relaxes again, until after 8 s to 10 s the elastic recovery is almost completed. This load and relief cycle is repeated six times, corresponding to six passes by a tractor.

The density after elastic recovery is of practical significance. Already after the first load cycle at a maximum piston pressure of 200 kPa, at 0.56 g cm^{-3} it is 17% higher than at 50 kPa (0.48 g cm^{-3}). Even after the sixth compaction cycle too, the 50 kPa variant with 0.54 g cm^{-3} failed to achieve the value that was attained already after the first cycle by the 200 kPa variant. The diminishing increase of pressing and recovery density with the number of loading and relief cycles becomes visible in the degressive course of both curves. Because the curve of the recovery density for the experiment with 200 kPa pressing pressure runs a little more steeply than that at 50 kPa maximum pressure, the density increase after each cycle is higher for the 200 kPa variant.

The pressing pressures of 50 kPa or 200 kPa in this example are the pressures at the pressing piston specified by the program control. At the pressing cylinder base a pressure reduced by the influence of the wall friction is measured. With a linear pressure drop over the height of the ensiling material, the mean pressing pressure in the material is

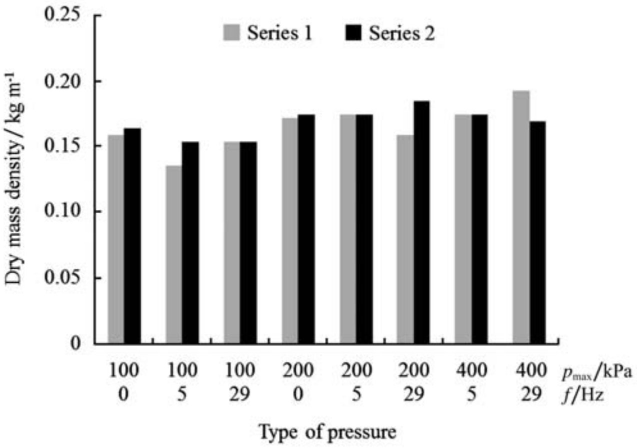
$$p_m = \frac{p_p + p_b}{2} \tag{2}$$

where, p_m is mean pressing pressure in the material, kPa; p_p is pressing pressure at the piston, kPa; p_b is pressing pressure at the cylinder base, kPa.

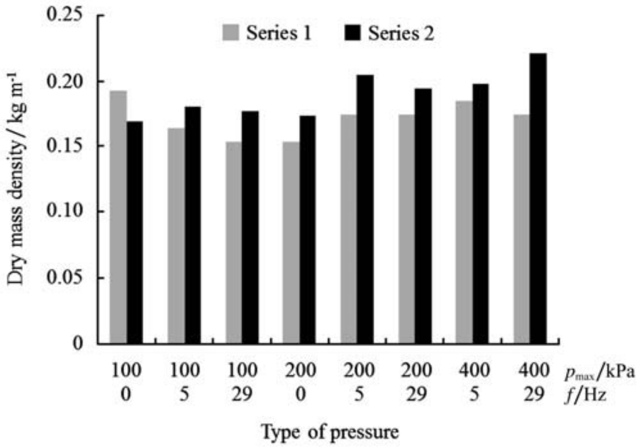
The pressing pressure p_m was 5% lower in all experiment variants than the pressure at the pressing piston. For a clearer presentation and because the trend of the effects on the ensiling material density does not change as a result of this, in the following evaluations the pressure at the pressing piston is always stated. This corresponds to the pressure under the wheel of a compacting vehicle.

3.2 Influence of the compaction variants on the ensiling materials density

The end densities after six double cycles in each case increase as expected if the maximum pressing pressure p_{max} is increase from 100 kPa, through 200 kPa to 400 kPa (Figure 5). In the case of drier material with a dry mass content of 34% (Figure 5b), the increase in density from one pressure stage to the next is more strongly pronounced than with more moist material with only 26% dry mass (Figure 5a). Series 2 is a repeat measurement of Series 1 in the reverse time sequence of experiment variants. The generally low deviations between Series 1 and Series 2 show the good reproducibility of the experiments.



a. D_M = 26%



b. D_M = 34%

Figure 5 End density after six double cycles for grass second cut with

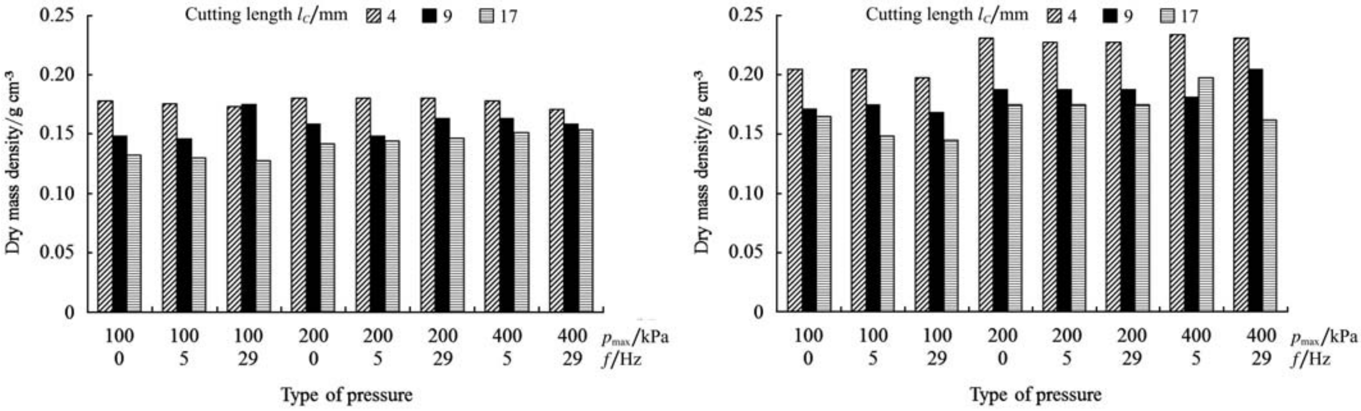
In our own experiments, with a higher dry mass content, a higher compaction effect occurs. Different findings are available on this in the literature. Edner (1995) established that with the increasing D_M content, the compaction effect was lower but the elastic recovery all the greater instead. Bernier-Roy et al. (2001) listed empirical equations of other authors to estimate the dry mass density. According to different equations, a higher dry mass content leads to a higher dry mass density. In their own compaction experiments with a rolling wheel, Bernier-Roy et al. (2001) found out that drier wilted grass can be compacted better than moister grass. In the case of maize, however, no influence of moisture became apparent.

One explanation for the contradictory results could lie in the fact that the compaction effect displays a moisture-dependent optimum (Dernedde, 1983). When drying the ensiling material there is initially a reduction of the turgor pressure in the cells of the leaves and stems and thus a reduction in stiffness. Up to about 50%-60% D_M content, the compactability improves as a result. At even higher D_M contents, however, the cells shrink until the vacuoles touch in the cells. As a result the stiffness of the material increases again. However, this happens in a dry mass range that is not customary in practice.

With diminishing cutting length, the end density is reduced in each load variant after six double cycles. The end densities reached are lower for more moist material at 24% D_M (Figure 6a) than for drier material at 33% D_M (Figure 6b).

The influence of the vibration is less clear. In a comparison of 100 kPa quasi-static versus 100 kPa 5 Hz or 100 kPa 29 Hz, hardly any differences in the end density become visible (Figure 7).

The vibrating load frequently leads to a lower end density by comparison with the quasi-static load. In compaction with vibration, the rising and lowering load means altogether a shorter period of activity of the pressure load, resulting in lower end densities. The loading variants with 200 kPa 5 Hz and 200 kPa 29 Hz on the other hand reach the same mean pressure as the quasi-static compaction with 100 kPa, frequently lead to somewhat elevated end densities. In the case of the load variant 200 kPa quasi-static too, higher end densities only result when the vibration is carried out with the doubled maximum pressure of 400 kPa (Figure 8). If the same mean pressure as in the quasi-static load is applied, it becomes apparent that ultimately the higher maximum pressure leads to higher end densities.



a. D_M = 24% b. D_M = 33%

Figure 6 End density after six double cycles for grass from the first cut with

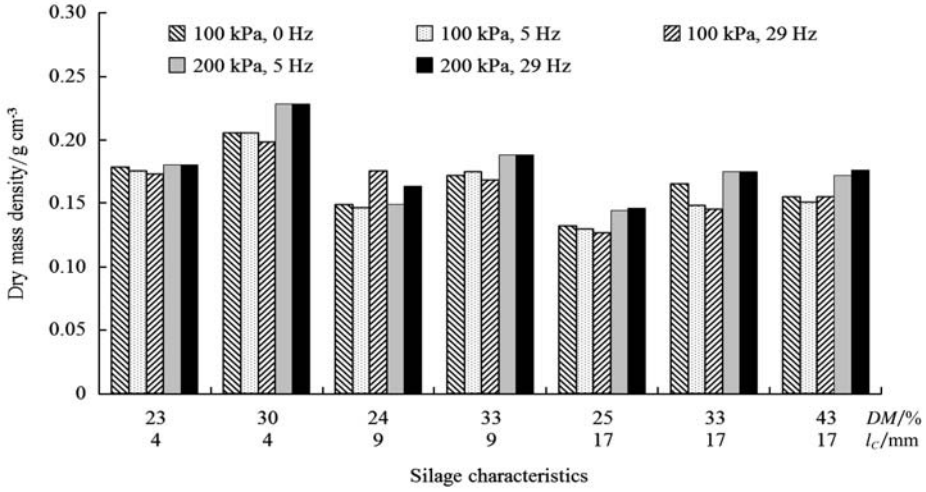


Figure 7 End density after six double cycles for grass from the first cut for 100 kPa maximum pressure with and without vibration and 200 kPa with vibration

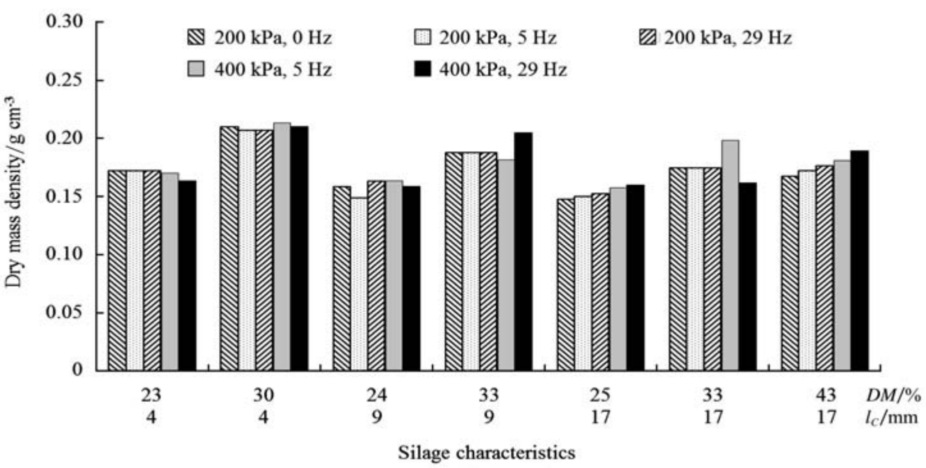


Figure 8 End density after six double cycles for grass from the first cut for 2 bar maximum pressure with and without vibration and 4 bar with vibration

The ensiling material densities applied over the number of compaction cycles follow a logarithmic function for all compaction variants with slight deviations (Figure 9).

With the exception of the variant 400 kPa 29 Hz, the density values after each compaction cycle are higher if the pressing pressure is higher. The curves for 200 kPa, 5 Hz and 29 Hz are congruent and run closely beneath the curve for 200 kPa 0 Hz.

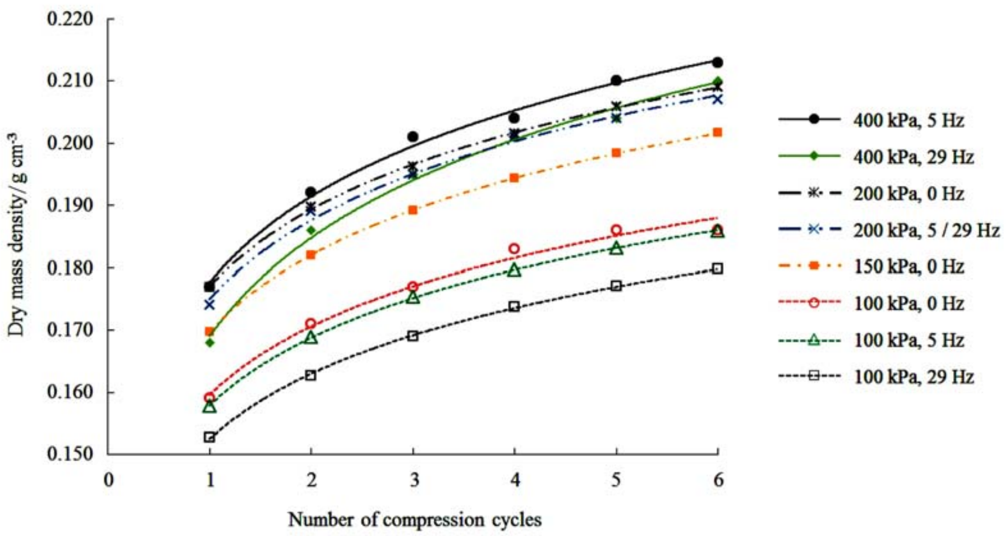


Figure 9 Dependence of the dry mass density on the number of compaction cycles for grass from the first cut, D_M 30%, l_C 4 mm

3.3 Variance analytical examinations

A variance analysis with the fixed effects maximum pressure (p_{max}), cutting length (l_C) and frequency (f), as well as the interaction cutting length times frequency, shows only maximum pressure and cutting length as significant fixed effects (Table 3). The random effect dry matter content (D_M) is also significant. With a coefficient of determination of $R^2 = 0.888$ the model explains most of the scatter. The frequency alone and in interaction with the cutting length is not significant. With the interaction frequency times cutting length it was examined whether the frequency has an influence at short cutting lengths and not at long cutting lengths. However, no difference was found.

Table 3 Variance analysis with independent variable end density and the factors dry mass content, load pressure, chopping length, frequency and chopping length – frequency interaction

Source	Degree of freedom	Sum of squares	Average of the squares	F	Significance
Modell	21	0.27506488	0.01309833	31.16	< 0.0001
Error	82	0.03446574	0.00042031		
Corrected sum	103	0.30953062			

Factor	Degree of freedom	Type III Sum of the squares	Average of the squares	F	Significance
D_M	5	0.22312808	0.04462562	106.17	<0.0001
p_{max}	2	0.01875265	0.00937633	22.31	< 0.0001
l_C	2	0.00585187	0.00292594	6.96	0.0016
f	2	0.00043850	0.00021925	0.52	0.5955
$l_C \cdot f$	6	0.00103174	0.00017196	0.41	0.8710

The frequency can be included in the model if the mean compaction pressure (p_{mean}) is used in the model instead of the maximum pressure (Table 4). Accordingly, the frequency possesses a significant influence on the end density. The coefficient of determination is also good at $R^2 = 0.885$.

Table 4 Variance analysis with independent variables end density and the factors dry mass content, chopping length, medium compaction pressure and frequency

Source	Degree of freedom	Sum of squares	Average of the squares	*F*	Significance
Modell	12	0.27401791	0.02283483	58.51	< 0.0001
Error	91	0.03551271	0.00039025		
Corrected sum	103	0.30953062			
Factor	**Degree of freedom**	**Type III Sum of the squares**	**Average of the squares**	***F***	**Significance**
D_M	5	0.22312808	0.04462562	114.35	< 0.0001
l_C	2	0.00599993	0.00299997	7.69	0.0008
f	2	0.00361874	0.00180937	4.64	0.0121
p_{mean}	2	0.01896340	0.00948170	24.30	< 0.0001

4 Conclusions

Initial systematic examinations of the influence of vibration in the model experiment show that at equally high maximum pressure, the dynamic compaction method does not allow any higher end densities to be achieved in the wilted grass than the quasi-static compaction method. The vibrating compaction only leads to higher end densities if the vibration is combined with a higher maximum pressure. This procedure is expedient because according to information supplied by manufacturers, vibratory rollers build up additional vertical forces as a result of the imbalance in the rolling element that – depending on the frequency – are equal to or higher than the static weight force (JCB, 2012; Hamm, 2012). The superimposition of static weight force and additional imbalance force brings about the improved compaction. In practice, a reduction of the compaction outlay of about 0.5 tractor min t^{-1} is shown (Häbler et al., 2008).

A further additional advantage in practice, is that roller elements compact over the entire working width. By comparison with tractors with wheels, the working width is increased by 100%.

It is to be assumed that as a result of the compaction of ensiling material by vibratory machines, the load on the silo walls will increase. However, there are not yet any reliable investigation results on this (Gruyaert et al. 2007; Langley, 2000). Further examinations are necessary before recommendations for use can be made.

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