Radiometric density measurement for silage compaction in bunker silos

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Abstract: Certain minimum densities should be targeted when storing silage in bunker silos. However, farmers lack facilities to measure the actual density and then steer the compaction passes. This study was aimed at developing a measuring device for onsite density measurement. The basis of the measuring device was a source of caesium radiation with an activity of 37 MBq and a sodium iodide scintillation detector. The measuring device used the backscattering method. The source and detector were located in a measuring wheel that was connected with the tractor via the rear three-point linkage. During measuring passes on bunker silos both the density increase in the case of several crossings and the elastic recovery of the material could be seen clearly. In connection with satellite-based position determination, the silo surface can be mapped according to density. As a result of the random decay of the caesium, the error in density measurement was only ±4% at 600 kg m^{-3}.

Keywords: silage compaction, bunker silo, silage density, radiometric measuring device

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1 Introduction

Horizontal silos can absorb high mass flows of silage material. From storage intake, the material has to be compacted by driving over it. For a long time it is well known which density should be achieved. However, farmers lack a measuring method enabling them to figure out and steer the compaction process on the basis of the silage density.

In order to measure the density of silage in practice, samples are drilled out from the silo using special drills (Muck und Holms, 2000; Kleinmans et al., 2005; Latsch und Sauter, 2011) or silage blocks are cut out with a silo block cutter (Wagner et al., 2004; Latsch und Sauter, 2011). The density is calculated from the volume taken and the associated mass. However, both these methods can only be applied after the storage period when the silage is removed.

In order to calculate the density during storage intake of the silage material, Häbler (2008) figured out the cargo mass on each transport vehicle and measured the associated volume change in the silo using a laser theodolite. In this way the average silage density can be measured for a defined silo space. However, this principle does not show local differences in density.

In another method, roller vehicles were equipped with distance sensors both in front of and behind the roller bodies. The distance to the subsoil was measured in front of and behind the roller bodies. The difference

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between these distances was then a measure for the compaction. This principle, known from road building (ABG, 1997), was tested successfully in horizontal silos (Häbler, 2008; Tölle et al., 2009). By this method the actual density cannot be figured out, instead, the compaction effect can.

For a relatively long time methods for measuring density or layer thickness on the basis of radiometry have been known. Radiometric measurements are used for soils, construction materials and sediments, as well as for natural materials such as wood (Malan and Marais, 1992; Macedo et al., 2002), tobacco (Okumoto, 1987), ice cream (Badr, 2012) starch suspensions (Kempf et al., 1976), grain (DLG, 2001), straw and silage bales (Mumme and Katzameyer, 2007; Gläser et al., 2007; Sun et al., 2012) and silages (Kuhn, 1976; Gläser and Kuhn, 1997).

When preparing their own projects, Fürll et al. (2008) examined various factors targeting continuous measurement of density during silage production – penetrometer, depth to which the tractor or measuring wheel sinks in, the film pressure measuring system, ultrasonic thickness measurement, georadar, microwave scatter field probe and radiometric measuring probe. In a comparison, the microwave scatter field probe and radiometric probe proved to be promising solutions. However, the subsequent measurements with a microwave scatter field probe did not show the desired connection with the material density. For this reason the radiometric measuring method was selected as the preferred solution for measuring density.

Accordingly, to meet requirements, a measuring unit for use on the bunker silo should be able to:

- measure density during movement of the tractor,
- avoid clogging of the measuring unit in forward and reverse movement,
- provide consistent height guidance in order to keep measuring faults low,
- be suitable for road traffic,
- possess compatible mounting facilities for common tractor types,
- display a robust design for use in agricultural practice.

2 Materials and methods

The core part of the measuring device consists of a caesium radiator with an activity of 37 MBq and a sodium iodide scintillation detector. The measuring system detects the gamma photons radiated back from the material. Caesium was chosen as a source because it provides a definite correlation between the number of backscattered gamma photons and the density of the material (Gläser and Kuhn, 1997). Scattering and absorption processes of gamma photons are overlapping inside the material. In the case of caesium the backscattering process dominates in the density range up to 1,000 kg m^{-3} in comparison to the absorption. Therefore, caesium enables the measurement.

The caesium source is located in a shielded container made of lead. The gamma photons of the caesium-137 source only emerge at the exit aperture of the shielded container and are directed exclusively to the material to be measured.

In preliminary experiments on a lab-scale pilot plant, the optimal geometric arrangement of source and detector were figured out (Geyer and Hoffmann, 2012). This arrangement was then realised for the measuring passes on the silo in a measuring wheel (Figure 1).

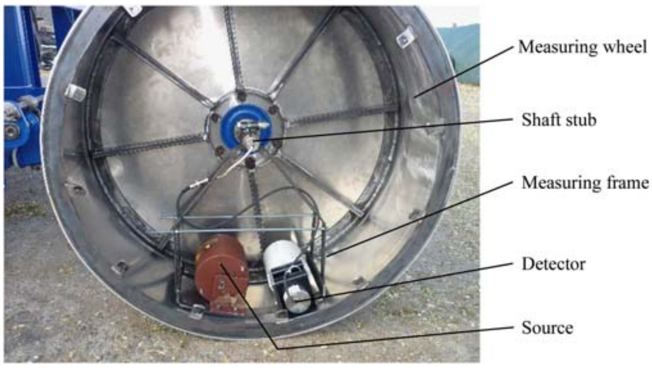


Figure 1 Measuring wheel with source and detector in the measuring frame

The measuring wheel had a diameter of one meter and a design width of 0.4 m. Its jacket surface was made of 5 mm aluminium sheet, so that as few gamma photons as possible were absorbed when the radiation passes through it. The source and detector were mounted on a measuring frame in the wheel. The frame was firmly connected at the wheel centre with a shaft stub via a clamp connection. The shaft stub was firmly mounted on the upward link. The upward link was part of a four-joint system and was always carried parallel to the three-point linkage of the tractor (Figure 2). With this construction method the upward link was always carried perpendicular to the subsoil. Consequently, the measuring apparatus was automatically oriented to the surface of the material to be ensiled.

Figure 2 Measuring wheel at the three-point linkage of the tractor

The design is suitable for road traffic. When transferring from one silo to another the measuring device can remain mounted on the tractor.

First of all, the radiometric measuring device was calibrated in mounted condition. For this, natural raw materials of known density were placed beneath the measuring wheel and the impulses of the radiation backscattering were measured. This method is based on the principle that organic materials are similar in their stochiometric composition and thus also display similar mass absorption coefficients (Gläser, 1992; Macedo et al., 2002). The materials used were hemp shives (woody fragments of the hemp stem), balsa, spruce and oak, as well as oats and rye grains. In addition, the impulse rates for air and water were measured. Balsa was sorted to two samples: The first sample with a density of 95 kg m^{-3}, while the second with a density of 185 kg m^{-3}. One spruce sample was measured in the natural density state with 430 kg m^{-3}, the other after a mechanical compression with 880 kg m^{-3}.

For each sample the backscattered photons were counted for 1 second with 100 repetitions. This means every measurement series consists of 100 values. A quadratic regression was done with all values of all series by using the statistical software SAS 9.3.

The measuring wheel was tested altogether eight times on bunker silos (location, date, crop, dry matter content):

- Trebbin, 23.09.2011, chopped maize, 40.4%
- Sperenberg, 30.09.2011, chopped maize, 37.0%
- Klein Schulzendorf, 13.10.2011, chopped sweet sorghum, 20.6%
- Gross Kreutz, 15.05.2012, chopped wilted grass, 33.4%
- Lietzow, 22.06.2012, chopped wilted grass, 34.5%
- Ketzin, 20.09.2012, chopped maize, 31.1%
- Lietzow, 04.10.2012, chopped maize, 34.5%
- Klein Schulzendorf, 15.10.2012, chopped wilted grass, 47.5%

The measuring passes were always conducted together with the roller vehicles of the respective farms (Figure 3).

Figure 3 Measuring pass on a bunker silo with chopped maize (20.09.2012)

The gamma photons scattered back from the ensiled material were counted and saved using the Field Operator 300 of the company WTK Elektronik (Neustadt, Germany). In the year 2012 data from a Differential Global Positioning System (DGPS) were added in order to be able to allocate the density values to concrete positions in the silo.

The purpose of the measuring passes was to show the expected increase in silage density for repeated roller passes. The second goal was to measure the local density of ensiled material when the vehicle tracks were continuously offset.

An error estimation was carried out for the radiometric density measurement. First of all it was necessary to estimate to what extent the random decay of the caesium influences the density value calculated. The second error component estimated was the extent to which the ensiled material expands back again after being driven over and measured (elastic recovery).

3 Results and discussion

3.1 Calibration of the radiometric measuring device

The calibration in air, various organic materials and water shows a quadratic connection between the given material density and the impulse rate in the backscattering (Equation (1)). To figure out the density, the equation converted for this purpose is to be used with negative signs in front of the radical expression (Equation (2)).

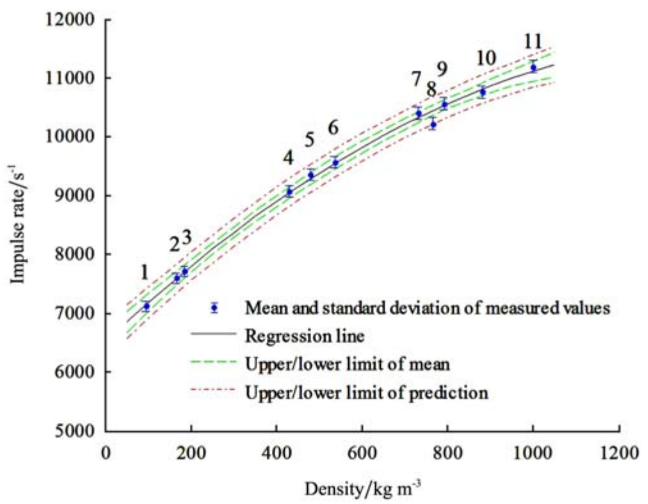
$$I = -0.002268 \cdot \rho^2 + 6.87148 \cdot \rho + 6517.57751 \qquad (1)$$

$$r^2 = 0.99$$

where, I = impulse rate , s^{-1}; ρ = density, kg m^{-3}.

$$\rho_{1,2} = 1514.87654 \pm \sqrt{1514.87654^2 - \frac{I - 6517.57751}{0.002268}} \qquad (2)$$

To take the background radiation into account, the calibration was renewed at each experimental location prior to the compacting passes.

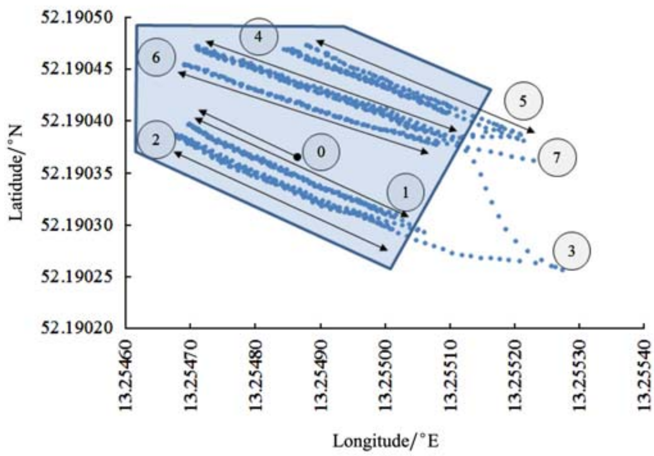


1. Balsa, low density 2. Hemp shives 3. Balsa, high density 4. Spruce, natural 5. Oats, loosely poured 6. Oats, firmly tapped 7. Rye, loosely poured 8. Oak 9. Rye, firmly tapped 10. Spruce, compressed 11. Water

Figure 4 Calibration curve with confidence areas for the radiometric density measuring device

3.2 Measuring passes determining density on the bunker silos

The compaction passes on the silo can be plotted on the basis of the GPS coordinates (Figure 5). Beginning from the starting point ①, a number of compacting passes ran in one track. From point ③ outside the silo, a changeover was made to the other side of the silo in order to compact the silage material there with a number of passes.



⓪ ... ⑦ numbers of tracks or turning points

Figure 5 Compaction trips on a clamp silo with multiple crossings in selected movement tracks

In three consecutive compaction passes in the track/rut ①, an increase in density became evident from the first forward pass to the second and subsequently to the third (Figure 6). The measuring system was thus in a position to figure out the compaction effect of repeated roller passes in a track or rut.

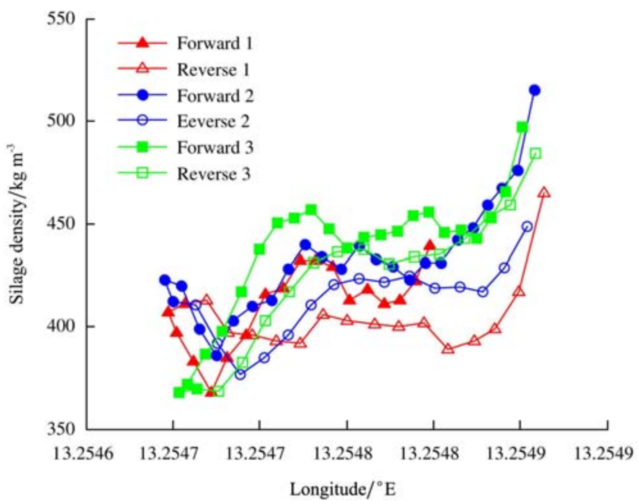


Figure 6 Density curve for three consecutive forward and reverse trips in one track, wilted grass, 15.10.2012

A higher density was measured during forward movement than in reverse movement. In forward movement the heavy tractor first rolled over the material and the density was then be measured. Some time elapseed before the following reverse movement, during which the material expanded back. During reverse movement the density was measured after this elastic recovery. Only by then was the next compaction operation carried out by the tractor.

Using the longitude and latitude, the compaction trips can be shown three-dimensionally (Figure 7). For better clarity, only the last trip was shown respectively. The densities achieved were evaluated via colour grading of the measuring points, from red for insufficient density to green for sufficiently compacted silage. Basically it was apparent that the density values on the silo vary strongly depended on the position. In principle, with this density position allocation and appropriate software, the roller vehicle driver has a tool enabling him to steer his further trips.

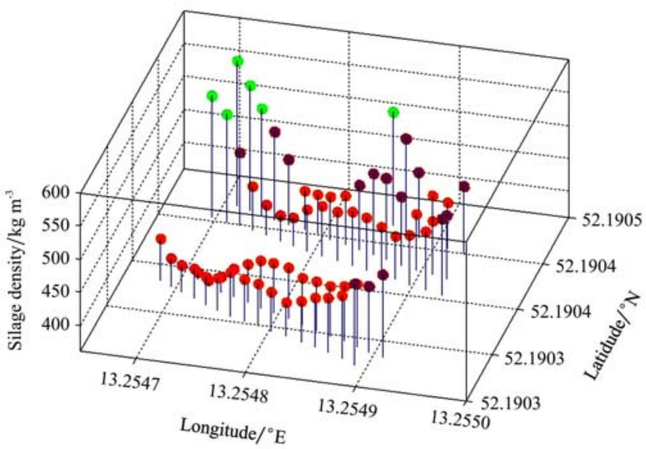


Figure 7 Measured silage density as a function of longitudes and latitudes on a clamp silo with wilted grass (green dots for high density, red dots for low density)

3.3 Error estimation

The density of the silage must be calculated from an individual value of the impulse rate. It was significant that the impulse rate emanating from the caesium source was not constant, but in view of the random decomposition of the caesium atoms a Poisson distribution was sufficient. For impulse rate I and standard deviation σ of a Poisson distribution, the following applies:

$$\sigma = \sqrt{I} \tag{3}$$

With a probability of 68%, an individual value lies in the range $\langle I-\sigma, I+\sigma \rangle$. Assuming that an impulse rate of I = 9824 s^{-1} is measured, according to Equation (2) this corresponds to a density of 600 kg m^{-3}. As a consequence of the measuring uncertainty, the impulse rate lies in the range $\langle$9725 s^{-1}, 9923 $s^{-1}\rangle$. According to Equation (2), this results in a density range of $\langle$576.45 kg m^{-3}, 624.18 kg $m^{-3}\rangle$. The error in the density as a consequence of the random decomposition of the caesium atoms which cannot be influenced is thus $\langle$-23.55 kg m^{-3}, 24.18 kg $m^{-3}\rangle$ at 600 kg m^{-3}. This corresponds to a relative error of $\langle$-3.92%, 4.03%$\rangle$, i.e. about 4%.

The silage expands again a little after a crossing. The elastic recovery can be measured using the online density measurement. If the vehicle moves forward and back in one vehicle track (Figure 3), then as a result of elastic recovery the density at a particular place is generally lower during reversing than it is during forward movement. However, the driver on the roller vehicle cannot use this information as he does not generally reverse in the same track. Usually the driver drives in laterally offset tracks. Furthermore, the density may be increased by other roller vehicles or reduced by new material.

A number of papers about estimating elastic recovery have been published. The values for reverse expansion fluctuate between 0% (Bernier-Roy et al., 2001) and 39% (Savoie et al., 2004). Often values between 8% and 15% are stated (Edner, 1985; Bernier-Roy et al., 2001). The great differences of these values are caused due to different material parameters but above all due to different experimental arrangements. Most experiments are based on press pot trials. An exception to this is formed by experiments conducted by Edner (1985), in which the silage density was figured out in practice in bunker silos with the aid of a gamma backscatter probe. Edner (1985) stated in the mean value that the silage density was reduced by about 8.3% in the density range less than 600 kg m^{-3} and 12.1% in the range 600-700 kg m^{-3} as a result of elastic recovery. The recovery time was very long. The time extended from the end of the storage at a day to the continuation of the storage on the following day. The elastic recovery of grass was higher than in maize, though both materials showed a large scatter width.

The experimental arrangement by Edner comes closest to the measuring task pursued by this paper. It is to be assumed that the silage density measured during forward movement needs to be reduced by about 10% arithmetically in order to obtain the final density. On reversing, the density is measured before the compaction vehicle rolls over the measuring point. Consequently, the true density is at least as high as the measured density.

4 Conclusions

By arranging source and detector in a trailed measuring wheel, the silage density can be measured online during movement. In conjunction with data from a Differential Global Positioning System (DGPS), the density values can be allocated to certain positions in the silo. Consequently, the prerequisites for density mapping of the silo surface exist.

The calibration of the radiometric measuring device with the aid of agricultural products displays a close connection between the impulse rate and the silage density. As a consequence of the random decay of the caesium atoms, a relative measuring error of 4% results at a silage density of 600 kg m^{-3}.

After a number of passes in one track or rut, an increase in the silage density was shown. The silage density in reverse movement was lower than that in forward movement as a result of elastic recovery of the silage. The silage density measured in forward movement needs to be reduced arithmetically by about 10% in order to reach a permanent end value. On reverse movement it is to be assumed that the true density is at least as high as the measured density.

The measuring passes on the bunker silo have demonstrated the radiometric density measurement functions in practical use. Further experiments with a modified analysis software will follow.

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