M. Della Zassa, M. Zerlottin, D. Refosco, A.C. Santomaso, P. Canu, Improved compaction of dried tannery wastewater sludge, (2015) Waste Management, 46, 472-479.
DOI: http://dx.doi.org/10.1016/j.wasman.2015.08.038

Improved compaction of dried tannery wastewater sludge

M. Della Zassa[a], M. Zerlottin[b], D. Refosco[b], A.C. Santomaso[a], P. Canu[a1]

[a]Dept. of Industrial Engineering - University of Padua - Via Marzolo, 9 - 35131 Padova, Italy
[b]Acque del Chiampo S.p.A. - Via Ferraretta, 20 - 36072 Arzignano (VI) - Italy

Abstract

We quantitatively studied the opportunities to improve the compaction of a granular waste, possibly combining with pelletization. The goal is increasing the mass storage capacity of a given storage volume, and reducing the air and moisture permeability, that often trigger uncontrolled, exothermic spontaneous reactions in waste powders. The study is based on dried wastewater treatment sludges from tanneries, but the indications are valid and useful for any waste in the form of powder, cohesive enough to be pelletized. Measurements of bulk density have been carried out at the industrial and laboratory scale, using different packing procedures, amenable to industrial processes. Waste as powder, pellets and their mixtures have been considered. The bulk density of waste as powder increases from 0.64 t/m^3 (simply poured) to 0.74 t/m^3 (tapped) and finally to 0.82 t/m^3 by a suitable, yet simple, packing procedure that we called dispersion, with a net gain of 28% in the compaction by simply modifying the collection procedure. Pelletization increases compaction by definition, but pellets packing is relatively coarse. Some increase in bulk density of pelles can be achieved by tapping; vibration and dispersion are not efficient with pellets. Mixtures of powder and pellets is the best packing policy. The best compaction results was achieved by controlled vibration of a 30/70%wt mixture of powders and pellets, leading to a final bulk density of 1 t/m^3, i.e. an improvement of compaction by more than 54% with respect to poured powders, but also larger than 35% compared to pure pellets simply poured. That means increasing the mass storage capacity by a factor of 1.56. Interestingly, vibration can be the most or the least effective procedure to improve compaction of mixtures, depending on vibration features.

Keywords: thermal treatments, dry sludge, solid waste management, apparent density, waste densification, pelletization.

1 Introduction

Several solids waste materials are available as particles, possibly with a broad size distribution, spanning from submillimiter fines to centimeters. This is very common for industrial wastes. A very broad category includes sludges after drying. The most common source of sludge is wastewater treatment, where they are unavoidable byproducts. Difficulties in effective sludge disposal may become the bottleneck for the whole water treatment process, and even propagate upstreams, jeopardizing the activities that require the wastewater treatment. Sludge production can be reduced by properly operating on the water treatment process (Khursheed et al., 2011). Further reduction of the sludge mass requires water removal, calling for extra energy input. Dewatering achieves an average solids contents of 25-30%wt; dewatered sludge must find environmentally compatible use,

1 Corresponding Author: paolo.canu@unipd.it

otherwise its landfilling can determine significant leachate production with groundwater pollution hazard (Allen, 2001). Further, sludge produced from some industrial wastewater can be even more problematic, because of metal and biodegradation resisting species content. This work addresses a general issue with reference to a specific sludge, produced by treatment of effluents dominated by tannery wastewater. In this case, dewatered sludge is even refractory to fermentation. It cannot be incinerated, because some constituent may lead to very toxic airborne emissions. It is then dried, removing a significant amount of mass as water, and disposed as individual big-bags, in a dedicated landfill. Water removal by thermal treatments is a very effective method to reduce the mass and size of a waste. Drying can be carried out with a number of technologies, where the key factor is the heat transfer method (convective or conductive). Often a low oxygen environment must be maintained, to prevent undesired combustion. Tannery sludges revealed potential reactivity when dried (Zerlottin et al., 2013; Della Zassa et al., 2012). Reactiviy was also reported for other materials and wastes, such as refuse-derived fuel (Yasuhara et al., 2010), paper, food, textiles and other municipal solid wastes (Moqbel et at, 2010), coal (Nelson et al., 2007), and municipal wastewater treatment sludges as well (Poffet et al., 2008), all of them containing oxidable specie and having a large specific surface, typical of granular solids. The mechanism (Zerlottin et al., 2013, Poffet et al., 2008) is facilitated by exposure to air and moisture, in turn related to the porosity of the storage. This motivates a specific investigation to reduce the porosity of temporary and long term storages. In addition to pelletization, we aim to quantify the potential of increasing the effective use of available storage volume, by augmenting the bulk density.

Apparently, the literature on wastes does not report studies concerning the modification of the bulk density of granular wastes, which is an issue that received some attention on the general powder technology literature. Aggregates of particles can arrange filling the available volume to a different extent, depending on the filling procedure (Santomaso et al., 2003) and subsequent mechanical treatments, such as shaking or tapping (Knight et al., 1995; Akiyama et al., 1986). The bulk density can then vary significantly. Unfortunately, a large part of the Literature refers to ideal, spherical particles, often just monodispersed (i.e. with a single characteristic size) (Gray, 1968; Benenati et al., 1962) with theoretical speculations on the compaction evolution mechanism (Linz, 1996). Mixing particles with significantly different sizes allows a further increase of packing. The effect has been studied for binary mixtures (i.e. with two sizes) of spheres (Rassouly, 1999; Zheng et al., 1995), and for more complex particle size distributions (Ouchiyama, 1981; Hoffmann et al., 1995), possibly including irregular shapes (Podczeck et al., 1996; Finkers et al., 1998). In this work we experimentally investigate the extent of compaction of dried wastewater sludge, either as powder, pellets or mixture of them, that can be practically achieved with procedures that can be taken to the industrial context. It is assumed that a larger compaction reduces the permeability of gases supporting exothermic reactions, in addition to increase the space utilization and reduce the impact of waste storages.

2 Materials and Methods

All the measurements have been carried out on a sludge originating from a single, large (1.5 millions equiv. inhabitants) wastewater treatment plant, almost exclusively dedicated to tanneries wastewater. Dried sludge is a powders that can be pelletized. Different methods for bulk density measurements are compared and applied to powders, pellets and mixtures of them. Details of both materials and methods are reported first.

2.1 Reference waste

This experimental work is based on a single material, which is a wastewater treatment sludge, thermally dried. The plant treats municipal and industrial wastewater, the latter largely prevailing and quite uniform in its origin, mainly collecting the local tannery district effluents. The size of the plant can be synthetically given in terms of dried sludge production rate, which is 72 tons/d on average, at 11% residual moisture. Drying is achieved through four lines, using both direct and indirect heating. The average residual moisture content, 11%, varies between a minimum of 8% to a maximum of 15%. Further details on this sludge and its production process are reported in a previous work (Zerlottin et al., 2013). Drying yields a granular solid, Figure 1, with brittle granules never exceeding 4 mm in size. Safety concerns, discussed elsewhere (Zerlottin et al., 2013) and the need to more effectively use the available storage volume suggest pelletization. The resulting pellets have cylindrical shape, Figure 1, with a constant diameter of 6 mm and variable length, the average being 19 mm.

Figure 1: dried sludge. As produced (left) and after pelletization (right).

The size distribution of the sludge as powder has been determined by sieving (AS 200, Retsch) using sieve openings of 4000, 3360, 2830, 1410, 1000, 800, 600 e 400 µm and approx. 0.5 kg of material. Pellets are unsuitable for sieving, misleading the size analysis. In this case, we used image analysis techniques, collecting high resolution 2D digital images analyzed with suitable graphics software (UTHSCSA ImageTool 3.0, University of Texas). We measured the different lengths of individual pellets, given that the diameter is constrained by the extruder head.. Note that image analysis provides the abundance of particle of a given size based on the length, while sieving is based on the relative mass. The two measurements can be consistently compared if the distribution of pellets lengths is converted to mass (Allen, 1997) as:

$$w_i=\frac{m_i}{\sum m_i}=\frac{\rho_s V_{p,i} f_i}{\sum \rho_s V_{p,i} f_i}=\frac{\rho_s \frac{\pi}{4} d_p^2 L_{p,i} f_i}{\sum \rho_s \frac{\pi}{4} d_p^2 L_{p,i} f_i}=\frac{L_p f_i}{\sum L_p f_i}$$

where m_i is the amount of mass in the i-th class, f_i and w_i are the number and mass fractions, d_p, L_p, V_p and ρ_s are the pellet diameter, length, volume and density respectively. In this particular case (cylindrical pellets) the expression of the mass fraction is particularly simple because the density and the pellet diameter are constant. Figure 2 shows the measured cumulated size distributions. For powders, the average size is 1.2 mm; no granules exceeds 4 mm. Pellets are very narrowly distributed about an average length of 19 mm.

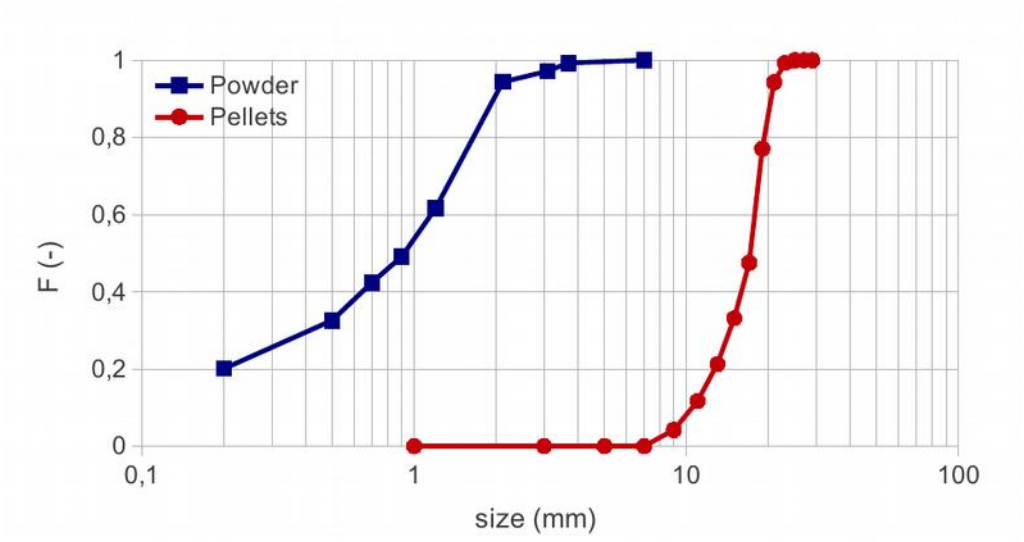

Figure 2: Particle size distribution (cumulated) of both the pelletized (right) and the powder (left) sludge.

The packing of particulate solid is related to its flow properties (Santomaso et al., 2003; Mohammadi et al., 1997). Powder flowability can be characterized in many ways and dramatically affects the performances of solids handling processes (De Jong et al., 1999). The simplest method is based on the static repose angle and the Hausner's ratio (HR). The first one has been measured with a simple standardized apparatus (Santomaso et al., 2003), while the HR is given by the tapped and

DOI: http://dx.doi.org/10.1016/j.wasman.2015.08.038

poured bulk densities ratio. The waste used in this study as powder is a free-flowing material, having a static repose angle of 39° and HR = 1.16. It implies that the bulk density can be significantly increased by a suitable, yet simple, pouring technique, described in the following. The free-flowing properties of pellets do not require a measure to be confirmed.

2.1 Density measurements

The amount of mass per unit storage volume is given by the bulk (or apparent) density, defined as (Gray, 1968):

$$\rho_b = \frac{mass\ of\ solids \in a\ given\ packing\ arrangement}{unit\ volume\ of\ the\ packing}$$

where the packing (sometimes called 'bed' of particles) is an assembly of solid particles and voids among them, possibly including the porosity internal to the solid particles. The true (or intrinsic density) is based on the purely solid volume, without any account of interstitial (inter- and intra-particles) voids. Apparent and intrinsic densities can be related to volume fractions. The most common fraction is called porosity, ε, defined as the ratio between volume of voids (internal and external) and total volume, i.e. $\varepsilon = V_{void}/V_{tot}$. Its complement, $\nu = 1 - \varepsilon$, is called the solids fraction and it is a measure of the compaction degree. The total volume refers to the bed, while the void is only due to the intraparticles space. The following relations among volume fractions and densities hold

$$\nu = \frac{\rho_{bulk}}{\rho_{true}} \qquad \rho_{bulk} = \rho_{true}(1-\varepsilon) = \rho_{true}\nu$$

While simple in principle, the measurement of bulk density may yield very different results by varying the procedure. The issue has been systematically investigated in a methodological work by our research group (Santomaso et al., 2003). The different methods, their significance and variability are now briefly recalled.

We define and measure the bulk density in 4 different ways, each one reflecting a specific procedure approximating the experimental practice, thus amenable to industrial implementation.

- **Poured** density - it is obtained by simply pouring the particles into a graduated vessel through a hopper. It is ruled by an international standard (ISO 3923-1, equivalent to ASTM B417 and EN 23923-1)

- **Tap** density - it is obtained by vertically tapping the receiving vessel. The measurement is a function of the extent of tapping. It is not standardized, although commercial instruments are available. We used a custom made one (Santomaso et al., 2003) where the rotation of the camshaft below the container determines a very uniform and reproducible tapping.

- **Dispersed** density - it is obtained by pouring the material through a sieving mesh. It is affected by the height of the sieve with respect to the collecting vessel, but it can yield packings even higher that by tapping. A pouring height of 0.5 m has been selected. The device used has been described elsewhere (Santomaso et al., 2003). With powders we used two screens with square opening, respectively of 4 and 5 mm, arranged staggered, 0.5 m above the receiving vessel, high enough to allow the particles to reach their final ensemble settling velocity in air, thus reaching the maximum of packing, once collected.
- **Vibrated** density - it is similar to the tap one, but using a vibrating base. It is affected by the geometry, amplitude, frequency and duration of the vibration. We used the sieving apparatus (AS 200, Retsch), operating at 50 Hz, with different amplitude (A=0÷3mm, nominally), for 15 minutes, although less then 10 minutes were always enough to stabilize the final bed volume. We always used a large container (12 cm in diameter; 1.8 L total volume) and approx. 0.5 kg of sludge as powder.

All the four techniques have been used for determining the bulk density of dried sludge in the form of powders. Difficulties arise with pellets, due to their larger size and elongated shape. The standard receiving vessel in the apparatuses mentioned above is too small (25 ml) to contain a sufficient number of pellets for a statistical average. A larger vessel (12 cm in diameter; 1.8 L total volume) has been used with pellets and mixtures of powders and pellets. In case of mixtures (powders and pellets) a preliminary uniform stirring was applied. Tapping was obtained by dropping the large vessel from a 10 cm height, at frequency of approximatively 1.2 Hz. The dispersed density was obtained with pellets using a sieving net with 1.2 cm square openings. The technique was not applied to mixture, because it loses significance, due to segregation.

Finally, the intrinsic density has been determined by pycnometry (displacement of a slowly wetting fluid, in this case water).

3 Results

The initial bulk density measurements are obtained, at the plant scale. They define the benchmark of all the following studies and they reflect the current practice in this plant, also representative of similar industrial plants producing wastes as powders. The waste (here a dried sludge) is poured from a temporary storage silo hopper, about 1m above a receiving big-bag of approx. 1 m^3 capacity. Note that the big-bag is a flexible container. The resulting bulk density was found to be 0.65 t/m^3. The filled bag can be compacted using the forklift truck to tap it on the ground, increasing the bulk density to approx. 0.73 t/m^3.

Filling the same type of big-bags with pelletized sludge leads to a bulk density approx. equal to 0.72 t/m^3, as extrapolated from smaller volume measurements, also allowing for the accommodation provided by a flexible containment. The compression of the powder to form pellets compensates for the larger porosity of an assembly of pellets. Still, the final use of available volume is comparable to a tapped powder, thus the pelletizing does not lead to any significant gain of mass storage.

The bulk density values measured in the plant set the reference for our study, in addition to the intrinsic density of the pellets, which is the maximum amount of mass per unit volume that we may ever achieve; it was found to be 1.3 t/m^3. Note that the intrinsic density of pellets is twice the poured density of powders industrially measured, leading to a theoretical doubling of the storage capacity, within the same given volume. In other words, the volume fraction of solids, ν, is 0.5 after pouring of powders, i.e. only 50% of the storage volume is effectively occupied by solids.

Table 1 summarizes, the initial information available. The following study aims at determining the conditions (packing procedures and combinations of powders and pellets) that maximize the mass per unit volume. We will discuss separately the cases of sludge as powder, as pellets, and mixtures thereof.

Table 1: summary of initial measurements, from the industrial practice.

Sludge	Poured density [t/m^3]	Tapped density [t/m^3]	Intrinsic density [t/m^3]
Powder	0.65	0.73	1.3
Pellet	0.72	-	1.3

3.1 The apparent density of powders

All the techniques described above have been used with dried sludge in the form of powder. Specifically, we investigated the asymptotic effect of tapping (Santomaso et al., 2003), increasing the number of strokes from 50 to 1200. Dispersed and vibrated density have been measured according to the methods describe above. Figure 3 summarizes all the measurements. The number of strokes is relevant for tapped density alone; the other density values are reported for comparison. The tapped density increases with the amount of tapping, as expected, starting from the value of the simply poured powder. Interestingly, the poured density measured with the laboratory apparatus is the same as measured on the industrial scale, on a 1 m^3 scale, confirming the representativeness of the lab scale technique for powders. Also the maximum density achieved by tapping is only slightly higher of the one measured industrially (see Table 1), likely because of the better uniformity and duration of the process at the lab scale.

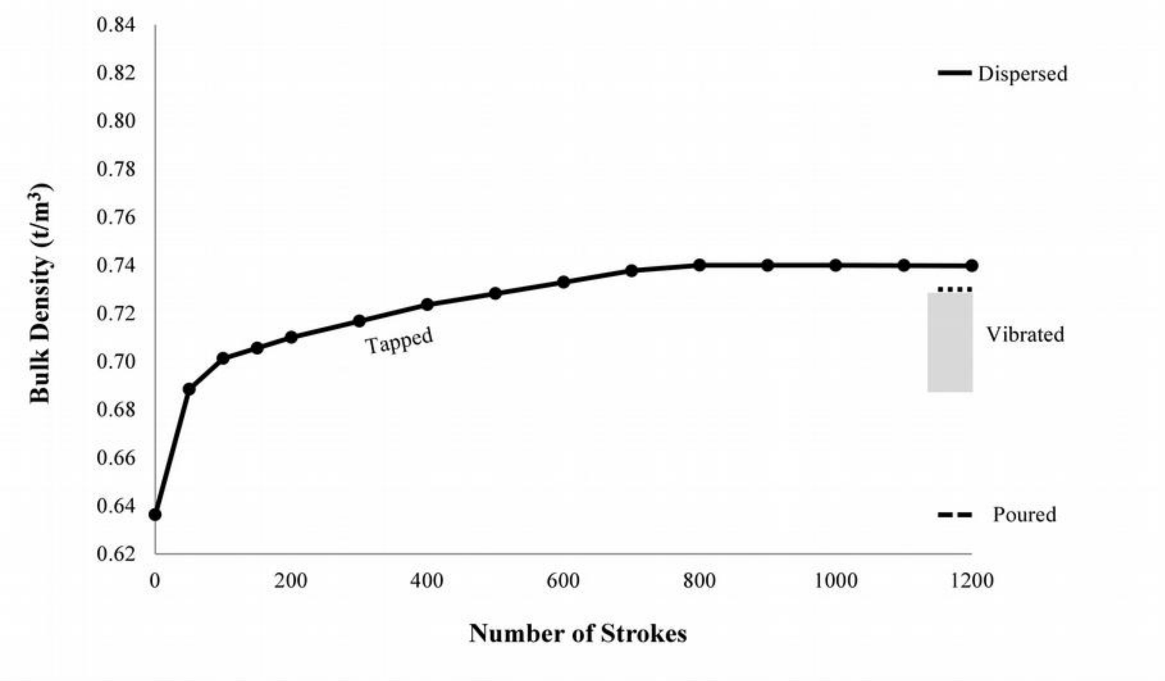

Figure 3: Tapped density of dried sludge powder as a function of number of strokes. Poured, vibrated (shaded area), and dispersed density values are 0.636, from 0.69 to 0.73, 0.82 t/m^3, respectively.

Since vibrated density may be affected by the amplitude and frequency of vibration, and these are design parameters for industrial vibrating devices, we investigated these factors, constrained by the limitation of the device used, operating at constant frequency. We systematically varied the amplitude of the vibrating plate between 0.2 and 2 mm. The energy transferred to the solids is expected to vary accordingly. The kinetic energy per unit mass is given by $E_{KIN} = v^2/2$. i.e. it is proportional to the square of the container displacement velocity. In a purely unidirectional harmonic oscillation the instantaneous velocity is linearly proportional to the amplitude, A, as $v(t) = -2\pi f\ A\ sin(2\pi f\ t)$, leading to $E_{KIN} \sim A^2$ at fixed frequency. We chose to report the results as a function of the relative kinetic energy, *RE,* i.e. the value with respect to a reference, set to the smallest amplitude, 0.2 mm:

$$\Re = \frac{E}{E_{Rif}} = \frac{A^2}{(0.2mm)^2}$$

We tested the amplitude values 0.2, 0.5, 1.0, 1.3, 1.5, 1.7, 2.0 mm, always at 50Hz and for 15 min. The vibrated densities obtained are shown in Figure 4, together with an estimation of uncertainty, determined by replicated experiments. The results vary in a rather narrow range, but still it is clear that the density is lower at extreme amplitudes, as evidenced by the parabolic interpolation.

M. Della Zassa, M. Zerlottin, D. Refosco, A.C. Santomaso, P. Canu, Improved compaction of dried tannery wastewater sludge, (2015) Waste Management, 46, 472-479.
DOI: http://dx.doi.org/10.1016/j.wasman.2015.08.038

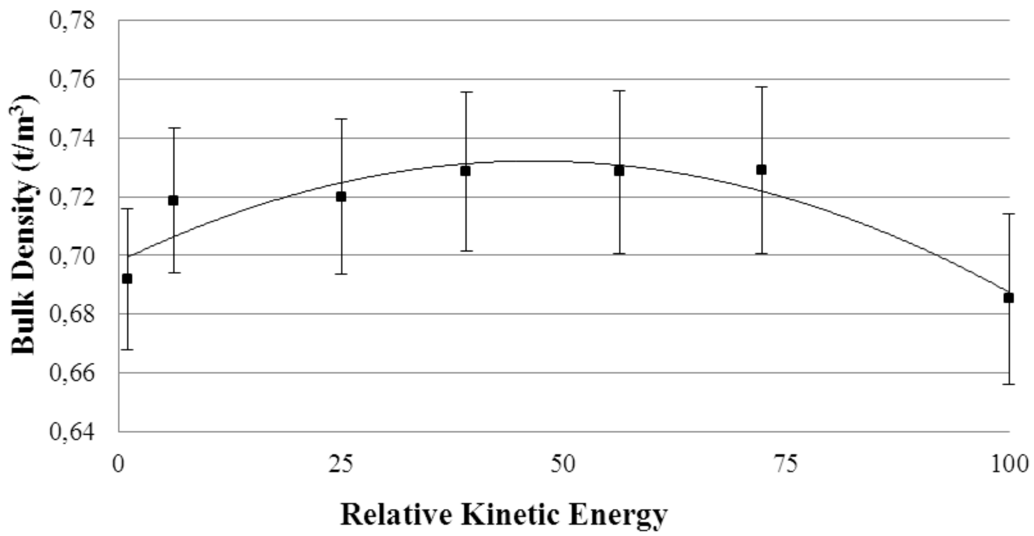

Figure 4: Vibrated density of dried sludge powder as a function of the relative kinetic energy due to different vibration amplitudes.

As anticipated in Figure 3, the vibrated density spans a range of values, with a maximum of approx. 0.73 t/m^3 at an intermediate amplitude, in the range investigated (from 0.2 to 2.0 mm). An amplitude too small does not provide enough energy to effectively rearrange the packing towards a higher compaction. Large amplitudes cause some fluidization to occur, thus aerating the packing during its rearrangement. The role of the surrounding fluid in vibrated bed has been the subject of a long debate since the seminal work by Faraday (1831). Nowadays it is established that the surrounding fluid (air) can affect the dynamics of a vibration dilated granular bed impacting on the formation of convective cells inside the bed, on the extent of segregation (Naylor *et al.*, 2003), on the formation of pressure waves in the bed, and can assist the fluidization of the bed. Predicting the final value of bed porosity (i.e. bulk density) after vibration or tapping is not trivial at all since irreversible processes develop, possibly leading to different porosity for the same vibration or tapping intensity. (Nowak *et al.*, 1997). Also, Literature typically investigates idealized calibrated or monodispersed materials (glass ballottini, sand). Here we have a combination of broad PSDs and very irregular shapes, so that pure experimental evidences are reported. Still a confirmation of an expansion of the bed compatible with the fluidization hypothesis is the observed increase in volume of the bed of powder during vibration.

Within an industrial view, the optimal combination of amplitude and frequency to be applied to a vibrating table requires dedicated measurements. It is not obvious that vibration is useful for compaction. Also, our data indicate that the increase of density by vibration of powders is at best comparable with tapping, an easier and more predictable practice.

The most astonishing result from Figure 3 is the much higher density obtained by the simple dispersion technique, 0.82 t/m^3 which is almost 11% higher than tapped density and 28% of the poured density, achieving a volume fraction of solid of 63%. The result was expected, following previous indications (Santomaso et al., 2003), being the waste (dried sludge) a free-flowing powder. Note that the large scale application of dispersing the powder while filling big-bags is quite feasible, although sieved occlusion may result from unusual 'particles' (like filaments) and issues of fines dispersion in the workplace environment must be addressed.

3.2 The apparent density of pelletized sludge

In principle, we may try to apply the same techniques described above to sludge pellets as well. However, the size of pellets requires much larger containers to collect meaningful, scale independent results. The main confusing effect is due to the container's walls, where the particle arrangement can be quite different from the bulk. Vessels large enough are required to reduce the ratio between boundary region and overall volume. Literature (Zou et al., 1996) provides correlations to account for the wall effect on the average density for spherical particles. Accordingly, with our pellets assumed as 1cm equivalent diameter spheres, the wall effect extends to 1 cm. Accordingly, we used a 12 cm diameter collecting vessel, for pouring, tapping, dispersed and vibrated density measurements. All the results are reported in Figure 5, similarly to Figure 3.

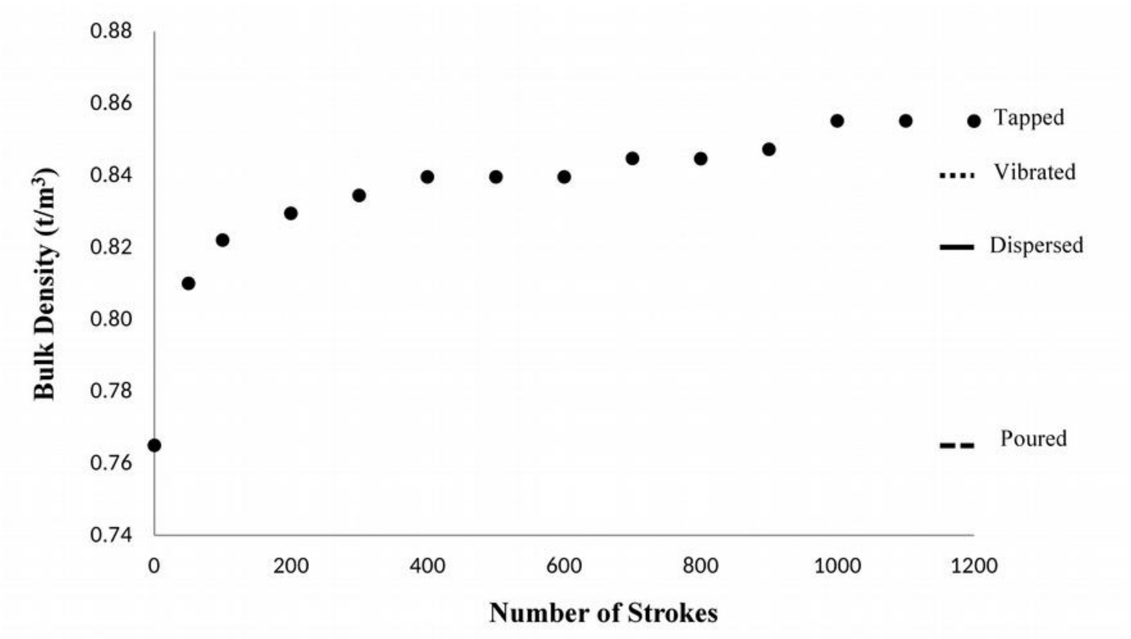

Figure 5: Tapped density of pelletized dried sludge as a function of number of strokes.
Poured, vibrated (shaded area), and dispersed density values are 0.765, 0.84, 0.82 t/m^3, respectively.

The values are always higher than for powder, thanks to the overall gain due to compression. Further, Figure 5 shows that additional increase in effective use of volume can be obtained by tapping. Tapped density can rise up to 0.86 t/m^3 from the initial 0.76 t/m^3 value after pouring, with a

13% increase in the use of the available volume, which now reaches 66% solids fraction. The maximum density improvement by vibration is again close to that of tapping, but still slightly lower. The amplitude of vibration turned out to be less influential, having measured the same vibrated density at 1 and 2.4 mm amplitude. Again, the effectiveness (or detrimental) effect of vibration is strongly dependent on the material properties.

Interestingly, the dispersed density is not higher than tapped one, as expected from large, free-flowing particles. It reflects the difficulty to select a proper sieve to distribute such elongated particles and the reduced mobility of the packing particles, because of their shape. Theoretically, the highest amount of solids per unit volume would be obtained by arranging pellets perfectly aligned, side by side. Figure 6 shows two possible close arrangements. They lead to ν=0.78 for the square order and ν=0.91 for the triangular pattern, i.e. more than 90% of the available volume would be occupied by solids.

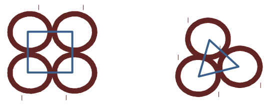

Figure 6: Theoretical closed packing of cylindrical pellets. Square (left) and triangular (right) pattern.

Since such ordered arrangements of pellets cannot be practically achieved neither by vibrating or uniformly filling a container by gravity (dispersion pouring), we must conclude that pellets alone yield a maximum density by tapping, equal to 0.86 t/m^3 or ν=0.66, with a large unexploited potential of filling the residual void. We may combine powders and pellets to overcome this limitation.

3.3 The apparent density of mixtures of powders and pellets

Following the intuition and the discussion on the maximum density achieved by pellets, we may expect that filling the voids between pellets with powder can lead to an even higher amount of mass per unit volume. Now the question is determining the optimal proportion of powders and pellets and a procedure such that particles fill the voids between pellets as effectively as possible.

We considered mixtures with fixed total mass of approx. 0.8 kg, distributed between powders and pellets in different weight fractions. We chose mixtures having 0%, 30%, 40%, 50%, 70%, and 100% wt. of powder, the remainder being pellets. We measured the poured, vibrated and tapped (up to steady-state) bulk densities. Dispersed density is intrinsically impossible to obtain because of the large difference of particle size that prevents the identification of a suitable dispersing screen. All the results are reported in Figure 7, where two vibrating amplitudes are considered.

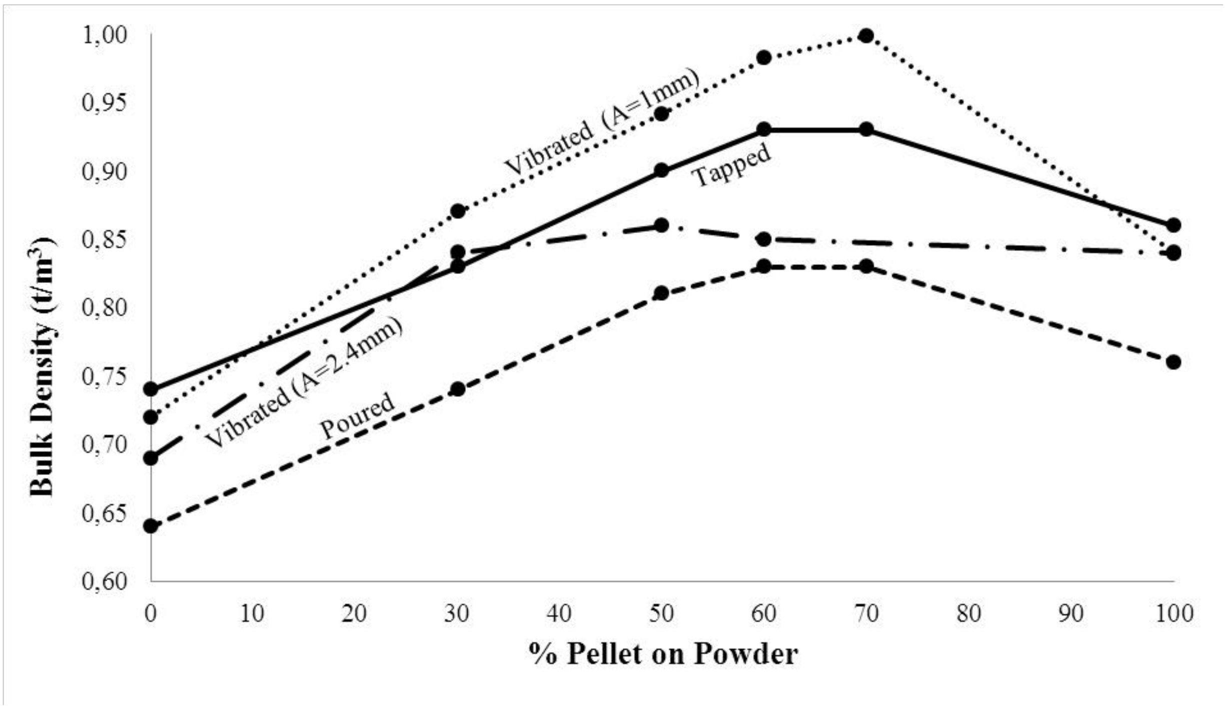

Figure 7: Poured, vibrated (A=1mm and 2.4 mm) and asymptotic tapped density of several mixtures of powder and pelletized dried sludge.

According to the expectations, all types of bulk density indicate an advantage in using mixtures instead of powders of pellets alone (i.e. the values on the right and left edges of the curves). However, the optimal proportion is not obvious, as already reported (Finkers et al., 1998), except approximately for the large amplitude vibrations. The optimal packing is in the region of 30 to 40%wt of powder. The highest packing is obtained by small amplitude vibration, able to produce a bulk density of 1 t/m^3, corresponding to a solids fraction ν=0.77 with a net improvements on the simply poured dried sludge powder by 54%. Interestingly, the same technique leading to the highest compaction, i.e. vibration, also leads to a very poor packing if operated with too large amplitude. In this case, the fluidization of the bed triggers the so called “Brazilian nut” effect (Bridgwater, 1976), where the larger particles (the pellets) gradually emerge and float on top of a fluidized bed of powder. Eventually, the mixture segregates, leading to a layering of two single phases, powder or pellets. The effect occurs over quite a large range of mixture composition, as apparent from Figure 7.

On the contrary, a more gentle vibration stimulates the percolation of powders in the coarse packing of pellets, leading to an high solids content. Tapping is not as effective in promoting an effective mobility of powders in between pellets. It is likely that even higher densities could be obtained for given couples of materials by optimizing the vibration properties, including the amplitude, as shown here, the frequency and the 2 dimensional motion (vertical displacement, possibly with some rotation). Without a proper investigation on the effect of vibration, it is safer to use tapping, which is always beneficial and simple to apply.

The results on mixtures are certainly affected by the relative size of powders and pellets. We were constrained to the sized used because of the rigidity of the production process. We expect that the highest density always occurs with uneven proportions of powders and pellets, but the precise optimal combination and the density gain may vary with size ratio.

All the results are summarized in Figure 8, comparing pure powders, pure pellets and 30/70%wt mixture of powders and pellets. Results are reported in terms of solids content achieved per unit total volume, i.e. compaction degree, because it directly informs about the efficiency in the use of the storage volume and the reduction of intraparticle spaces, available for gas diffusion .

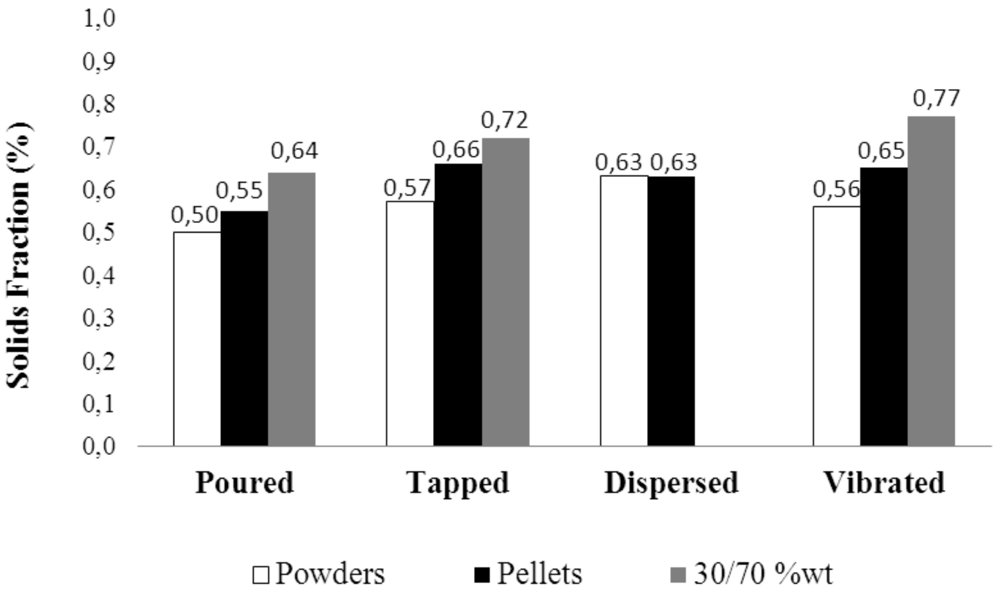

Figure 8: Solids fraction of dried sludge as powders, pellets and their 30/70 %wt mixture, according to different compaction processes.

For each type of density, we see an improvement from powders to pellets and then mixtures. The dispersed density is an exception, both because it cannot be easily obtained for mixtures, and it already leads to quite high densities also for powders, approaching the result of pelletization. Comparing the procedures, it is evident that pouring is the less efficient one, while tapping and (suitable) vibrations achieve the closest packing for pellets and mixtures. Dispersion is extremely efficient in packing powders. Overall, we see that volume exploitation can be increased from 50 to 77%, i.e. a 54% improvement in capacity of the storage volume, by selecting the best combination of processes and materials. At the same time, the voids that allow air and moisture permeation can be approx. halved, from 50 to 23%, dramatically dropping the hazard of waste reactivity.

M. Della Zassa, M. Zerlottin, D. Refosco, A.C. Santomaso, P. Canu, Improved compaction of dried tannery wastewater sludge, (2015) Waste Management, 46, 472-479.
DOI: http://dx.doi.org/10.1016/j.wasman.2015.08.038

The industrial viability of preparing calibrated mixtures of powders and pellets for storage is quite straightforward, by simply using volumetric feeders and a suitable filling arrangement, possibly inspired by the concept and effectiveness of the dispersed density procedure.

4 Conclusions

We quantitatively studied the opportunities to improve the compaction of dried sludge from a wastewater treatment plant, possibly using pelletization. The motivation is twofold, increasing the mass storage capacity of given landfilling volumes and reducing the air and moisture permeability, that has been proven to promote possibly uncontrolled exothermic spontaneous reactions with the waste studied here, as well as other wastes.

Measurements of bulk density have been carried out at the industrial scale, at 1 m^3 scale and in the laboratory, with hundreds of grams, using different packing procedures, amenable to industrial processes. Waste as powder, pellets and their mixtures have been considered.

We experimentally demonstrated that:

- waste as *powder* takes a great advantage of the dispersion procedure to improve its bulk density, more effectively than tapping. Densities increase from 0.64 t/m^3 (simply poured) to 0.74 t/m^3 (tapped) and finally 0.82 t/m^3 by dispersion, with a net gain of 28% in the compaction;
- waste as *pellets* is already more compacted by definition, but the pellets arrange with lots of void. Tapping increases compaction by 13% (from 0.76 t/m^3 to 0.86 t/m^3); compared to simply poured powders, the improvement is more than 34%. Vibration and dispersion are not very efficient.
- *Mixtures* could be very effective to exploit the available volume, but the optimal proportion is not obvious and the packing procedure deserves surprises. The best compaction is achieved by small amplitude vibration of a 30/70%wt powders/pellets mixture, leading to a final bulk density of 1 t/m^3. It means an improvement of the content of solids per unit volume by more than 54% with respect to poured powders, but also larger than 35% compared to pure pellets simply poured. Interestingly, vibration can be the most or the least effective procedure to improve compaction, depending on vibration features. It is likely that even higher compaction can be achieved with powder and pelletized waste by a more careful optimization.

The study concludes that a given storage volume can be reduced by a factor of 1/1.54 (i.e. approx. to 2/3 the original size) with simple modifications of the waste management procedures. In addition, the well-known hazard of waste storage self-heating due to reactions supported by air and moisture can be dramatically reduced.

The economic advantage is determined by the local cost of waste disposal and energy, as well as the waste production rate. Pelletization introduces fixed and variable costs. Distributing the fixed costs over 5 years, and accounting for the extra energy requirements we estimate a net saving of 25% on the current cost of waste disposal, if a 30/70 tapped mixture (0.92 t/m^3) is used to replace simply poured powders (0.64 t/m^3).

References

Akiyama, T., Miyamoto, Y., Yamanaka, N., Zhang, J. Q., 1986. Densification of powders by mean of air, vibratory and mechanical compaction. Powder Technology 46, 173- 180.

Allen, A., 2001. Containment landfills: the myth of sustainability. Engineering Geology 60, 3-19.

Allen, T., 1997. Particle size measurement, B. Scarlett , G. Jimbo eds., Chapman and Hall, London.

Benenati, R. F., Brosilow, C. B., 1962. Void fraction distribution in beds of spheres. AIChE Journal 8 (3), 359-361.

Bridgwater, J., 1976. Fundamental powder mixing mechanisms. Powder Technol. 15, 215.

De Jong, J. A. H., Hoffmann, A. C., Finkers, H. J., 1999. Properly determine powder flowability to maximize plant output, Chemical Engineering Progress, 25, 34.

Della Zassa, M., Biasin, A., Zerlottin, M., Refosco, D., Canu, P, 2013. Self-heating of dried industrial wastewater sludge: lab-scale investigation of supporting conditions. Waste Management, 33(6), 1469-1477.

Faraday M., 1831. On a Peculiar Class of Acoustical Figures; and on Certain Forms Assumed by Groups of Particles upon Vibrating Elastic Surfaces. Philos. Trans. R. Soc. London 121, 299-340.

Finkers, H. J., Hoffmann, A. C., 1998. Structural ratio for predicting the voidage of binary particle mixtures. AIChE Journal 44 (2), 495-498.

Gray, W. A., 1968. The packing of solid particles. Chapman and Hall Ltd, London.

Hoffmann, A. C., Finkers, H. J., 1995. A relation for the void fraction of randomly packed particle beds. Powder Technology 82, 197-203.

Khursheed, A., Kazmi, A. A., 2011. Retrospective of ecological approaches to excess sludge reduction. Water Research 45 (15), 4287-4310.

Knight, J.B., Fandrich, C.G., Lau, C.N., Jaeger, H. M., Nagel, S. R., 1995. Density relaxation in a vibrated granular material. Phys. Rev. E 51, 3957-1995.

Linz, S. J., 1996. Phenomenological modeling of the compaction dynamics of shaken granular systems, Phys. Rev. E 54, 2925-2930.

Mohammadi, M. S., Harnby, N., 1997. Bulk density modelling as a means of typifying the microstructure and flow characteristics of cohesive powders. Powder Technology 92, 1-8.

Moqbel S., Reinhart D., Chen R.-H., 2010, Factors influencing spontaneous combustion of solid waste, 24 Waste Management , 30, 1600–1607.

Naylor M.A., Swift M.R., Knight P.J., 2003. Air-driven Brazil nut effect, Physical Review E 68, 012301

Nelson, M. I., Chen, X. D., 2007. Survey of experimental work on the self-heating and spontaneous combustion of coal. Rev Eng. Geol. 18, 31-83.

Nowak, E.R., Knight, J.B., Povinelli, M.L., Jaeger, H.M., Nagel, S.R., 1997. Reversibility and irreversibility in the packing of vibrated granular material .Powder Technology, 94 (1), 79-83.

Ouchiyama, N., Tanaka, T., 1981. Porosity of a mass of solid particles having a range of sizes. Ind. Eng. Chem. Fundam. 20, 66-71.

Podczeck, F., Sharma, M., 1996. The influence of particle size and shape of components of binary powder mixtures on the maximum volume reduction due to packing. International Journal of Pharmaceutics 137, 41-47.

Poffet, M., Kaeser, K., Jenni, T.A., 2008. Thermal runaway of dried sewage sludge granules in storage tanks. Chimica 62, 29-34.

Rassouly, S. M. K., 1999. The packing density of 'perfect' binary mixtures. Powder Technology 103, 145-150.

Santomaso, A.C., Lazzaro, P., Canu, P., 2003. Powder flowability and density ratios: the impact of granules packing. Chemical Engineering Science 58, 2857–2874.

UTHSCSA ImageTool program - University of Texas, Health Science Center at San Antonio, Texas http://compdent.uthscsa.edu/imagetool.asp

Yasuhara, A., Amano, Y., Shibamoto, T., 2009. Investigation of the self-heating and spontaneous ignition of refuse derived fuel (RDF) during storage. Waste Management 30, 1161–1164.

Zerlottin, M., Refosco, D., Della Zassa, M., Biasin, A., Canu, P., 2013. Self-heating of dried wastewater sludge. Waste Management 33 (1), 129-137.

Zheng, J., Carlson, W. B., Reed, J. S., 1995. The packing density of binary powder mixtures. Journal of the European Ceramic Society, 15, 479-483.

Zou, R. P., Yu, A. B., 1996. Wall effect on the packing of cylindrical particles. Chemical Engineering Science 51 (7), 1177-1180.