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The impact of compaction, moisture content, particle size and type of bulking agent on initial physical properties of sludge-bulking agent mixtures before composting

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A B S T R A C T

This study aimed to experimentally acquire evolution profiles between depth, bulk density, Free Air Space (*FAS*), air permeability and thermal conductivity in initial composting materials. The impact of two different moisture content, two particle size and two types of bulking agent on these four parameters was also evaluated. Bulk density and thermal conductivity both increased with depth while *FAS* and air permeability both decreased with it. Moreover, depth and moisture content had a significant impact on almost all the four physical parameters contrary to particle size and the type of bulking agent.

Keywords:
Composting
Physical parameters
Compaction
Moisture content
Particle size

1. Introduction

The key role played by physical properties of organic materials treated by composting has been brought to light by several studies (Druilhe et al., 2008; Gea and Richard, 2008; Malinska and Richard, 2006; Mohee and Mudhoo, 2005; Van Ginkel et al., 2002; Veeken et al., 2003). Bulk density, Free Air Space (*FAS*), air permeability and thermal conductivity are four physical parameters of particular importance. These parameters are all interconnected and have an impact on biodegradation kinetics and also on heat and mass transfer in the composting system (such as oxygen supply, water evaporation and heat balance). Lower permeabilities result in a decrease in oxygen availability and airflow across the matrix, causing heat accumulation and high temperatures which inhibit microbial activity (Haug, 1993). With low thermal conductivities, heat generated by the metabolic activity of micro-organisms is not evacuated efficiently (even more if thermal Péclet values are low), causing high temperatures too. Low *FAS* decreases the degradation rate (Richard et al., 2002) and may lead to anaerobic conditions with gaseous and odorous emissions (Veeken et al., 2003).

Difficulties often occur in composting experiments because the effects of compaction on physical properties are ignored, or information about these effects is lacking. As soon as the pile of waste is built, the settlement of the composting matrix begins. This settlement, called primary settlement or physical compressive settlement (Gourc et al., 2010; Yue et al., 2008), is related to the vertical load and results in compaction. At local scale, it leads to a decrease in *FAS* and air permeability and can therefore affect the efficiency of oxygen supply and heat and moisture removal (Veeken et al., 2003; Yue et al., 2008). These effects of compaction on physical properties are often ignored; or information about these effects is lacking. Similarly, despite its obvious importance on the process, thermal conductivity is currently not well considered in the existing literature. The link between compaction and thermal conductivity is, therefore, rather unclear.

This study had two main objectives. Firstly, it aimed to investigate the impact of compaction on initial physical properties of organic solid wastes. Leaning on the existing literature, four key parameters were selected (among the numerous parameters which play a role in the composting process): bulk density, *FAS*, air permeability and thermal conductivity. Secondly, the study investigated how three preparation parameters (moisture content, particle size and the type of bulking agent) impacted these physical properties. The study was carried out on mixtures of urban sludge and bulking agents. Sludge could not be composted alone because of their lack of physical structure. Hence, they had to be mixed with bulking agents. Two moisture contents, two particle sizes and two different bulking agents were, therefore, selected and tested.

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Nomenclature

α_1	numerical coefficient (–)	h_0	initial level before settlement (m)
α_2	numerical coefficient (–)	H	height of the material bed (m)
α_3	numerical coefficient (–)	K	air permeability (m^2)
β_1	numerical coefficient (–)	L	characteristic length (m)
β_2	numerical coefficient (–)	La	lage number (–)
β_3	numerical coefficient (–)	m_i	mass added to the layer *i* (kg)
ΔP	pressure drop (Pa)	M_i	mass of the layer i (kg)
η	passability (m)	MC_{wb}	moisture content in wet basis (–)
λ	thermal conductivity (W m^{-1} K^{-1})	n	mole of gas (mol)
μ	air viscosity (Pa s)	P	gas pressure (Pa)
ρ	air density (kg m^{-3})	Pe_{th}	Péclet number (–)
ρ_w	bulk density of water (kg m^{-3})	Q	dissipated electrical power per unit length (W m^{-1})
ρ_{wb}	bulk density in wet basis (kg m^{-3})	R	gas constant (J K^{-1} mol^{-1})
Φ	degree of saturation (–)	R_{eK}	permeability-based Reynolds number (–)
A	numerical coefficient (–)	T	gas temperature (K)
B	compressibility (–)	T_P	probe temperature (K)
BD_i	bulk density of the layer *i* (kg m^{-3})	U	superficial air velocity (m s^{-1})
C_p	thermal capacity (J kg^{-1} K^{-1})	V	gas volume (m^3)
D	thermal diffusivity (m^2 s^{-1})	V_{fl}	volume to fill line (m^3)
FAS	Free Air Space (%)	z	depth (m)
h_i	settlement of the layer i (m)		

A thorough understanding of how compaction affects the physical properties and of the interconnections between compaction, bulk density, *FAS*, air permeability and thermal conductivity is of great interest for further advances in process control and analysis. Similarly, the comprehension of how moisture content, particle size and the type of bulking agent impact the physical parameters cited above is also fundamental to the preparation of mixtures before composting.

2. Methods

2.1. Sample preparation and characteristics of materials

The substrate tested in these trials was an urban sludge mixed with bulking agents. Two types of bulking agents were used: recycled and fresh wooden palettes. The urban sludge came from a wastewater treatment plant, the recycled wooden palettes used as bulking agents were collected from a composting platform and had already undergone many composting cycles (a dozen) while the fresh ones were directly bought from a retailer.

For each urban sludge-bulking agent mixtures, two moisture contents (50% and 65%) and two meshes of bulking agents (<20 mm and >20 mm) were tested, leading to a total of eight different mixtures. As on the industrial site, the volumetric ratio of the sludge/bulking agent mixtures was fixed at 1/3 (which corresponded to a dry mass ratio of 0.147). The two moisture contents were selected to test a low and a high value of the range which can be observed on-site. To minimize changes in the fresh materials, the sludge was sealed in plastic bags, stored frozen at −20 °C and thawed as needed in a refrigerated room at 4 °C. Likewise, the prepared mixtures were kept at 4 °C between two sets of measurements in the "Schaub-Szabo" and the "CPP" devices.

In order to lighten the writing, sludge-recycled palettes mixtures will be referred to as mixtures M and sludge-fresh palettes mixtures as mixtures M′.

2.2. Experimental setup

2.2.1. "Schaub-Szabo" device

The experimental device used to simulate compaction and to determine the variation of bulk density with depth (Schaub-Szabo and Leonard, 1999) consisted of a cylindrical Plexiglas container for the material and a set of weights with a platform scale to apply vertical loads. The container was approximately 700 mm high with an inside diameter of 388 mm, and a fill line was marked 400 mm from the bottom. Inside the container, a bottom grid allowed potential water loss (leachates) from the sample, and the container was perforated at the bottom so that the water can be collected in a recipient placed below.

Practically, the recipient containing the sample was weighed; the sample was placed in the container until it reached the fill line, and the recipient was weighed again. The mass of the sample (M_1) was determined by difference and the bulk density of the first layer (BD_1) calculated according to:

$$BD_1 = \frac{M_1}{V_{fl}}$$

where V_{fl} is the volume to fill line (0.04729 m^3).

To determine the bulk density in the second layer (BD_2), known masses were placed on top of the sample to apply a load equivalent to the mass M_1 to the sample in the container. The masses used were steel disks with a diameter of 380 mm (slightly less than the Plexiglas container) and adjusted by adding a known volume of water on top of them. The loading was applied for 24 h, until the material stabilized to a constant volume.

At the end of the compression, the settlement of the matrix (h_2) was recorded. Then, the loading system was removed and fresh material was added to get a 400 mm (h_0) height. The mass added (m_2) was calculated as follows:

$$M_2 = BD_2 \cdot V_{fl} \cdot \left(1 - \frac{h_2}{h_0}\right)$$

The above procedure was repeated, layer by layer, to simulate six layers of material, which corresponded to a pile of waste of 2.4 m high. A relationship between bulk density and depth for each mixture was finally obtained.

2.2.2. CPP device

The bulk density profiles obtained from the "Schaub-Szabo" device were re-created in a modified air pycnometer and *FAS*, air permeability and thermal conductivity were measured at each step of compaction. The apparatus used (called "CPP" for compaction/

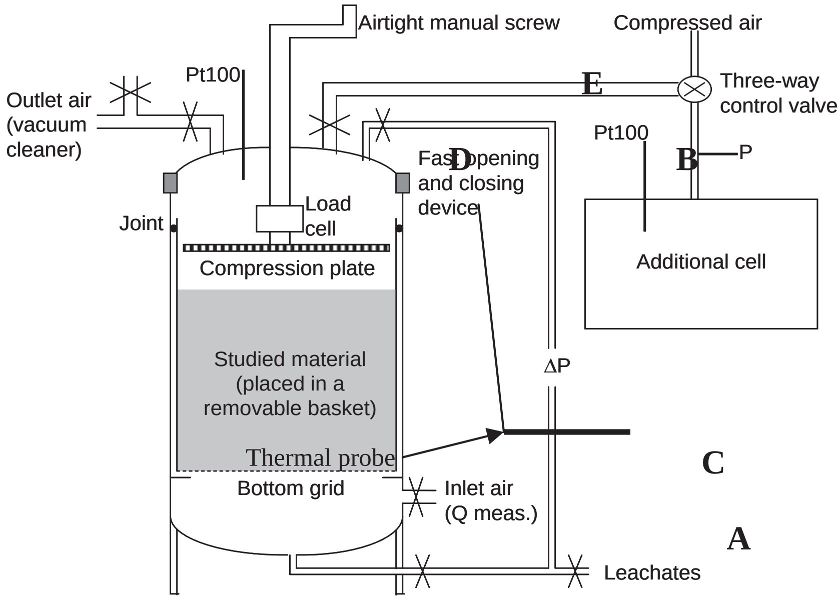

Fig. 1. Schematic representation of the "CPP" device.

porosity/permeability) was the same as described in Druilhe et al. (2008). It combined features of an air pycnometer with these of an air permeameter as illustrated in Fig. 1. A thermal probe was also directly embedded in the composting material to measure the thermal conductivity of the mixture.

Measurements could occur under various degrees of compaction. The sample was placed in a removable basket designed to hold about 40–60 L of mixture. Once the basket loaded and the volume known, the bulk density of the sample could be modified by adjusting the depth of a perforated compression plate, which was manually controlled by an airtight screw.

Measurements of *FAS*, air permeability and thermal conductivity were conducted at each bulk density calculated before in the "Schaub-Szabo" device. Thus, relationships between these parameters and depth, and also between themselves were established.

FAS measurement: Free Air Space (*FAS*), also cited as air-filled-porosity in the literature, characterizes the volume of air available in the organic matrix (Druilhe et al., 2008). It was measured by air pycnometry, a measurement method based on the Boyle–Mariotte's law: $PV = nRT$; where P is the pressure (Pa), V the volume (m^3), n the mole of gas (mol), R the gas constant ($J\,K^{-1}\,mol^{-1}$) and T the temperature (K). Two chambers, the sample cell and the additional cell, were connected with a valve so that they could be isolated from each other (see Fig. 1). Two PT100 temperature probes (one in each cell) and an absolute pressure transducer (0–3.5 absolute bar, accuracy 0.08% F.S. – Druck PTX610) were used to follow temperature and pressure evolutions during the measurement.

Practically, pipes used to air-permeability determination were initially closed (A, B, C and D on Fig. 1). Then, the removable basket was filled with the substrate, the sample cell was closed and initial pressure and temperature values were recorded. The cells were isolated and the additional cell was pressurized with compressed air to 2.5–2.8 absolute bar. Once the temperature and the pressure inside the additional cell stabilized (about 12 min later), their values were recorded. The valve was opened, starting to establish the equilibrium between the two cells. Resulting pressure and temperature values were recorded at specific times until the end of the experiment and finally, *FAS* was calculated (Druilhe et al., 2008).

Air permeability measurement: Air permeability measures the ability of air to flow through a porous media. It is linked to the pressure drop induced across a material bed by a given airflow at a superficial velocity. A general equation, known as the Dupuit–Forchheimer equation, describes the relationship between the pressure drop ΔP and the air permeability K:

$$\frac{\Delta P}{H} = \frac{\mu}{K} \cdot U + \frac{\rho}{\eta} \cdot U^2$$

where H is the height of the material bed (m), μ is the air viscosity ($Pa\,s^{-1}$), ρ the air density ($kg\,m^{-3}$), η the passability (m) and U the air superficial velocity ($m\,s^{-1}$). The first order term stands for viscous forces law while the second order term represents inertial forces. To determine which of these terms prevails, the flow regime must be determined. If the flow is laminar, viscous forces prevail and the second order term can be neglected (Darcy's law). On the other hand, in a turbulent flow situation inertial forces cannot be ignored and both terms are important.

The Reynolds number is classically used to determine the flow regime. Its expression differs according to the characteristic dimension chosen. In this case, the permeability-based number Re_K is the most commonly used (Hénon, 2008; Nield and Bejan, 2006; Richard et al., 2004):

$$Re_K = \frac{\rho \cdot U}{\mu} \sqrt{K}$$

Yet, another dimensionless number have been proposed by Richard et al. (2004) the Lage number La:

$$La = \frac{\rho \cdot K \cdot U}{\mu \cdot \eta}$$

When La or R_{eK} is <1, the flow is laminar and the Dupuit–Forchheimer equation can be simplified to Darcy's law. On the other hand, when La or R_{eK} is >1, the flow is turbulent and both terms must be kept.

Practically, the additional cell was disconnected from the sample cell (E on Fig. 1) and the pipes closed before for *FAS* measurement were now opened (A, B, C and D on Fig. 1). The airflow across the bed material was generated with a vacuum cleaner (superficial velocity between 0 and 0.075 m/s), measured with an airflow meter (0–500 L/min, accuracy 3% F.S. – McMillan model 100) and two pressure drop sensors (0–25 Pa and 0–160 Pa, accuracy 0.4% F.S. – Aschcroft CXLdp) were used depending on the studied material. The pressure drop across the sample (of known height H) was measured under various experimental velocities and La, R_{eK}, and the air permeability K were determined.

Thermal conductivity measurement: Thermal conductivity reflects the ability of the matrix to conduct heat. It was measured with an unsteady state probe method which is a commonly used technique on porous materials (Chandrakanthi et al., 2005; Iwabuchi et al., 1999; Van Ginkel et al., 2002). The thermal probe consists of a heating wire and a thermocouple which measures the temperature at this source. When supplied with a constant electric power Q, the temperature of the probe T_P increases as a function of time. After a certain period of time, the elevation of temperature reaches an asymptotic regime. Therefore, the graph of the rise in probe temperature versus the logarithm of the time gives a straight line, and the thermal conductivity λ (W m^{-1} K^{-1}) can be calculated from the slope A:

$$\lambda = \frac{Q}{4\pi \cdot A}$$

Practically, the probe was embedded directly at middle height into the composting material (see Fig. 1). The electric power was supplied by a constant power generator and the thermocouple of the probe was connected to a data acquisition terminal. Thermal conductivity measurements were directly made with the dedicated software.

Similarly to the Reynolds number in fluid mechanics, in thermal diffusion the thermal Péclet number Pe_{th} is used to determine if the flow is whether mostly convective or diffusive. It is defined as the ratio between convective and diffusive energy transport in a flow field:

$$Pe_{th} = \frac{U \cdot L}{D} = \frac{\rho \cdot C_p \cdot U \cdot L}{\lambda}$$

where D is the thermal diffusivity (m^2 s^{-1}), L is a characteristic length (m), U the superficial velocity (m s^{-1}), λ thermal conductivity (W m^{-1} K^{-1}), ρ the air density (kg m^{-3}) and C_p the thermal capacity (J kg^{-1} K^{-1}). At high thermal Péclet values ($\gg$1), molecular conduction predominates whereas at low thermal Péclet values ($\ll$1), thermal diffusion dominates heat transport.

2.3. Statistical analysis

A statistical analysis was carried out to identify which factors and their interactions had a significant impact on physical parameters. Four independent variables were used (namely depth, moisture content, particle size and type of bulking agent) and two normalized values, −1 and +1, were considered for each of them. For depth, these two values corresponded to the first (−1) and sixth layers (+1) – from −0.4 to 0 m and from −2.4 to −2 m in depth respectively – simulated with the Schaub-Szabo device; for moisture content to 50 (−1) and 65% (+1); for particle size to <20 mm (−1) and >20 mm (+1); and for the type of bulking agent to recycled (−1) and fresh (+1) wooden palettes. Therefore, a negative impact of the variable "type of bulking agent" on one of the physical responses would mean that this response decreased when switching from recycled palettes to fresh ones. The four responses investigated were bulk density, *FAS*, air permeability and thermal conductivity.

The significance of variable effects and interactions was determined using a Student test at a confidence level of 95% ($P < 0.05$). All statistical analyses were performed with the software Statgraphics (Centurion XV, Warrentown, Virginia, USA).

3. Results and discussion

3.1. Evolutions of physical parameters with depth

Evolutions of bulk density with depth obtained with the "Schaub-Szabo" device are presented in Fig. 2; and measured *FAS*, air permeability and thermal conductivity data at these various bulk densities are presented respectively in Figs. 3–5.

As far as in-depth evolutions were concerned, the trends on Figs. 2–5 were clear: bulk density and thermal conductivity both increased with depth while *FAS* and air permeability both decreased with it. These results were consistent with the existing literature (Richard et al., 2004; Schaub-Szabo and Leonard, 1999; Van Ginkel et al., 1999; Veeken et al., 2003); except for thermal conductivity because its relationship with depth has not been studied yet.

As soon as the pile of waste was built, the physical settlement began. Under the effect of its own weight, the porous matrix settled down leading to an increase in its bulk density (its volume decreased while its mass remained the same). As a result, the physical structure changed and with it, the size and shape of the pores of the matrix, resulting in a decrease in *FAS* and air permeability. Moreover, as thermal conductivity of air (0.026 W m^{-1} K^{-1}) is significantly lower than the thermal conductivity of water (0.6 W m^{-1} K^{-1}) or solid (>0.1 W m^{-1} K^{-1}), and as *FAS* decreased with depth, the more depth increased, the less available air there was. Therefore, thermal conductivity was expected to increase.

As shown in Fig. 2, the mixtures $M2$ and $M'2$ (<20 mm, 65% moisture content) had a different behavior from the other mixtures. The bulk density of $M2$ and $M'2$ increased by +36.4% and +30.9% respectively between the surface and the bottom of the simulated pile; which was to compare with relative increases of $M1$ (+17.4%), $M'1$ (+23.7%), $M3$ (+13.8%), $M'3$ (+11.6%), $M4$ (+13%) and $M'4$ (+9%).

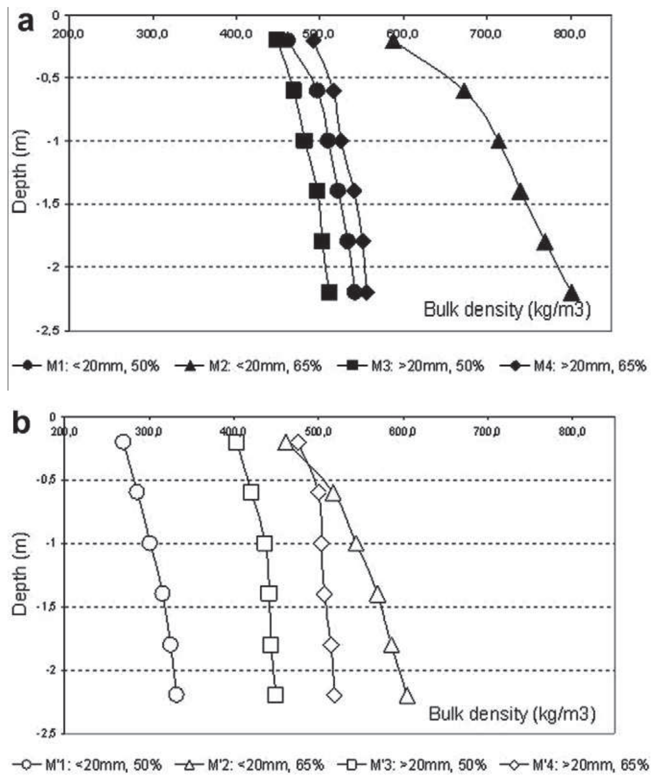

Fig. 2. Bulk density as a function of depth at different moisture contents and particle sizes (a: sludge–recycled palettes mixtures; b: sludge–fresh palettes mixtures).

The results also showed that, for sludge – recycled palettes mixtures, the more the mixture was compacted, the more its bulk density increased and its *FAS* decreased with depth (Figs. 2a and 3a). The mixture *M*2 (<20 mm, 65% moisture content), which had the highest increase in bulk density (+36.4%) had the highest decrease in *FAS* as well (-31.1%), and so on with the three other mixtures (*M*1, *M*3 and *M*4). With sludge–fresh palettes mixtures, this *FAS*/bulk density/depth relationship was not so clear (Figs. 2b and 3b). The four sludge–fresh palettes mixtures had close relative evolutions of *FAS* (between -8.0% and -12.2%). However, *M′*2 was still the mixture with the highest in-depth relative decrease in *FAS*.

As far as air permeability was concerned and as shown in Fig. 4, qualitatively *M*2 and *M′*2 (<20 mm, 65% moisture content) did not seem to have higher in-depth evolutions than the other mixtures. However, by calculating their relative evolutions, two different groups were brought out: on the one hand, mixtures *M*1, *M*3 and *M*4/*M′*1, *M′*3 and *M′*4 with close relative evolutions (between -37.3% and -44.3% and -31.6% and 38.9% respectively) and on the other hand, mixtures *M*2 and *M′*2 with higher evolutions (-81.6% and -51.2% respectively). As a result, like with bulk density and *FAS*, *M*2 and *M′*2 were again the mixtures with the highest in-depth air permeability relative evolutions. Nonetheless, the difference between *M′*2 and the three other sludge–fresh palettes mixtures was not as clear as between *M*2 and the three other sludge–recycled palettes mixtures.

Again, like with bulk density, *FAS* and air permeability, the mixture which had the highest in-depth evolution of thermal conductivity was the mixture *M*2 (see Fig. 5a), made of thin particles (<20 mm) and with a high moisture content (65%): +46.3% when at the same time the relative evolutions of *M*1, *M*3 and *M*4 oscillated between -2.8% and +27.0%. However, the observation was different for sludge–fresh palettes mixtures, as the mixture *M′*2 (<20 mm, 65% moisture content) did not have the highest

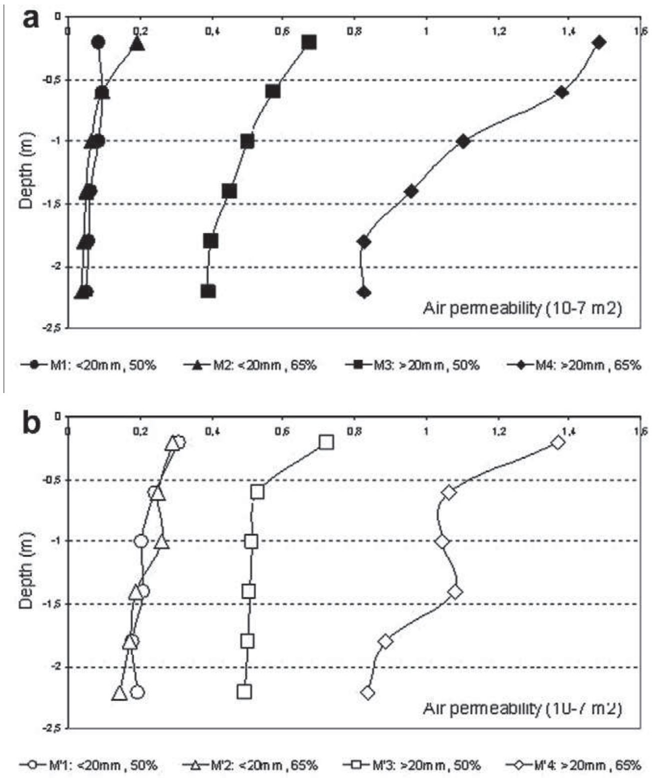

Fig. 4. Air permeability as a function of depth at different moisture contents and particle sizes (a: sludge–recycled palettes mixtures; b: sludge–fresh palettes mixtures).

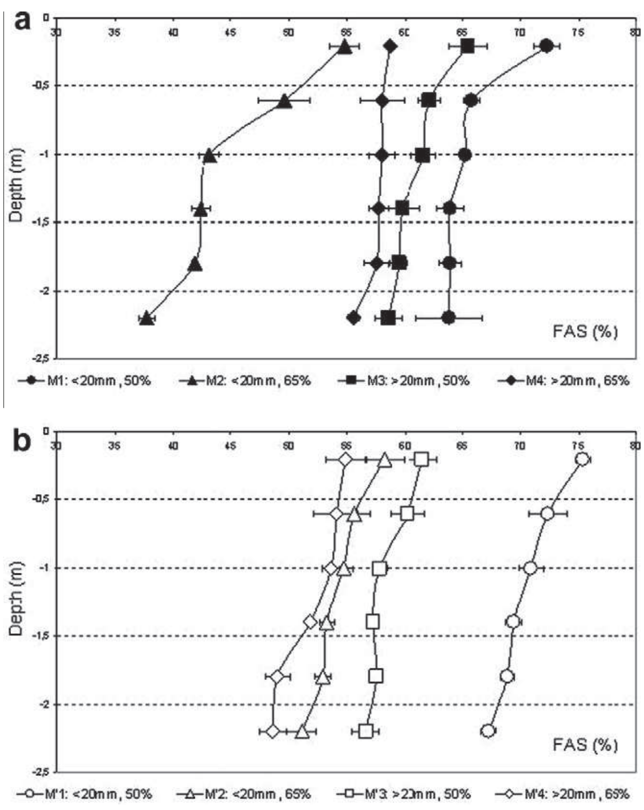

Fig. 3. FAS as a function of depth at different moisture contents and particle sizes (a: sludge–recycled palettes mixtures; b: sludge–fresh palettes mixtures).

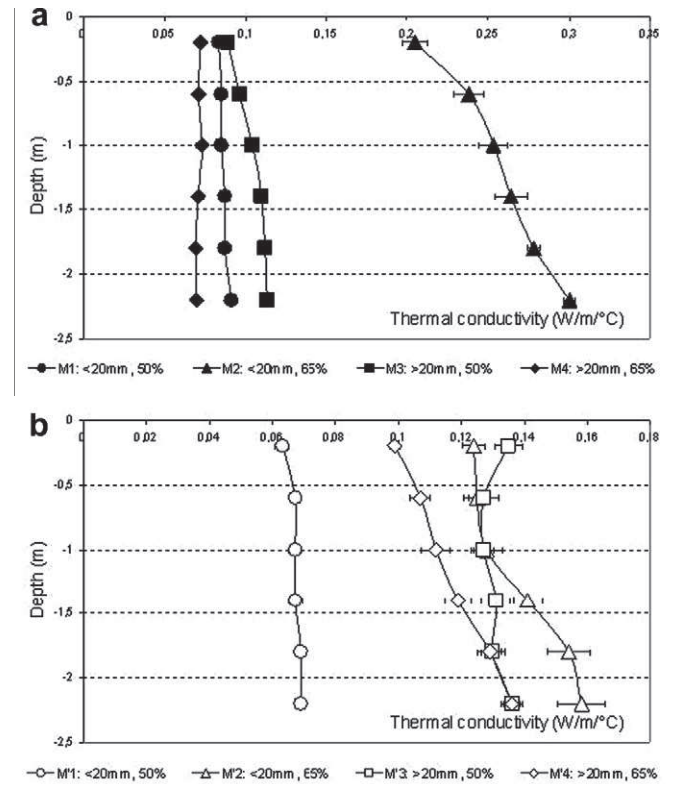

Fig. 5. Thermal conductivity as a function of depth at different moisture contents and particle sizes (a: sludge–recycled palettes mixtures; b: sludge–fresh palettes mixtures).

in-depth evolution (see Fig. 5b) and two groups had similar behavior: on the one hand the two wet mixtures (65% moisture content) $M'2$ and $M'4$ with high relative evolutions (between +27.4% and +37.4% respectively) and on the other hand, the two dry mixtures (50% moisture content) $M'1$ and $M'3$ with weak evolutions (between +9.5% and +0.7% respectively).

The results were slightly different according to the type of bulking agent (recycled or fresh wooden palettes). With sludge–recycled palettes mixtures ($M1/2/3/4$), fine particles combined with high moisture content made the compaction easier (and stronger in-depth evolutions for the four physical parameters cited above) as they weakened the physical structure of the organic matrix. Nonetheless, these observations were not that clear with fresh palettes ($M'1/2/3/4$) for bulk density, *FAS* and air permeability and gave even an opposite result for thermal conductivity.

Many researchers have investigated the efficiency of bulking agent in terms of resistance to settlement. Yue et al. (2008) found bark was better than cornstalk while McCartney and Chen (2001) showed that, when mixed with biosolids, wood chips were better bulking agents than leaves, which themselves were better than straw. Likewise, Schaub-Szabo and Leonard (1999) and Barrington et al. (2003) showed that wood shavings were better bulking agents as compared to straw, which had a softer structure that tends to collapse when they are wet. It is important to understand that, even if the two types of bulking agent tested in this study are different (fresh and recycled wooden palettes), yet they are much more alike than, for instance, straw and sawdust as shown in (Zhao et al., 2011) or bark and cornstalk as studied by Yue et al. (2008).

The four physical parameters were all mathematically correlated with depth. The bulk density-depth relationship matched an equation of the form $\rho_{wb}(Z) = A \cdot Z^B$ (Schaub-Szabo and Leonard, 1999; Yue et al., 2008) and the correlations were quite good for the eight mixtures (with correlation coefficients R^2 ranging from 0.962 to 0.9963). For sludge–recycled palettes mixtures, three of the four mixtures ($M1$, $M3$ and $M4$) had close compressibility values B (0.05–0.07) whereas the value of $M2$ was approximately twice as much (0.125). For sludge–fresh palettes mixtures, mixtures $M'3$ and $M'4$ made of particles >20 mm had a compressibility value of the same order (0.04). The two other mixtures made of thin particles <20 mm had higher compressibility values: 0.090 for $M'1$ and 0.111 for $M'2$. As a result, mixtures globally bore compaction more easily when made with fresh bulking agents than with recycled ones (especially with coarse particles >20 mm). And compaction was enhanced by the characteristics of $M2$ and $M'2$ (high moisture content and thin particles).

A $FAS(Z) = \alpha_1 \cdot Z^{\beta_1}$ relationship was used to link *FAS* and depth (z) but only six mixtures ($M1$, $M'1$, $M2$, $M'2$, $M3$ and $M'3$) gave a good match, with R^2 values higher than 0.8 (between 0.9095 and 0.9779). Air permeability (K) was also correlated to depth with a similar equation: $K(Z) = \alpha \cdot Z^{\beta_2}$. Only six mixtures fitted the equation well ($R^2 > 0.8$): $M2$, $M3$, $M4$, $M'1$, $M'3$ and $M'4$ (R^2 values between 0.8563 and 0.997). At last, only four mixtures gave a good match for the correlation $\lambda(Z) = \alpha_3 \cdot Z^{\beta_3}$, between thermal conductivity (λ) and depth: $M2$, $M3$, $M'1$ and $M'4$ (R^2 values between 0.8918 and 0.9722).

A, α_1, α_2 and α_3 coefficients from above equations depended all on the mixture, meaning that they were all specific to the substrate. B, β_1, β_2 and β_3 coefficients could be separated into two groups for sludge-recycled palettes mixtures: $M2$, made of thin particles and with high moisture content, on one side and $M1$, $M3$ and $M4$ on the other side. Indeed, the coefficients of $M2$ were up to three times higher than these of the other mixtures which, once again, shed a light on his difference towards the other mixtures. However, as far as sludge-fresh palettes mixtures were concerned, $M'2$ had still the maximal evolutions for bulk density and *FAS* but they were closer to these of the other mixtures. Moreover, because of the lack of good correlations (with R^2 values >0.8) in air permeability and thermal conductivity, β_2 and β_3 coefficients could not be compared.

3.2. Impact of moisture content, particle size, type of bulking agent and compaction on physical parameters

The results of the statistical analysis are presented in Table 1 below. It displays the impact of a given parameter or interaction on the four physical parameters studied, if it is whether positive or negative and its significance.

3.2.1. Bulk density

The statistical analysis (Table 1) showed that bulk density was significantly influenced by three of the four factors, which in order were: moisture content, type of bulking agent and depth. Bulk density increased with an increase in moisture content; which was an expected result (Agnew and Leonard, 2003; Ahn et al., 2008; Druilhe et al., 2008; Kim et al., 2008; Madejon et al., 2002; Malinska and Richard, 2006). Besides, the negative impact of the type of bulking agent on bulk density meant that bulk density was higher with recycled palettes (450–800 kg/m^3) than with fresh ones (270–600 kg/m^3). This result was logical given that bulk density of bulking agent alone was higher with recycled palettes (369 kg/m^3) than with fresh ones (265 kg/m^3). The higher bulk density of recycled palettes might be explained by the fact that, as it had undergone many composting cycles, it incorporated some residual sludge which weakened the physical structure of the bulking agent, making it more easily subject to compaction. At last, bulk density logically increased when depth increased (see Fig. 2), as previously shown by many researchers (Iqbal et al., 2009; Malinska and Richard, 2006; McCartney and Chen, 2001; Van Ginkel et al., 1999; Yue et al., 2008).

Particle size did not have a significant effect on bulk density (Druilhe et al., 2008), but intervened in three significant interactions. The negative interaction between moisture content and particle size meant that the positive effect of moisture content on bulk density was higher at low particle size (<20 mm). The positive interaction between particle size and the type of bulking agent showed that the increase in bulk density from fresh to recycled palettes was higher with thin particles (<20 mm). Besides, the negative interaction between particle size and depth indicated that the in-depth increase in bulk density was higher with particles <20 mm and corroborated what has been said earlier: physical rearrangements within the organic matrix were more efficiently limited by coarse particles than by thin ones. The interaction between depth and moisture content (even if it was not significant) was also interesting because the positive sign indicated that the in-depth increase in bulk density would be maximum at high moisture content (65%). The physical structure was, therefore, more stable with dry materials (50% moisture content) than with wet ones (65% moisture content).

This statistical analysis confirmed what has been said in Section 3.1: $M2$ (<20 mm, 65% moisture content) had the highest increase in bulk density followed in order by $M1$, $M3$ and $M4$, and similarly with $M'2$, $M'1$, $M'3$ and $M'4$. These results were also coherent with the order of compressibility values B.

3.2.2. FAS

FAS was significantly influenced by only two factors: first moisture content, and then depth (see Table 1). As expected, *FAS* decreased when moisture content increased (Haug, 1993; Madejon et al., 2002; Malinska and Richard, 2006; Mohee and Mudhoo, 2005). As shown in Fig. 3, it also decreased when depth increased, which was logical and coherent with the existing literature (Iqbal

Table 1

Statistical analysis [+: positive impact, -: negative impact, +++/—: $P \leqslant 0.0001$, ++/–: $0.0001 \leqslant P \leqslant 0.01$, +/-: $0.01 \leqslant P \leqslant 0.05$, (+)/(-): $P \geqslant 0.05$ (non significant)].

	Bulk density	*FAS*	Air permeability	Thermal conductivity
Depth (D)	++	–	—	(+)
Moisture content (MC)	+++	—	+++	++
Particle size (PS)	(-)	(-)	+++	(-)
Bulking agent (BA)	—	(+)	+	(-)
D/MC interaction	(+)		-	(+)
D/PS interaction	-	(+)	–	
D/BA interaction				
MC/PS interaction	–	++	+++	–
MC/BA interaction			(-)	(-)
PS/BA interaction	++	–	(-)	++

et al., 2009; Malinska and Richard, 2006; McCartney and Chen, 2001; Mohee and Mudhoo, 2005; Richard et al., 2004).

Particle size did not have a significant impact on *FAS*. Yet, Ahn et al. (2009) noted that *FAS* decreased with decreasing particle size. The type of bulking agent tested in this study did not have a significant impact either, but its interaction with particle size did. This negative interaction meant that the tendency of *FAS* to increase when switching from recycled palettes to fresh ones would be significant with thin particles <20 mm: *FAS* ranged from 37% to 72% with recycled palettes <20 mm and from 51% to 75% with fresh ones <20 mm. Besides, the range of *FAS* stayed always higher than 30%, which is commonly considered to be the limiting value for the process (Annan and White, 1998; Haug, 1993; Madejon et al., 2002; Mohee and Mudhoo, 2005; Schulze, 1962).

The positive interaction between particle size and moisture content was also significant; meaning that the negative impact of moisture content on *FAS* was maximal at low particle size (<20 mm).

3.2.3. Air permeability

The statistical analysis proved that all four factors were of significant importance: in order, particle size, moisture content, depth and finally the type of bulking agent, which was way less significant than the three previous factors (Table 1). The fact that air permeability increased when particle size increased was legitimate because by increasing particle size, the size of the pores between these particles increased as well. Therefore, air travelled more easily through the organic matrix and air permeability increased (Agnew and Leonard, 2003). Now, speaking of the increase in air permeability with an increase in moisture content, it was a much more complex situation. Usually, an increase in moisture content goes with a decrease in air permeability: air within the pores of the matrix is chased away by water. However, previous researchers (Druilhe et al., 2008; Poulsen and Moldrup, 2007; Richard et al., 2004) had already noticed an increase in air permeability when moisture content increased. They explained that when moisture content increases water is dragged into the small pores of the matrix, creating larger aggregates which in turn lead to larger inter-aggregate pores and result in an increased air permeability. Furthermore, as illustrated in Fig. 4, air permeability decreased as depth increased (Richard et al., 2004; Veeken et al., 2003). The positive effect of the type of bulking agent on air permeability meant that air permeability values were lower with recycled palettes (0.03–1.5 10^{-7} m^2) than with fresh ones (0.15–1.4 10^{-7} m^2).

Three interactions were also significant: the positive interaction between particle size and moisture content, the negative ones between depth and particle size on the one hand, and between depth and moisture content on the other hand. The positive interaction between particle size and moisture content meant that the increase in air permeability with an increase in moisture content was maximal at particle size >20 mm. As said before, some researchers have shown that air permeability can increase when moisture content increases as well. But, until now, this phenomenon had only been observed with thin particles (<5 mm in Poulsen and Moldrup and a particle diameter of about 2 mm in Richard, Veeken et al.). In this study however, it also happened (and the impact on air permeability was maximal) with coarse particles. Finally, the negative interaction between depth and moisture content showed that the decrease in in-depth air permeability would be maximal at high moisture content. It justified what has been said before about the better stability of the physical structure of dry materials.

3.2.4. Thermal conductivity

According to the statistical analysis, thermal conductivity was significantly influenced by only one factor, moisture content, and increased with it. This was an expected result because water (0.06 W m^{-1} K^{-1}) has a higher thermal conductivity than air (0.026 W m^{-1} K^{-1}). Therefore by increasing moisture content, the pores of the matrix were filled with water and then, thermal conductivity increased. These results were in accordance with the existing literature, even if the substrates were quite different, like borage seeds (Yang et al., 2002), grain dusts (Chang et al., 1980), beef manure (Houkom et al., 1974), dairy cattle feces mixed with sawdust (Iwabuchi et al., 1999), leaf composts (Chandrakanthi et al., 2005) or compost-bulking agent materials (Ahn et al., 2009).

On Fig. 5, thermal conductivity seemed to increase with depth but the statistical analysis revealed that depth alone did not have a significant impact and neither in interaction with another factor.

The type and particle size of bulking agent, although they did not have significant impacts alone, intervened with significant interactions. The first interaction was negative and between moisture content and particle size. It meant that the increase in thermal conductivity with an increase in moisture content was maximal at low particle size. It also meant that at high particle size (>20 mm), the impact of moisture content on thermal conductivity became negative. Another interpretation of this interaction is that, at high moisture content (65%), thermal conductivity tended to increase when particle size decreased. These results were in agreement with the study of Ahn et al. (2009) who observed an increase in thermal conductivity for eleven different composting materials when grinding them from 10 cm to 0.5 mm. An explanation to this phenomenon was that decreasing particle size created more thermal contacts between particles which, combined with high moisture content, led to an increase in thermal conductivity. The second significant interaction brought to light was positive and between particle size and the type of bulking agent. The tendency of thermal conductivity to decrease when switching from recycled palettes to fresh ones was significant with particles <20 mm: 0.083–0.3 W/m/°C with recycled palettes and 0.063–0.158 W/m/°C with fresh ones.

3.3. Links between physical parameters

During this study, the links between physical parameters themselves were also investigated. However, only one correlation could have been established for both types of mixtures: a linear equation linking *FAS* and bulk density (ρ_{wb}) (see Fig. 6), similar to the equations available in the existing literature (Agnew and Leonard, 2003; Mohee and Mudhoo, 2005; Stoffella and Kahn, 2001):

Sludge-recycled palettes mixtures:

$$FAS(\%) = 102.45 - 0.0805 \cdot \rho_{wb}(kg \cdot m^{-3})$$

$$(R^2 = 0.8803)$$

Sludge–fresh palettes mixtures:

$$FAS(\%) = 92.118 - 0.0744 \cdot \rho_{wb}(kg \cdot m^{-3})$$

$$(R^2 = 0.8912)$$

All the other relationships found (bulk density-thermal conductivity, *FAS*-air permeability, *FAS*-thermal conductivity air permeability-thermal conductivity, etc.), were specific to each mixture (Figures not shown). These relationships, linear or logarithmic, gave various results according to the parameter and the mixture, with correlation coefficients ranging from 0.3088 to 0.9913. For instance, the air permeability-bulk density relationship showed an increase in air permeability when bulk density decreased, which confirmed the existing literature (Agnew and Leonard, 2003; Poulsen and Moldrup, 2007; Richard et al., 2004; Veeken et al., 2003). This increase was higher with particles >20 mm than with particles <20 mm, whatever the bulking agent.

Poulsen and Moldrup (2007) found that log(*FAS*) and log(air permeability) are linked by a linear equation. However, this relationship did not give better correlation coefficients than the direct linear equation *FAS*-air permeability.

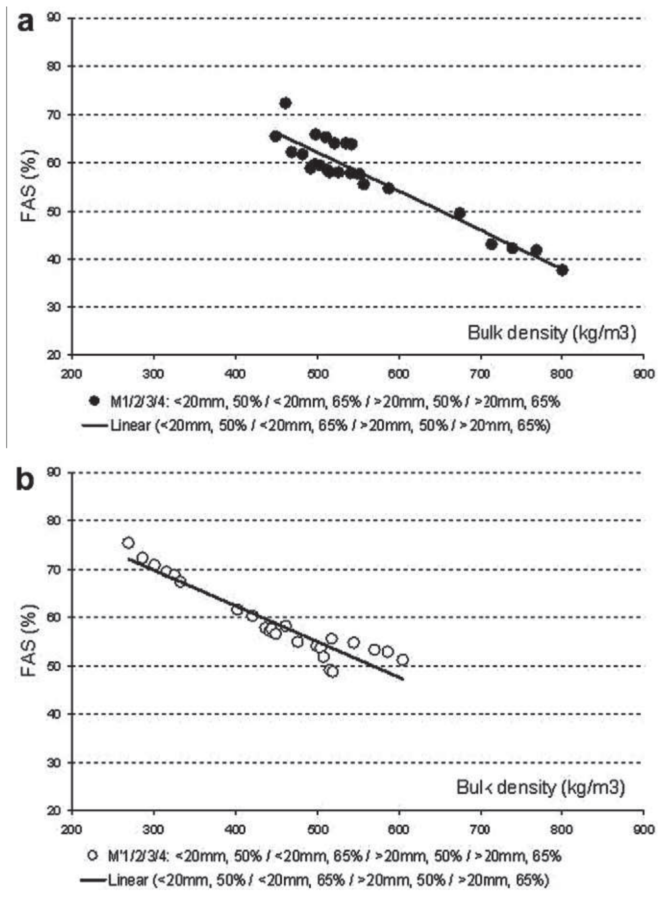

Fig. 6. FAS as a function of bulk density at different moisture contents and particle sizes (a: sludge–recycled palettes mixtures; b: sludge–fresh palettes mixtures).

Furthermore, Chandrakanthi et al. (2005) suggested an empirical relationship linking *FAS*, thermal conductivity (λ) and the degree of saturation (Φ), defined as:

$$\phi = \frac{MC_{wb} \cdot \rho_{wb}}{FAS \cdot \rho_w}$$

where MC_{wb} is the moisture content (in wet basis), $\rho_{wb}$the bulk density (in wet basis) and ρ_w the bulk density of water (1000 kg/m^3). Later, they showed that Φ had the strongest influence on λ and simplified their previous equation in a linear relationship between λ and Φ. The results of this linear relationship was partly confirmed: plotting thermal conductivity against degree of saturation gave good results for five of the eight mixtures (R^2 between 0.8109 and 0.9838): *M*2, *M*3, *M*′1, *M*′2 and *M*′4. However, it is important to note that they confirmed this relationship for *FAS* and Φ values ranging from 69% to 85% and from 0.25 to 0.80 respectively, which was pretty far from the ranges of values obtained in this study (from 38% to 75% and from 0.002 to 0.01 respectively).

4. Conclusion

Moisture content (50% and 65%) of tested sludge-bulking agent mixtures significantly impacted initial bulk density, *FAS*, air permeability and thermal conductivity. Particle size of bulking agent (<and>20 mm) had a significant influence on air permeability whereas the type of bulking agent (fresh or recycled wooden palettes) significantly affected bulk density and air permeability. Bulk density and thermal conductivity both increased with depth while *FAS* and air permeability both decreased with it. Moreover, several correlations were available between initial physical parameters but only the *FAS*-bulk density linear relationship could be used whatever the mixture.

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