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STUDY OF THERMAL CONDUCTIVITY IN ORGANIC SOLID WASTES BEFORE COMPOSTING

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EXECUTIVE SUMMARY

In France, like in all developed countries, the amount of solid wastes generated per year has increased continuously since the 1960s. To hold back this trend, waste policies have been set up, as illustrated by current EU waste policy and its five main priorities: prevention, reuse, recycling, recovery and disposal. Composting can be defined as the process whereby aerobic micro-organisms convert organic substrates into compost: a hygienic, biostable product that can be beneficially applied to land (Haug, 1993; Mohee & Mudhoo, 2005). Therefore, it fits perfectly with the fourth priority, recovery, which fosters extraction of useful material or energy from wastes. In this context, interest towards composting has increased continuously during the last few years. During treatment, micro-organisms breakdown organic matter and produce carbon dioxide, water and heat. Heat generated by biological activity modifies moisture content and temperature conditions. These changes result in the appearance of a temperature peak in first days of treatment and most pathogens are killed by the high temperatures reached (around 70-80°C), turning waste into a hygienic product.

Among the various physical parameters taking part in the composting process, thermal conductivity seems to be of major importance, and could be used as an indicator to follow heat transfers within the organic matrix. However, as all physical parameters involved in the process, the initial preparation of the substrate (adjustment of moisture content or C/N ratio, addition and mixing with bulking agent □) has an influence on the physical parameters involved in the process (such as bulk density, Free Air Space or air permeability) and thus, on thermal conductivity. Moreover, 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 leads to compaction. Despite its major importance, until now little has been written on thermal conductivity in composting, in particular about its link with compaction. That's why this study focus on it and aims to investigate how it evolves with (i) compaction or depth within the pile of waste, (ii) preparation parameters of the substrate and (iii) temperature. This investigation was carried out on mixtures of urban sludge and wooden palettes used as bulking agents.

To understand how preparation parameters of the mixtures would affect thermal conductivity, two moisture content (50 and 65%), two types (fresh and recycled) and two meshes of bulking agent (< and > 20 mm) were tested. The influence of compaction (or depth) was evaluated in two steps. First, a □Schaub-Szabo□ device (strongly inspired by the apparatus described in *Schaub-Szabo and Leonard* (Schaub-Szabo & Leonard, 1999)) was used to get depth-bulk density profiles in the different substrates. Then, these bulk densities were re-created in a modified air pycnometer where thermal conductivity was measured with a thermal probe directly embedded in the composting sample. Therefore, a link between thermal conductivity and compaction (or depth) could be established. On the other hand, the study of the impact of temperature on thermal conductivity was carried out in 10 liter cells where biological activity was prevented by a nitrogen atmosphere. The cells were filled with the same eight sludge-wooden palettes mixtures as before, and a thermal probe was put directly inside each sample. Then, they were put in different constant-temperature baths with target temperature from 5 to 75°C.

In this study, thermal conductivity increased with depth and a statistical analysis highlighted the fact that it was only significantly impacted by moisture content (among the three preparation parameters cited above). Moreover, the impact of temperature on thermal conductivity was clear and a linear relationship between these two parameters could be established. Each correlation was specific to the substrate but with a similar slope. These results are interesting in two ways: first, until now little has been written on thermal conductivity in organic solid wastes, and in particular about its link with compaction. Besides this originality, the data obtained can now be used in numerical modeling to get a more thorough and accurate way to model heat transfers, an essential part of modeling composting systems.

1. INTRODUCTION

Nowadays, over 800 million tons of wastes are generated each year in France. To control the rise in the amount of waste produced since several decades now, waste policies have been set up in France as in most developed countries to fight this phenomenon. Current waste policy in the EU follows five main priorities, which in a hierarchical order are: prevention, reuse, recycling, recovery and disposal. Prevention encourages the community to reduce the amount of waste generated and to be more efficient in the use of resource. If waste cannot be prevented, as many of the materials as possible should be recovered, preferably by reuse and recycling. Energy and material recovery aims to foster extraction of useful material or energy from wastes. And disposal, as the least desirable option, must be handled with maximum precautions to minimize negative environmental outcomes. As a consequence, composting fits perfectly in the frame of material recovery and that is why during the last few years, interest has grown towards it as a way to treat organic wastes.

Composting can be defined as the biological organic matter decomposition process which occurs in aerobic conditions. At first sight, it could be seen as a quite simple process: with the proper mixture of water, oxygen and nutrients, micro-organisms breakdown organic matter of waste to produce compost. Yet, at micro scales it involves complex processes. These processes are of three types: biological processes and heat and mass transfers. Biological processes are linked to the activity of the decomposing micro-organisms which, provided with oxygen, turn organic matter into compost and produce heat, water and other gaseous compounds as well (mainly carbon dioxide). Their biological activity (consumption of oxygen and production of water and carbon dioxide) leads to mass and volume reduction of the substrate and organic matter stabilization. Furthermore, most pathogens are killed when the peak of temperature (70-80°C) is reached in the first days of treatment.

In return biological activity generates heat, leading to changes in moisture content and temperature conditions. Regarding heat transfers, thermal conductivity is a key role parameter. It is impacted by numerous parameters and among them moisture content, contact between particles and temperature seems to be of great importance. Contact between particles is link to particle size: the thinner the material, the more contacts there is. As moisture content, particle size is a preparation parameter which is set when the substrate is prepared.

As soon as built, the pile of waste is subject to compaction because its physical structure is unable to bear its own weight. One solution to that issue, widely used, is to add some bulking agents to solidify the pile. Nevertheless, in addition to the fact that these bulking agents added should not exceed a certain amount (to keep an acceptable C/N ratio for instance), this primary settlement or [physical compressive settlement] as some authors called it (Gourc et al., 2010; Yue et al., 2008), cannot be avoided and its impact on initial physical characteristics should not be ignored, as it is usually the case because of the lack of information about it.

The original idea of this paper is to focus on thermal conductivity as it seems to be a physical parameter of major importance in regards to heat transfers in composting and yet, not actually well-considered in the existing literature. Therefore, this study aimed to investigate the links between thermal conductivity and (i) compaction or depth within the pile of waste, (ii) preparation parameters of the substrate and (iii) temperature. All experiments were carried out on urban sludge-bulking agent mixtures, with two different moisture contents, two particle sizes of bulking agent and two types of bulking agent (but quite similar anyway).

In order to perform thermal conductivity measurements at different heights (or under different degrees of compaction) we proceed in two steps, using two sets of apparatus. First a [Schaub-Szabo] device (named after its designer) was used to simulate compaction occurring in the pile and link compaction, depth and bulk density. Then, the sample was placed in another device, called [CPP] device, where the previous measured bulk densities were recreated. Here, thermal conductivity was measured using a thermal probe directly embedded in the sample. On the other hand, to evaluate the impact of temperature on thermal conductivity, measurements were made with thermal probes placed inside 10 liter cells, filled with substrate and where biological activity was inhibited with a nitrogen atmosphere.

2. MATERIALS AND 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 a dozen composting cycles 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).

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.

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 was inspired by the device designed by Schaub-Szabo & Leonard (Schaub-Szabo & Leonard, 1999). It 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.

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 m³).

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 discs 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 hours, 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 and thermal conductivity measurement

The bulk densities previously measured in the □Schaub-Szabo□ device were recreated in a □CPP□ device, which was originally used to measure porosity and permeability of compacted materials (□C□ stands for

compaction, ρ for porosity and P for permeability in the acronym (CPP). It was the same apparatus as described in Druilhe, Benoist et al. (Druilhe et al., 2008) with a thermal probe directly embedded in the composting material. Thermal conductivity measurements were conducted at each bulk density calculated before in the Schaub-Szabo device. Thus, the relationship between thermal conductivity and depth was brought to light.

To recreate the 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 was modified by adjusting the depth of a perforated compression plate, manually controlled by an airtight screw. Thermal conductivity 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 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 ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) 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. 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.

2.2.3 Thermal conductivity cells

In parallel, the impact of temperature on thermal conductivity was also investigated. The experiment was carried out in 10 liter cells filled with substrate. Thermal conductivity was measured with a thermal probe placed inside the sample; and the same protocol described in 2.2.2 was applied to the eight sludge-bulking agent mixtures studied. To ensure that temperature was the only changing parameter during the experiment, biological activity had to be inhibited. Indeed, the physical structure of the matrix could be modified under the effect of micro-organisms breaking down organic matter. Therefore, the cells were supplied with nitrogen to inhibit biological activity during the measurements.

The cells were put in different constant-temperature bath with target temperatures ranging from 20 to 75°C, by steps of 5°C. In addition, thermal conductivity measurements were performed right after the samples were taken out of the refrigerated room (and before they reached the ambient temperature) at 5, 10 and 15°C.

As said earlier, the peak of temperature in composting usually reaches temperature values around 70-75°C, that is why the maximum target value was set at 75°C.

2.3 Statistical analysis

A statistical analysis was carried out to identify which factors and their interactions had a significant impact on thermal conductivity. The four factors were considered were depth, moisture content and particle size and type of bulking agent (temperature, although studied in this paper, was not used as a factor in the statistical analysis). 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 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 Impact of depth, moisture content, particle size and type of bulking agent on thermal conductivity

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

Table 1: Statistical analysis [+: positive impact, -: negative impact, +++/---: $P \leq 0.0001$, ++/--: $0.0001 \leq P \leq 0.01$, +/-: $0.01 \leq P \leq 0.05$, (+)/(-): $P \geq 0.05$ (non significant)]

	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	++

As previously stated by some researchers before (Ahn et al., 2009; Chandrakanthi et al., 2005), thermal conductivity increased with compaction (or increasing bulk density) due to a reduction in the void space. On Figures 1 and 2 below, thermal conductivity seemed to increase with depth as well but the statistical analysis revealed that depth alone didn't have a significant impact and neither in interaction with another factor (see Table 1).

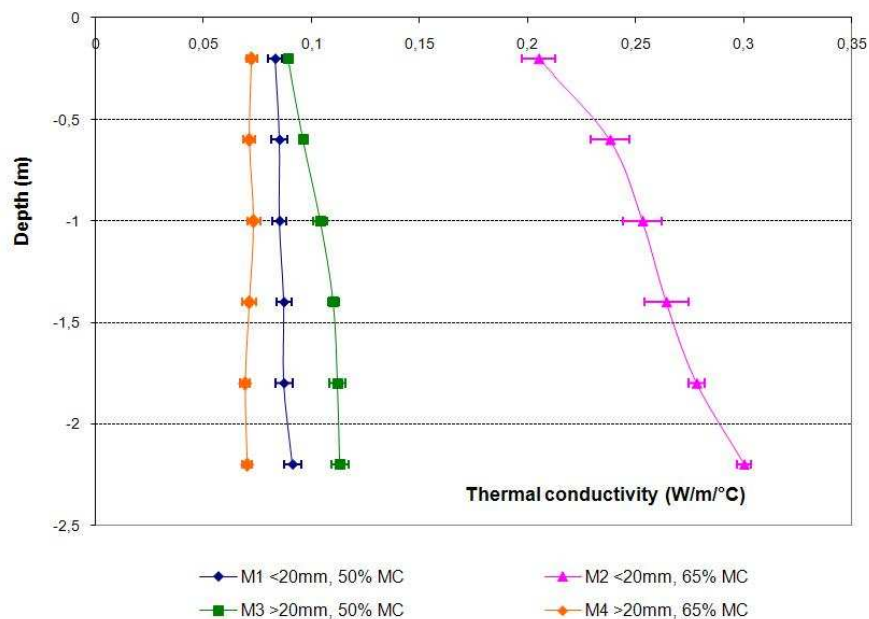


Figure 1: Thermal conductivity as a function of depth at different moisture contents and particle sizes (sludge – recycled palettes mixtures)

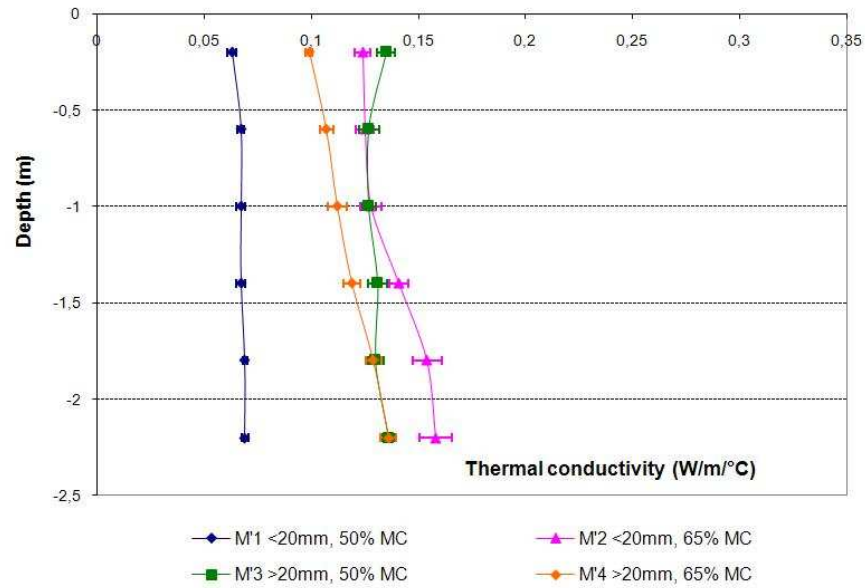


Figure 2: Thermal conductivity as a function of depth at different moisture contents and particle sizes (sludge – fresh palettes mixtures)

Among the three preparation parameters tested (moisture content, particle size and type of bulking agent), the statistical analysis shows that thermal conductivity was significantly influenced by only one factor, moisture content, and increased with it. This result was expected since in theory, thermal conductivity of water is higher than of air ($0.06 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1} > 0.026 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). Therefore, by increasing moisture content, the pores of the organic matrix were filled with water and then, thermal conductivity increased. These results were consistent with the existing literature, even if the experiments were performed on different substrates such as 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 (Chandrankanthi et al., 2005) or compost-bulking agent materials (Ahn et al., 2009).

The type and particle size of bulking agent, although they did not have significant impacts alone, intervened with significant interactions (as shown in Table 1). 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 ($> 20 \text{ mm}$), 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, Sauer et al. (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 (see Table 1). The tendency of thermal conductivity to decrease when switching from recycled palettes to fresh ones was significant with particles $< 20 \text{ mm}$: $0.083\text{-}0.3 \text{ W/m}^\circ\text{C}$ with recycled palettes and $0.063\text{-}0.158 \text{ W/m}^\circ\text{C}$ with fresh ones.

3.2 Evolution of thermal conductivity with temperature

As shown on Figure 3, thermal conductivity (λ) clearly increased with temperature (T). Between 5 and 75°C , thermal conductivity increased between two and five times depending on the mixture. Moreover, a linear relationship of the form $\lambda = a \cdot T + b$ was obtained, with correlation coefficients ranging from 0.946 to 0.989. b coefficients were all different, meaning that each correlation was specific to the mixture studied. However, they all had a similar slope a ($0.003\text{-}0.004 \text{ W/m}^\circ\text{C}^2$).

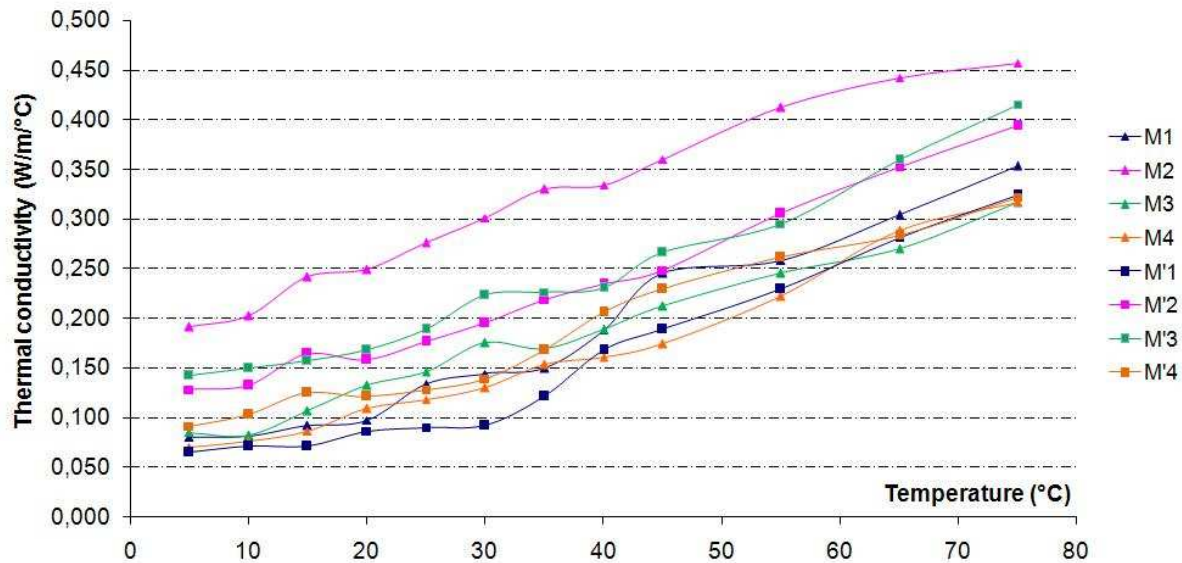


Figure 3: Thermal conductivity as a function of temperature at different moisture contents and particle sizes

These are interesting results because, although thermal properties are very important in composting, information on their values for various composting materials is lacking. In this way, the data provided by this study could be very useful, in particularly regarding numerical modeling.

Furthermore, these results were consistent with the little literature currently available. Van Ginkel (Van Ginkel et al., 2002) also showed that thermal conductivity of a mixture of chicken manure and wheat straw increased with temperature; and their relationship showed an almost perfect linearity according to the authors. Unfortunately, they did not give the value of the slopes they obtained so we could not compare. Similarly, Yang et al. (Yang et al., 2002) obtained a mathematical equation linking thermal conductivity of borage seeds to temperature and moisture content.

4. CONCLUSION

In this paper, the influence of three preparation parameters of the substrate (moisture content, particle size and type of bulking agent), depth (or compaction) and temperature on thermal conductivity in organic solid wastes was investigated. Knowledge about thermal conductivity in such substrates and its link with depth (or compaction) is quite poor at present. That is why this paper aimed to give some answers about what parameters influence thermal conductivity in organic solid wastes before composting.

Among the three preparation parameters tested and depth, thermal conductivity was only significantly influenced by moisture content. Contrary to what could have been expected from theory, depth (or compaction) didn't significantly impact thermal conductivity. On the other hand, temperature had a clear impact and a linear relationship between these two parameters was brought to light. Each correlation was specific to the substrate but with a similar slope. However, it is important to note that such results are only valid in the sludge-wooden palettes mixtures tested, and similar studies should be carried out on other substrates.

The data experimentally obtained can now be used in numerical modeling to improve existing heat transfers models, an essential step to get a more thorough and accurate modeling of whole composting systems.

5. Nomenclature

λ Thermal conductivity ($W.m^{-1}.K^{-1}$)

A	Numerical coefficient (-)
BD_i	Bulk density of the layer i ($kg.m^{-3}$)
FAS	Free Air Space (-)
h_i	Settlement of the layer i (m)
h_0	Initial level before settlement (m)
$M1$	Sludge-recycled wooden palettes mixture (particle size < 20mm, 50% moisture content)
$M2$	Sludge-recycled wooden palettes mixture (particle size < 20mm, 65% moisture content)
$M3$	Sludge-recycled wooden palettes mixture (particle size > 20mm, 50% moisture content)
$M4$	Sludge-recycled wooden palettes mixture (particle size > 20mm, 65% moisture content)
$M'1$	Sludge-fresh wooden palettes mixture (particle size < 20mm, 50% moisture content)
$M'2$	Sludge-fresh wooden palettes mixture (particle size < 20mm, 65% moisture content)
$M'3$	Sludge-fresh wooden palettes mixture (particle size > 20mm, 50% moisture content)
$M'4$	Sludge-fresh wooden palettes mixture (particle size > 20mm, 65% moisture content)
Q	Dissipated electrical power per unit length ($W.m^{-1}$)
T	Temperature ($^{\circ}C$)
V_{fl}	Volume to fill line (m^3)

6. REFERENCES

- Ahn, H.K., Sauer, T.J., Richard, T.L., Glanville, T.D. 2009. Determination of thermal properties of composting bulking materials. *Bioresource Technology*, **100**(17), 3974-81.
- Chandrakanthi, M., Mehrotra, A.K., Hettiaratchi, J.P.A. 2005. Thermal conductivity of leaf compost used in biofilters: An experimental and theoretical investigation. *Environmental Pollution*, **136**(1), 167-174.
- Chang, C.S., Lai, F.S., Miller, B.S. 1980. Thermal-Conductivity and Specific-Heat of Grain Dust. *Transactions of the Asae*, **23**(5), 1303-&.
- Druilhe, C., Benoist, J., Radigois, P., Tégliat, C., Trémier, A. 2008. Sludge composting: influence of the waste physical preparation on initial free air space, air permeability and specific surface. *ORBIT 2008*, Wageningen.
- Gourc, J.P., Staub, M.J., Conte, M. 2010. Decoupling MSW settlement into mechanical and biochemical processes - Modelling and validation on large-scale setups. *Waste Management*, **30**(8-9), 1556-1568.
- Haug, R.T. 1993. *The Practical Handbook of Compost Engineering*. Lewis Publishers, Boca Raton.
- Houkom, R.L., Butchbaker, A.F., Brusewitz, G.H. 1974. Effect of moisture content on thermal diffusivity of beef manure. *Transactions of the Asae*.
- Iwabuchi, K., Kimura, T., Otten, L. 1999. Effect of volumetric water content on thermal properties of dairy cattle feces mixed with sawdust. *Bioresource Technology*, **70**(3), 293-297.
- Mohee, R., Mudhoo, A. 2005. Analysis of the physical properties of an in-vessel composting matrix. *Powder Technology*, **155**(1), 92-99.
- Schaub-Szabo, S.M., Leonard, J.J. 1999. Characterizing the bulk density of compost. *Compost Science & Utilization*, **7**(4), 15-24.
- Van Ginkel, J.T., Van Haneghem, I.A., Raats, P.A.C. 2002. Physical properties of composting material: Gas permeability oxygen diffusion coefficient and thermal conductivity. *Biosystems Engineering*, **81**(1), 113-125.
- Yang, W., Sokhansanj, S., Tang, J., Winter, P. 2002. Determination of thermal conductivity, specific heat and thermal diffusivity of borage seeds. *Biosystems Engineering*, **82**(2), 169-176.
- Yue, B., Chen, T.B., Gao, D., Zheng, G.D., Liu, B., Lee, D.J. 2008. Pile settlement and volume reduction measurement during forced-aeration static composting. *Bioresource Technology*, **99**(16), 7450-7457.