Modelling sludge drying bed dewatering processes

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Abstract: In recent years, the problem of modeling the wastewater sludge dewatering processes in sand drying beds has gained considerable relevance. This paper reports the development of a sludge drying bed dewatering processes model. Through mass and heat balance approaches the mathematical model is used to predict the solid content of sludge along time. The efficiency of the proposed model was validated under different weather conditions, using data collected in a pilot installation set in a Portuguese wastewater treatment plant. Field experiments were performed from September 2016 to June 2017. Model predictions were generically consistent with the experimental data. The model, which is still under further development, is considered particularly interesting to design and manage sludge drying beds in arid and semi-arid regions.

Key-words: Sludge drying beds**,** Sludge dewatering, Modeling, Performance evaluation

1.Introduction

Drying beds have been used since the beginning of the twentieth century (Wang, et al., 2007). Sand drying beds, in particular, are the most widely used method of sludge dewatering in small treatment plants. The dewatering process in drying beds is based on drainage of leachate through sand and gravel supporting layers to the bottom of the bed, and evaporation of water from the surface, until a desired solids content (SC) is achieved. Climate factors affecting the operation of sand drying beds include humidity, temperature, radiation and rainfall (Strande et al., 2014).

Although there is some research on the evaluation of sand drying beds performance, such as the works done by Gharaibeh et. al. (2007) and Sousa (2012), in Australia and Brasil, recent developments on this field are scarce. The dewatering of wastewater sludge is a complex process, in which heat and mass transfer occurs simultaneously.

In this essay, a mathematical model was developed to support the design and management of sludge drying beds. The model estimates the solids content, through the dewatering process, given the initial sludge layer thickness and the prevailing meteorological conditions. The field experiments that were used to develop and validate the model were conducted in the Póvoa da Galega wastewater treatment plant, located in Lisbon, Portugal.

2.Methods

2.1 Field Experiments

Two sludge sand drying beds units were installed in a pilot facility, in the Póvoa da Galega wastewater treatment plant. Each unit surface area was about 1 m^2, filled with a supporting layer of coarse gravel (with a thickness of 0,2 m and diameters between 20 and 40 mm), fine gravel (0,1 m thickness, diameters form 8 to 12 mm) and sand (0,1 m thickness), fitted with a drainage tap to a container. A portable meteorological station was also installed in the facility, as shown in Figure 1, in order to continuously monitor the weather conditions, namely air temperature, solar radiation, relative humidity, wind velocity and precipitation.

Figure 1 - Pilot installation in the Póvoa da Galega wastewater treatment plant

The sludge applied to the experimental drying beds was remove directly from the anaerobic digester in the wastewater treatment plant. Samples were taken on the first three days and, after that, on days seven, fourteen, twenty one and twenty eight, in order to measure the moisture content throughout the cycle duration. Other physical-chemical characteristics of sludge were also analyzed, namely its bacteriological content (*escherichia coli* and *salmonella*). During the samples collection, care was taken to remove portions of sludge of different depths, in an attempt to obtain representative samples of the average characteristics of the sludge layer. On the first and third days of each cycle, samples of the leachate were also collected. Additionally, the depth of the sludge layer along the cycle was measured in order to evaluate the volume reduction associated to the dewatering process. The under drained liquid volume was collected in containers and measured. Laboratory tests were also carried out to evaluate the quality of this leachate, in terms of its Chemical Oxigen Demand (COD) and Total Suspended Solids (TSS), and the type of treatment it should be submitted to.

Three sludge dewatering cycles were conducted from September 2016 to June 2017, in order to evaluate the performance of the sludge drying beds during different weather conditions measured over the year. The initial SC of the sludge was also different between cycles, ranging from 2 %, in the first cycle, to 4 %, in the third one. In the first two cycles, the application depth of the sludge layers was 0,32 m and 0,2 m, respectively, in each drying bed. In the last cycle, only one sludge drying bed was considered, with a 0,32 sludge layer depth.

2.2 Mathematical Model

The mathematical model was formulated using a mass and heat balance approach that considers meteorological conditions and sludge layers initial characteristics, such as density, SC, thickness and superficial area. The mass and heat balance equations defined were applied to estimate the SC and thickness values from a given control volume of sludge, along the cycle.

According to the mass balance equation defined (expression (1)), the sludge water can be removed by evaporation through the sludge surface exposed to the air ($\mathrm{m}_{evaporatedwater}(\Delta \mathrm{t})$) or drained by the existing system for this purpose. On the other hand, since the control volume is exposed to the meteorological conditions, water can be added by precipitation over the bed. Appling this balance, the mass of water present in the sludge, at each calculation step ($\mathrm{m}_{\text{água}}(\mathrm{t})$) can be determined.

$$\mathrm{m}_{\text{water}}(\mathrm{t}) = \mathrm{m}_{\text{water}}(\mathrm{t}-1) + \mathrm{m}_{\text{rainfall}}(\Delta \mathrm{t}) - \mathrm{m}_{\text{drainedliquid}}(\Delta \mathrm{t}) - \mathrm{m}_{e\text{vaporatedwate}r}(\Delta \mathrm{t}) \qquad (1)$$

The mass of water precipitated over the control volume over a given time, $\mathrm{m}_{\text{rainfall}}(\Delta \mathrm{t})$, is obtain based on the weather station precipitation measures. The drained water mass, $\mathrm{m}_{\text{drainedliquid}}(\Delta \mathrm{t})$, can be determined, depending on the phase of the dewatering process in which the sludge is found, translated by its TH value, by expressions 2a) and 2b),

$$\mathrm{m}_{\text{drainedliquid}}(\Delta \mathrm{t}) = \mathrm{D}_{\text{acumulate}}(\mathrm{t}) - \mathrm{D}_{\text{acumulate}}(\mathrm{t}-1) \qquad \mathrm{SC} \geq 90\% \qquad (2a)$$

$$\mathrm{m}_{\text{drainedliquid}}(\Delta \mathrm{t}) = \frac{\mathrm{m}_{\text{rainfall}}(\Delta \mathrm{t})(\Delta \mathrm{t})}{\mathrm{m}_{\text{águaprecipitada}}(\Delta \mathrm{t}_{\mathrm{d}})} \times \mathrm{D}_{\text{acumulate}}(\Delta \mathrm{t}_{\mathrm{d}}) \qquad \mathrm{SC} < 90\% \qquad (2b)$$

where $\mathrm{D}_{\text{acumulate}}(\mathrm{t})$ represents the mass of accumulated water, drained away, each day, estimated from the values measured in the experimental tests. The mass of water evaporated from the surface of the control volume was calculated through the energy balance described below. According to equation (3), determined through the energy balance described below.

$$\begin{aligned} \mathrm{m}_{e\text{vaporatedwate}r}(\Delta \mathrm{t}) &= \\ &= \Big\{\Big[\alpha_{\mathrm{sl}}\Big((\mathrm{R}_{\text{solar}} \times \mathrm{A}_{\mathrm{sl}}) + \big(\varepsilon_{\text{atm}} \times \sigma \times \mathrm{T}_{\text{sky}}{}^{4} \times \mathrm{A}_{\mathrm{sl}}\big)\Big)\Big] \\ &\quad - [\mathrm{h} \times (\mathrm{T}_{\mathrm{sl}} - T_a) \times \mathrm{A}_{\mathrm{sl}}] \quad - \big[\varepsilon_{\mathrm{sl}} \times \sigma \times \mathrm{T}_{\mathrm{sl}}{}^{4} \times \mathrm{A}_{\mathrm{sl}}\big]\Big\} \times \frac{\Delta \mathrm{t}}{\mathrm{H}_{\mathrm{fg}}} \end{aligned} \qquad (3)$$

However, this balance does not take into account the total water mass present in the sludge, nor the different fractions in which it is distributed. The greater difficulty in removing the interstitial, adsorbed and cellular fractions from the water mass present in the sludge is translated in the slowing down of the water removal rate, in this case, by evaporation. In order to approximately consider this and other limiting factors, the mass of evaporated water calculated by equation (3) was, for the purposes of mass water balance, limited as a function of the SC of the sludge layer over the cycles. Thus, for SC values between 25 and 30%, the evaporated water mass considered was half of the value calculated through equation (3) and a tenth of that value for higher SC. In the expressions used, all values of mass, measured, accumulated or estimated on each day were obtained in kg. In the present study, the model was applied in a daily calculation step.

Since the heat transfers associated to the evaporation of the water mass present in the sludge to the surrounding air occur primarily by radiation and convection, the heat balance applied to calculate the evaporated water mass, represented through expression (4), considers the heat transferred to the sludge control volume by solar and atmosphere radiation, and from the control volume to the surrounding air through the radiation emitted from the sludge layer. The heat transfer by convection can hider be supplied to or lost from the sludge volume, as a function of the temperature difference between sludge and surrounding air. In the following equations, all values of heat transfer rates are expressed in W.

$$(Q_{radiation})_{absorbed} + (Q_{convection})_{in} = (Q_{radiation})_{emitted} + (Q_{convection})_{out} + Q_{evaporation} \quad (4)$$

The rate of radiation absorbed by the control surface, $(Q_{radiation})_{absorbed}$, can be written as follows:

$$(Q_{radiation})_{absorbed} = \alpha_{sl} \left((R_{solar} \times A_{sl}) + (\varepsilon_{atm} \times \sigma \times {T_{sky}}^4 \times A_{sl})\right) \quad (5)$$

where R_{solar} representes de solar radiation (W/m2), α_{sl} the solar radiation absorptivity of the sludge surface (dimensionless), for which a value of 0,8 was considered, $A_{sl}$the control volume surface area (m2), ε_{atm} the atmospheric emissivity under clear sky (dimensionless), σ the Stefan–Boltzmann constant (5.6697x10−8 W/m^2.K^4) and T_{sky} the sky temperature (K), measured by an empirical relation found by Berdahl and Martin (1984), which is related to the dew temperature, T_{dew} (ºC), the ambient temperature T_a (K), and where time, t_{00} (h), is measured from midnight, as the starting point,
by equation (6):

$$T_{sky} = T_a \left(0{,}711 + 0{,}56\,(T_{dew}/100) + 0{,}73(T_{dew}/100)^2 + 0{,}013\cos(15t_{00})\right)^{0{,}25} \quad (6)$$

The dew temperature can be estimated using equation (7):

$$T_{dew} = \frac{237{,}3\ \ln\left(\frac{\rho_{parcialv}}{6{,}108}\right)}{17{,}27 - \ln\left(\frac{\rho_{parcialv}}{6{,}108}\right)} \quad (7)$$

where $\rho_{parcialv}$ is the pressure of water vapor at the ambient temperature (hPa). The water vapor partial pressure can be expressed by equation (8):

$$\rho_{parcialv} = HR \times \rho_v \quad (8)$$

The saturated vapor pressure ρ_v (hPa) can be calculated from expression (9):

$$\rho_v = 6{,}108 \times 10^{(7{,}5 \times T_a)/(T_a + 237{,}3)} \quad (9)$$

Brutsaert (1982) expressed the atmospheric emissivity under clear skies by the following formula:

$$\varepsilon_{atm} = 1{,}24 \left(\frac{\rho_{parcialv}}{T_a}\right)^{1/7} \quad (10)$$

The rate of the heat emitted by radiation from the control volumes can be written as shown by expression (11):

$$(Q_{radiation})_{emitted} = \varepsilon_{sl} \times \sigma \times {T_{sl}}^4 \times A_{sl} \quad (11)$$

where T_{sl} represents the surface temperature of residuals (K) and ε_{sl} the emissivity of the sludge layer surface (dimensionless).

Heat transferred by convection is determined according to Newton's law of cooling (12):

$$(Q_{convection})_{in/out} = h \times (T_{sl} - T_a) \times A_{sl} \quad (12)$$

where h is the heat transfer coefficient ($W/m^2.K^{-1}$), determined as a function of the Nusselt number, Nu, (dimensionless) as shown in equation (13):

$$h = \frac{k}{L_c} \times Nu \quad (13)$$

In this equation, k represents the thermal conductivity of air (J/m2 K), Lc the characteristic length of the control surface (m). The Nusselt number is determined according to equations (14a) an (14b), as a function of the Raylegh number (equation (15), dimensionless) :

$$Nu = 0{,}54 \times Ra^{1/4} \qquad 10^4 < Ra < 10^7 \quad (14a)$$

$$Nu = 0{,}15 \times Ra^{1/3} \qquad 10^7 < Ra < 10^{11} \quad (14b)$$

$$Ra = Gr \times Pr \quad (15)$$

In equation (15), Pr is the Prandtl number of air (dimensionless) and Gr is the Grashof number (dimensionless), obtained by equation (16):

$$Gr = \frac{\beta \times g \times (T_{sl} - T_a) \times {L_c}^3}{\vartheta^2} \quad (16)$$

where g represents the gravitational acceleration (m/s2), ϑ^2 the kinematic viscosity of air (m2/s) and β coefficient of volume expansion.

Heat can be released from the control surface of the sludge layer by the change in phase of liquid water into water vapor. Heat rate by evaporation can be expressed by equation (17), where H_{fg} is the vaporization enthalpy (J/kg):

$$Q_{evaporation} = m_{evaporatedwater} \times H_{fg} \times \Delta t \quad (17)$$

The mass of water evaporated from the surface of the control volume can then be calculated as shown in equation (3) above.

Knowing the water mass at each calculation step, determined by equation (1), and the mass of existing solids in the sludge layer, m_{TS} (kg), according to equation (18), the SC of the sludge , at each calculation step, can be determined by equation (19) as follows:

$$m_{TS} = = (A_{sl} \times e_0 \times \rho_{sl}) \times SC(t = t_0) \quad (18)$$

$$SC\,(t) = \frac{m_{TS}}{m_{water}\,(t) + m_{TS}} \quad (19)$$

In these equations, t_0 represents the initial instant of calculation (days), e_0 and ρ_{sl} the sludge layer thickness and density at that instant (m).

3.Results and Discussion

3.1 Field Experiments

The sludge SC values obtained during the performed cycles in the two sludge drying beds installed are shown in Figure 2.

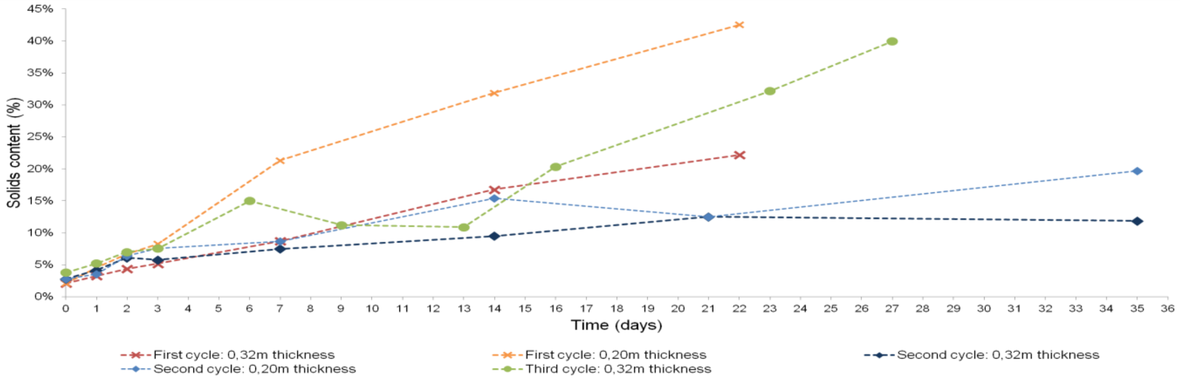

Figure 2 - SC values evolution for each drying bed in the three cycles performed

According to the experimental results observed in Figure 2, the sludge drying beds had better performance (correspondent to higher SC values and volume reduction) in cycles associated with higher air temperature and solar radiation values, and lower relative humidity and precipitation. While on the last cycle, performed on the months of May and July, that correspond to the beginning of the summer season in Portugal, a sludge SC value of 15% was obtained on the seventh day for a 0,32 m initial layer thickness, on the cycle conducted on October and November, when the autumn season ends, the sludge SC value for the same initial layer thickness, on the same day, was less than 8%, for the same initial depth of sludge applied.

For similar weather conditions, lower application depth sludge layers are more easily dehydrated. To illustrate this, Figure 3 shows the SC values measured on the first cycle, occurred between September and October, for the two different initial thickness values of the sludge layers applied to each bed.

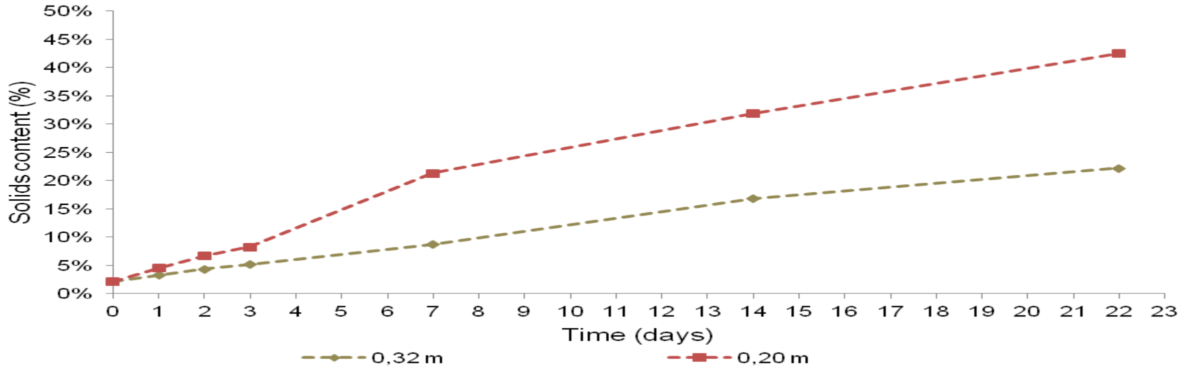

Figure 3 - First cycle SC evolution for 0,32 m and 0,2 m initial sludge layer thicknesses

As shown in this figure, in the lower application depth a final SC value of 43% was obtained, while in the higher application depth SC only reached a 22% value.

It was also observed that most of the sludge drainable water was removed in the first two to three days of the cycles, which corresponds to about 90% of water content (WC) values. For lower WC values, no significant values of effluent drained water were measured.

In the first and third cycles, the surface cracking of the sludge layer was observed, with consequent formation of clods in the dewatered sludge, as shown in Figure 4. In the 2nd cycle this phenomenon had a very small expression, due to the high precipitation verified in the corresponding period.

Figure 4 - Clumps formed by cracking and retraction of sludge

Regarding the sludge volume, reduction thickness values greater than 75% were observed in all of the performed cycles. Due to the horizontal retraction of sludge shown in figure 4, the volume reduction associated to the dewatering process is even higher than that. These values illustrate a great advantage of this dewatering process.

Observing the different drying curves of Figure 2, it generically appears that there is an increase in the dehydration rate after the first four to seven days of each cycle. This increase is probably due to the cracking of the sludge layer that has a propitious effect on the sludge water mass evaporation. In a more advanced phase of the cycles, the opposite effect is observed, that is, the slowing down of the dehydration process, translated by the smaller variation of TS values over time. This slowdown is justified by the decrease in the amount of water present in the sludge that can evaporate, that is, by the gradual increase in the difficulty of removing the different water fractions present in the sludge, as the amount of free water decreases.

Through the laboratory tests carried out during the experimental cycles, the effect of reducing pathogenic microorganisms associated with the sun exposure of the dehydrated sludge in drying beds was also verified, contributing favorably to the agricultural valorization potential of sludge, showing another advantage of sludge dewatering in sand drying beds.

3.2 Mathematical Model

Knowing the meteorological data, the beds dimensions, the sludge applied layers thickness and the initial SC value, the described model was applied to predict the values of SC and along the dehydration cycle in the experimental drying beds.

Figure 5 illustrates the water masses balance computed by the model for the thicker layers applied in each cycle.

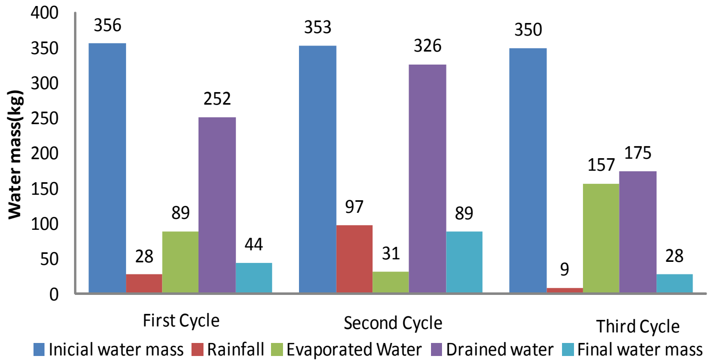

Figure 5 - Graphic representation of the water mass balance

The influence of the meteorological data on the natural dewatering process of the sludge in drying beds is again evidenced in this graph where, for the same sludge layer thickness, the liquid mass initially present in the sludge presented very similar values in the different cycles, and yet different final mass values were obtained, given the different masses of precipitated and evaporated water throughout the cycles.

The results obtained by the model also showed that, apart from precipitation, the meteorological parameter that mostly influence the evaporation process is solar radiation. Among the variables considered in the heat balance described above, the rate of heat transfer trough convection is the one that shows less influence on the evaporation process, since this is proportional to the difference between the temperature values of the sludge and the air which is naturally reduced.

Through the mass and heat balance equations the mathematical model included, a drying curve was obtained, predicting the SC. The drying curve obtained had good agreement between the predicted and experimental results, in particular in the cycles where the sludge surface cracking had less expression. To illustrate this observation, Figure 6 shows the comparison between model and experimental results from the first cycle, in which an extensive cracking of the sludge layer was observed, and the second cycle, where in which the cracks formation was barely noticed. In the first cycle, the predicted drying curve had a better agreement with the experimental results in the early stage of the cycle, as shown in Figure 6. For higher values of SC, the drying curve deviates from experimental results, mainly due to the cracks formed at the residuals surface.

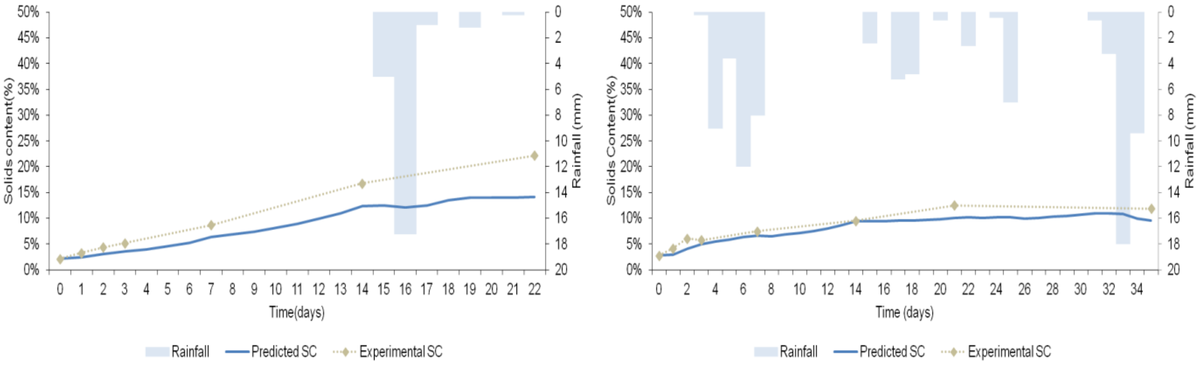

Figure 6 - Experimental results and drying curve obtained by the model for the first and second cycle

4.Conclusions

A sludge drying bed dewatering processes model was developed. This model takes into account the local meteorological conditions (temperature, solar radiation, relative humidity and rainfall) and the initial sludge layer thickness.

In order to verify the model, field experiments were conducted on a pilot installation, in Portugal. Throughout the various dewatering cycles performed in experimental drying beds, laboratory analysis were carried out on samples taken from the beds in order to determine the sludge SC evolution. During the course of each cycle, the sludge applied layer thickness was measured as a measure of the volume reduction associated with this process. In the laboratory, bacteriological analysis of sludge samples were carried out, as well as the determination of the leachate COD and SST values, in order to evaluate the type of treatment it should be submitted to.

It was observed that sludge drying beds present better performance, which means higher values of solids content and consequent reduction of volume in a shorter period of time, in cycles where the air temperature and solar radiation values were higher and relative humidity and precipitation registered values were lower. For the same meteorological conditions, thinner sludge layers were more easily dehydrated.

Generically, the predictions obtained by the model showed good agreement with experimental work, although some weaknesses have been identified in the calculation structure of the model.

It has been found that the developed model results are more approximated to the experimental results when the cracking of the sludge layer showed a reduced expression, due to the non-consideration of this phenomenon influence in the model. In cycles in which the sludge layer showed extensive cracking the values of SC obtained by the model showed better agreement with those determined experimentally in an initial phase. In a more advanced phase, when the formed cracks grow, the drying curve deviates from experimental results, with predicted values being lower than the experimental ones.

In order to better estimate the values of evaporated mass, it is recommended, for future work, the inclusion of the surface cracking influence on the sludge water mass removal by evaporation, in the model, through additional experimental tests, considering the consequent increase of the sludge area exposed to solar radiation.

It would also be interesting to characterize and determine the evolution of the different fractions of water, that is free, interstitial, adsorbed and intracellular water, throughout the dewatering processes. Thus, a better definition of the liquid mass drained in the beds and the limits considered for the evaporation process slowing down, due to the different characteristics of water fractions removal, could be reached.

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