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Evaluation of the use of modified paved drying beds compared to the conventional sand drying beds

A.A. Elbaz[a], A.M. Aboulfotoh[a,*], E.H. ElGohary[a], M.T. Reham[b]

[a]*Faculty of Engineering, Environmental Engineering Department, Zagazig University, Zagazig, Sharqia 44519, Egypt, Tel./Fax: +20 552304987; Mobile No: +20 1111784499; email: aseaf_1@yahoo.com/asalem@zu.edu.eg (A.M. Aboulfotoh), Tel./Fax: +20 552304987; Mobile No: +20 1064411131; email: Elbaz50@hotmail.com (A.A. Elbaz), Tel./Fax: +20 552304987; Mobile No: +20 1224896315; email: emadgohary97@gmail.com (E.H. ElGohary)*

[b]*Civil Engineering Department, The High Institute for Engineering and Technology, Al-Obour, Egypt, Tel./Fax: +20 244781997; Mobile No: +20 1017797984; email: rehamteama1111@yahoo.com*

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ABSTRACT

Sludge drying beds may be classified into five main types: conventional sand drying bed (CSDB), paved drying bed (PDB), wedge-wire, vacuum assisted, and solar drying bed. In this research, three configurations of PDBs were investigated experimentally in order to determine the best configuration by using drainage pipe placed in different locations in the basin, covered by geo-textile membrane and fine gravel filter. The best configuration of modified PDBs was compared with the CSDB. The effect of sludge layer height (30, 50, and 72 cm) and sludge types (waste activated sludge (WAS), thickened combined primary and waste activated sludge (CPAS), primary sludge and trickling filter humus) on the performance of modified PDB have been also studied. The results showed that using two pipes in the PDB; one in the bottom channel of the tank and the other in the corner of the tank is the best configuration that achieved a higher drainage water ratio in shorter drying time. The maximum dried solid content achieved by the CSDB was 16% after 12 d of drying, whereas the same solid content was achieved by the modified PDB after only 3.5 d of drying and the solid content increased to 47% after 12 d of drying. The results also showed that the best sludge layer height is 50 cm where the maximum dried solid content achieved by the modified PDB was 52% after 12 d of drying. The WAS and the thickened CPAS have the highest dried sludge solid content which was about 52%, 55% compared to the other types for 12 d of drying time. The modified PDB achieved the highest solid loading rate (598 kg/m^2 y) to obtain 20% dried solid content compared to the conventional PDB (191 kg/m^2 y) and conventional sand drying bed (225 kg/m^2 y).

keywords: Dewatering; Drying bed; Paved; Geo-textile; Thickened; Sludge; Solid loading rate; Trickling filter; Waste activated

1. Introduction

Dewatering is a physical separation process which is used principally for the reduction of the water content in the sludge [1,2]. The commonly used approaches of dewatering are classified into two main categories: mechanical and natural dewatering [1,3]. Natural dewatering occurs in basins open to the atmosphere where the water content can be reduced by evaporation, drainage, and decanting [1,4]. On the contrary, as the name implies, mechanical dewatering systems requires mechanical energy. Compared to mechanical systems, natural dewatering processes are less complex, easier to operate, and require less

* Corresponding author.

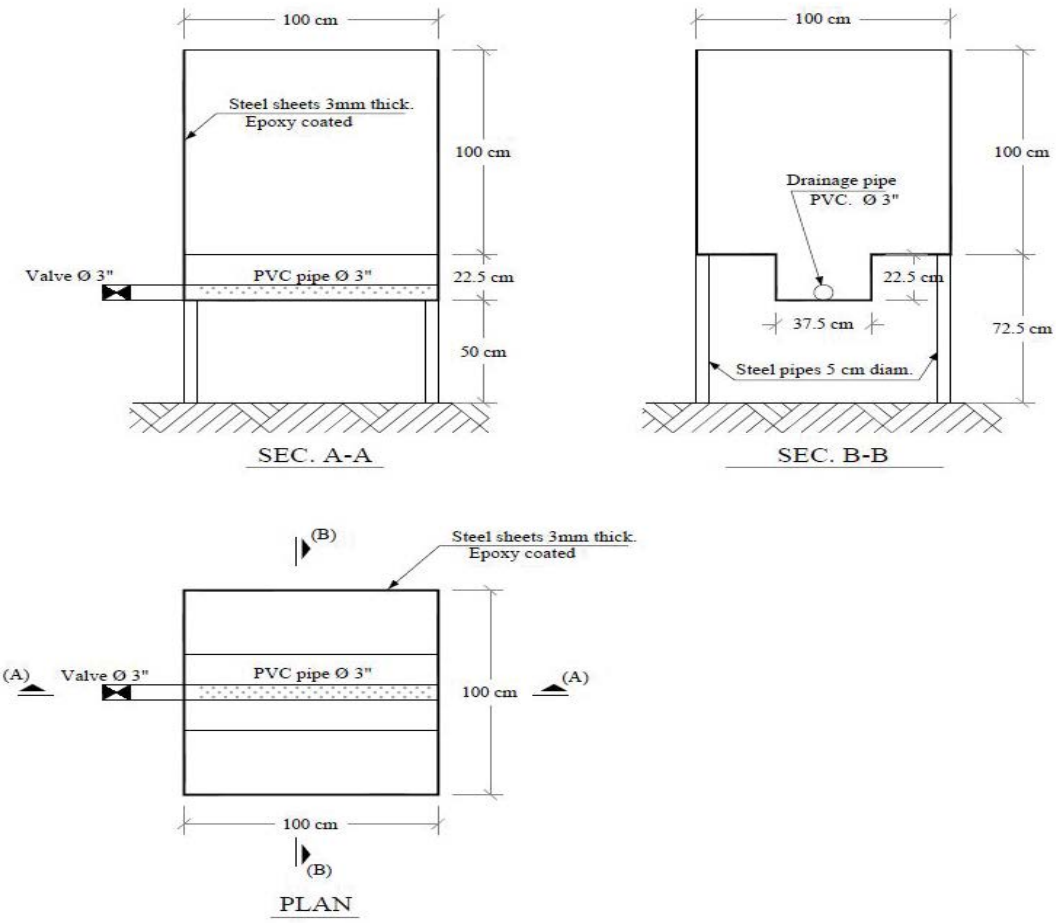

Fig. 1. Schematic view of the field experimental model.

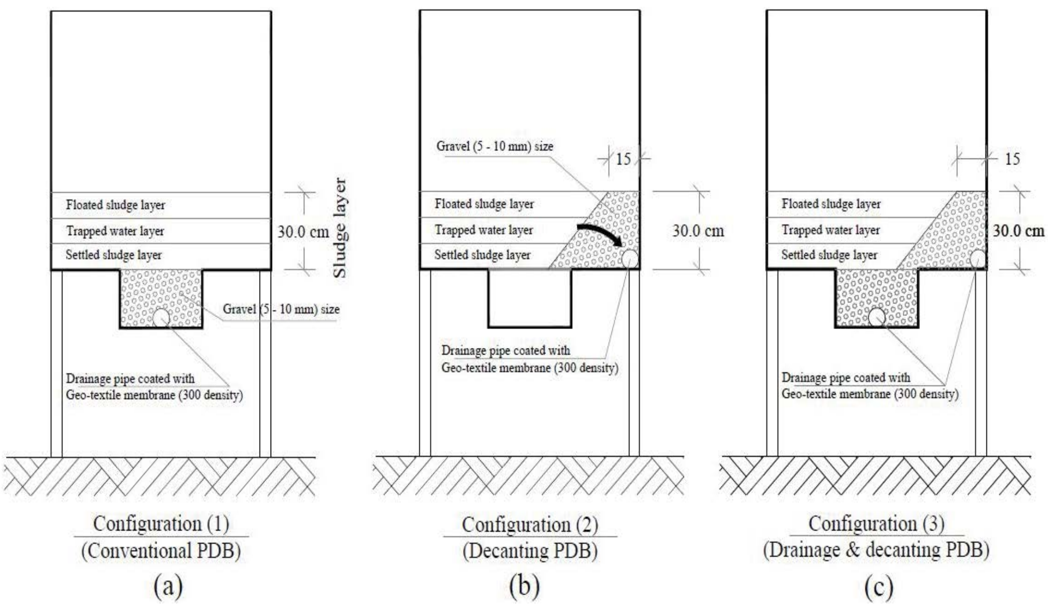

Fig. 2. Various configurations of the tested (PDB) models.

energy. Additionally, the natural dewatering systems can be classified into two commonly used schemes namely: sludge drying beds and sludge lagoons [5]. The review in the following paragraphs will focus only on the natural dewatering systems especially sludge drying beds, which is more relevant to the topic of the paper.

Sludge drying beds have been used since the beginning of the twentieth century [6]. The design of these beds depends strongly on the site, environmental, and climatic conditions as well as the solids loading rate (lb/ft^2/y) [7]. It should be located at least 100 m distance away from houses to avoid the odors problem [8]. Drying beds are generally used for small and medium communities or industrial wastewater treatment plants (WTPs).

Although drying beds are simple in design and operation, it requires a large area and its performance depends strongly on the climatic conditions [9–11]. It is worth mention that sludge treatment methods differ from one country to another due to differences in operating conditions and energy prices [12]. Sludge drying beds may be classified into five main types: conventional sand drying bed (CSDB), paved drying bed (PDB), wedge-wire, vacuum-assisted, and solar drying bed [9]. These types are discussed below.

Dewatering on CSDBs proceeds via two different mechanisms; water drainage and evaporation. Water drainage is the most important mechanism during the first 1–3 d [13] where the solid content can be as high as 15%–25%. Further water removal occurs via evaporation [6]. The principle of this method is based on spreading the sludge out and letting it dry. Typical sand beds consist of a layer of coarse sand (15–25 cm); supported on a gravel bed (25–30 cm) that incorporates selected tiles or perforated pipe under-drain. Sludge is placed on the bed in 20–30 cm layers and is allowed to dry, then the sludge can be removed manually or by mechanical equipment to the nearby landfill area. The water content can be reduced by about 40% after 10–15 d of drying under favorable conditions [14,15].

The advantages of using sludge drying beds are as follows: it is simple in operation without a need for skillful operators, low energy consumption, less sensitive to sludge variability, and low to no chemical consumption [3,9,14,15–18]. Despite these advantages, the use of sludge drying beds has several disadvantages such as lack of a rational engineering design approach allowing sound engineering economic analysis, it requires more land than fully mechanical dewatering methods, it requires a stabilized sludge (if it is not allowed to spread bad odors), it may be more visible to the general public and the removal of the dried sludge usually requires intensive labor [9,14–18].

PDBs may exist in two different configurations namely; drainage and/or decanting type. The drainage-type paved drying beds (DPDB) are rectangular and similar to the conventional drying beds with a vehicular track for cake removal. The paving is made of concrete, asphalt, or soil cement. The drainage pipe is placed below the unpaved area of the drying bed [6]. The settled sludge is periodically agitated by a tractor-mounted horizontal auger or another device to regularly mix and aerate the sludge to promote evaporation and percolation [19]. Solids concentration may range between 40% and 50% for 30–40 d of drying period in an arid climate for a 30 cm sludge layer [20]. In some systems, up to 1 m (3 ft) of liquid sludge is applied in the initial layer [9,20,21]. Field experience indicates that the use of PDBs results in shorter drying time, as well as more economical operation when compared with CSDBs [6]. However, it provided a sludge cake with a similar concentration of solids (25%) as the one obtained in the CSDB [1]. Paved beds have successfully worked with anaerobically digested sludge but are less desirable than sand beds for aerobically digested activated sludge [6,22–24].

The problem of using CSDBs (with 20–30 cm sludge layer) is that, it requires a large area of land for construction, and a period not less than 10–15 d (depending on weather conditions such as temperature and humidity) for drying and cleaning. With increasing the height of the sludge layer in case of limiting lands, it takes longer (several weeks) until it reaches the required degree of drying. Another problem with the sand drying beds is the loss of the sand layers during the process of cleaning, which requires compensation over time. Also, one of the main problems with the sand drying beds is that it must be manually cleaned without the use of mechanical equipment, which requires the division of beds into large groups of small beds to facilitate the process of cleaning. These defects and operating problems can be overcome by using the PDBs, which is recommended by several studies [1,6,24]. For that, the current study aims at optimizing the configuration of the PDB to achieve higher water drainage rates. This is conducted through investigating the effect of varying the position of the drainage and decanting pipes in the bed. Three positions were investigated in the present study. The results of the modified PDB were compared with the CSDB. The comparison included the following parameters: (i) the effect of water drainage rate and drying time, (ii) the effect of sludge depth on the drained water ratio and drying time in the modified PDB, (iii) the effect of sludge type on the drained water ratio and drying time. Four sludge types were investigated namely; thickened combined primary sludge and trickling filter humus (CPTF), thickened combined primary and waste activated sludge (CPAS), un-thickened primary sludge (PS), and thickened waste activated sludge (WAS). Finally, the study contributes in determining some of the effective parameters required for the design of sludge drying beds for waste water (solid loading rate).

2. Materials and methods

Sludge sources and materials used in the current study as well as the field experimental pilot plant will be described in the following subsections.

2.1. Sludge sources

It is well-known that the specifications of sludge from wastewater treatment processes differ from one plant to another. It depends on the specifications of the raw wastewater, the treatment processes, and the method of operation in each plant. For example, primary sludge (PS) is produced from primary settling processes and often has a very bad smell. It is rapidly digested if appropriate conditions are present. WAS is produced from biological treatment processes with an activated sludge system. Most of the solid materials in the WAS are living or dead bacterial cells (called bio-solid) and it does not often have an offensive smell like the primary sludge. Trickling filter humus (TF) is resulting from biological treatment processes with a trickling filter system. It has a higher solid content than the activated sludge but it decomposes at a slower rate. In most WTPs, the primary sludge (PS) is often mixed with WAS or TF and thickened together to obtain thickened CPAS or CPTF sludge.

This research aims at evaluating the use of modified PDBs for drying different types of sludge in different WTPs. In this study, four types of sludge from different sources were examined.

2.1.1. Sludge type I (CPTF)

This sludge was obtained from Qnayat WTP (located at Qnayat city, AL-Sharqia Gov.). This plant includes primary settling tanks followed by trickling filters and final settling tanks. Primary sludge (PS) is mixed with the tricking filter humus (TF) and concentrated together inside gravity thickeners. During the present study, two samples of thickened combined primary sludge and trickling filter humus are used. CPTF samples have a solid content (SC) of about 4.3% and 6.8%.

2.1.2. Sludge type II (CPAS)

This sludge was obtained from Shalshilmun WTP (located at Minya Alqamh, AL-Sharqia Gov.). This plant includes primary settling tanks followed by aeration tanks (activated sludge system) and final settling tanks. Primary sludge is mixed with the WAS and concentrated together inside gravity thickeners. During the present study, two samples of thickened CPAS are used. CPAS samples have a solid content (SC) of about 5.3% and 3.4%.

2.1.3. Sludge type III (PS)

This sludge was obtained from Shalshilmun WTP (located at Minya Alqamh, AL-Sharqia Gov.) described above. During the present study one sample of un-thickened primary sludge is used. PS sample has a solid content (SC) of about 2.6%.

2.1.4. Sludge type IV (WAS)

This sludge was obtained from Altal Alkabir WTP (located at Altal Alkabir city, Ismailia Gov.). This plant doesn't include primary treatment and wastewater directly enters the biological treatment basins (oxidation ditches). The only source of sludge is the WAS which is concentrated inside gravity thickeners. During the present study, one sample of thickened WAS is used. The thickened sludge has a solid content (SC) of about 3.6%.

2.2. Sand

The sand used in this study has a uniformity coefficient which is not more than four and the effective particle size ranged from 0.5 to 1 mm.

2.3. Gravel

Three types of gravel were used in this study: fine gravel (typically has an effective size of about 2–5 mm), medium gravel (typically has an effective size of about 5–10), and coarse gravel (typically has an effective size of about 10–15 mm).

2.4. Drainage pipe

A drainage pipe is made of PVC with diameter of 3 in (75 mm) and perforated (8 mm holes) in staggered mode was used in each model for draining the filtered water. This pipe was installed with minimum slope of 1% in different positions as clarified later in the experimental program.

2.5. Geo-textile membrane

In this study, the used geo-textile membrane was fabricated from polyester fiber with a surface density of 300 g/m^2. This membrane was used to cover the drainage pipe in the PDB models.

2.6. Field experimental models

In the current study, four experimental models made of epoxy-coated steel tanks (3 mm thick) were used. Each tank has a 100 cm width, 100 cm length, and 100 cm height. The tank is fixed on a base 72.5 cm height, consists of four steel pipes (5 cm diameter) as shown in Fig. 1. Each tank has a bottom channel (22.5 cm depth and 37.5 cm width) for installing the drainage pipe.

3. Experimental program and the measurements

The present study was divided into four phases as described below:

3.1. Phase I

Some researchers [25–27] reported that sludge in drying beds consists of three different layers; a layer of settled sludge and a layer of floating sludge with a layer of trapped water in between. This trapped water layer may require the use of decanting pipes to drain them out of the bed and thus accelerates the drying process. So, in the current study, the effect of using a drainage pipe (as a decanter) surrounded by fine gravel filter placed inside the bed (in the corner not in the bottom channel) was investigated.

In the first stage of the study, three configurations of the PDB were studied to determine the best one that achieves the highest drainage water ratio in short time. The difference in each configuration is the position of the drainage pipe as shown in Fig. 2.

3.1.1. Configuration 1: (conventional PDB)

In this configuration, the drainage pipe was covered with geo-textile membrane placed in the bottom channel of the tank, then the pipe was surrounded by a layer of medium size gravel (5–10 mm) as shown in Fig. 2a.

3.1.2. Configuration 2: (decanting PDB)

In this configuration, the drainage pipe was covered with geo-textile membrane placed in the corner of the tank, and the bottom channel of the tank is not used and covered by steel plate. Then the drainage pipe is surrounded by a layer of medium size gravel of total height of 30 cm (above the bottom of the tank) as shown in Fig. 2b.

3.1.3. Configuration 3: (drainage and decanting PDB)

In this configuration, a combination between the two previous configurations was done by using two drainage pipes covered with geo-textile membrane; the first pipe was placed in the bottom channel while the second was placed in the corner of the tank as shown in Fig. 2c.

After the three models were prepared, a layer of 30 cm height from the first sample of sludge type I (CPTF; with SC of 4.3%) was added to each model. This stage was done in November and December 2018, the air temperature was in the range 14°C–18°C, the three models have the same surface area and sludge layer thickness. Thus, the effect of evaporation was neglected, and the drained water volume with time was measured for each model.

It should be noted that the volume of sludge in each model is not the same. In the first model, the volume was 300 L while it was 210 L in the second and third models. This was due to the use of drainage pipe and gravel filter in the second and third models which occupy a portion of the volume (equivalent to 30% of the volume of sludge used in the first model). For this reason, when comparing the three configurations, the volume of filtered water from each model will not be used for comparison. Instead, the ratio of drained water (with time) to the initial volume of water in the sludge will be adopted in the comparison among the three models.

3.2. Phase II

In this stage, the modified paved drying bed (MPDB), according to the results of phase I, was compared to the CSDB taking into consideration the water drainage rate and drying time. The CSDB model consisted of a drainage pipe installed in the bottom channel without covering the pipe with geo-textile membrane and surrounded by a layer of coarse gravel with thickness of 15 cm (size of 10–20 mm). On top of this layer, there are two layers of gravel with 15 cm thickness but different gravel size (medium (size 5–10 mm) and fine (2–5 mm), respectively). Finally, on top of the gravel layers, there is a sand layer of 20 cm thickness (0.5–1 mm) as shown in Fig. 3. In the two (MPDB and CSDB), a layer of 30 cm height from the first sample of sludge type I (CPTF; with SC of 4.3%) was added to each model. This stage was done simultaneously with stage one (in November and December 2018). The drained water volume with time was measured.

3.3. Phase III

During this stage, the effect of sludge depth (in the MPDB) on the drained water ratio and drying time were studied. Three MPDB models were prepared, and a layer of the first sample from sludge type II (CPAS; with SC of 5.3%) was added to each model. A layer of 30 cm height was added to the first model, 50 cm and 72 cm were added to the second and third model, respectively. This stage was done in February and March 2019 where the air temperature ranged from 15°C to 23°C. The three models have the same surface area, the same sludge type, and the same climatic conditions. Accordingly, the effect of evaporation was neglected, and the drained water volume with time was measured.

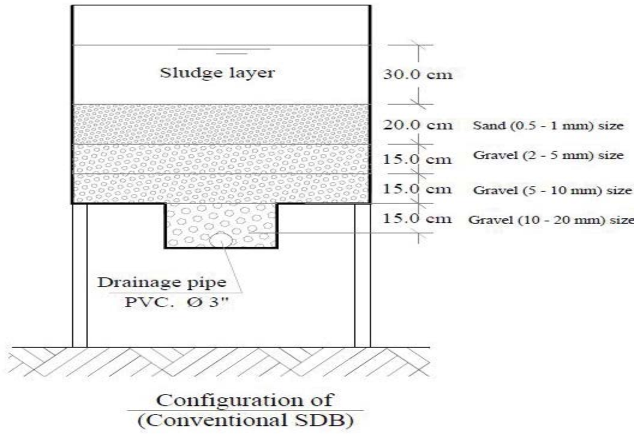

Fig. 3. Components of conventional sand drying bed (CSDB) model.

3.4. Phase IV

During this stage, the effect of dewatering of different sludge types on the drained water ratio and drying time using the MPDB were studied. Four MPDB models were prepared, a sludge layer of 50 cm height was added to each one. Sludge type I (CPTF; the second sample of SC 6.8%), was placed in the first model. Sludge type II (CPAS; the second sample of SC 3.4%) was placed in the second model. Sludge type III (PS; SC 2.6%) was placed in the third model. Finally, sludge type IV (WAS; SC 3.6%) was placed in the fourth model. This stage was done in March and April 2019 and the air temperature was in the range 15°C–26°C. The four models have the same surface area and the same climatic conditions. Thus, the effect of evaporation was neglected and the drained water volume with time was measured.

The measurements:

- *Total solids*: total solids concentration (TS) of sludge samples was analyzed at the Environmental Engineering Department laboratory, Faculty of Engineering, Zagazig University, Egypt, in accordance with "The Standard Methods for the Examination of Water and Wastewater, 20th Edition, 2000."
- *Measurement of drained water volume*: two plastic tanks (35 L volume) were used for the collection of drained water from each model. The volume of drained water was measured in the field at specific times (0.5 h, 2 h, 1 d, 2 d, 3 d, 4 d, 5 d, 6 d, 7 d, 8 d, 10 d and 12 d) using graduated cylinders.

- *Solid content* $(SC)_0$: the initial solid content of sludge sample was calculated as the following:
  Sludge density = (mass of 20 mL sludge sample/20 mL), g/mL, or kg/L.
  The initial solid content (SC), % = (TS/sludge density × 10,000).
- *Drained water ratio (DWR)*: DWR at specific times (0.5 h, 2 h, 1 d, 2 d, 3 d, 4 d, 5 d, 6 d, 7 d, 8 d, 10 d and 12 d) was calculated as the following:
  The initial mass of sludge layer = sludge density × sludge layer volume
  The initial volume of water in sludge layer
  = the initial mass of water in sludge layer
  = the initial mass of sludge layer × (1 – SC_0)
  Drained water ratio, % = (cumulative volumes of drained water/the initial volume of water in sludge layer) × 100
- *Dried sludge solid content (DSC)*: the solid content of dried sludge at specific times (0.5 h, 2 h, 1 d, 2 d, 3 d, 4 d, 5 d, 6 d, 7 d, 8 d, 10 d and 12 d) was calculated as the following:
  Mass of dried sludge layer = (the initial mass of sludge layer – cumulative volumes (or mass) of drained water)
  Initial mass of solids in sludge layer = (the initial mass of sludge layer × SC)
  Assuming the mass of solids in the sludge remains constant (neglecting the mass of escaped solids with drained water)
  Dried sludge solid content = (initial mass of solids in sludge layer/mass of dried sludge layer) × 100

4. Results and analysis

4.1. Optimizing the configuration of PDB

Fig. 4 shows the relation between drying time and drained water ratio for the three configurations of PDBs. After 1 h of drying, the drained water ratio achieved in the conventional PDB, decanting PDB, and drainage and decanting PDB was 7.7%, 2%, and 22%, respectively. After 1 d of drying, the drained water ratio increased to 15%, 15%, and 55% in the three models, respectively. After 5 d of drying, the drained water ratio increased to 61%, 49%, and 88% in the three models, respectively. Finally, after 12 d of drying, the drained water ratio increased to 73%, 60%, and 95% in the three models, respectively.

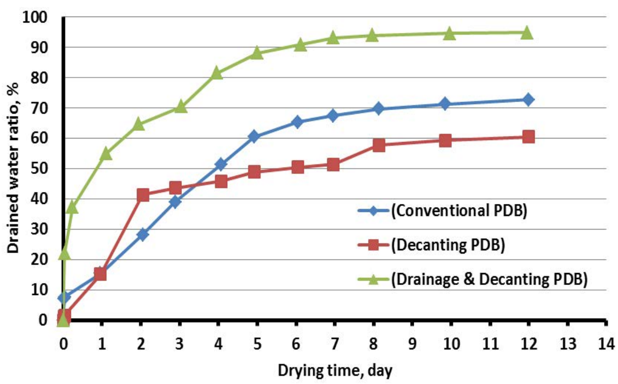

Fig. 4. Relation between drying time and drained water ratio for different configurations of PDB.

Fig. 5 shows the relation between drying time and dried sludge solids content for the three configurations of PDBs. After 5 d of drying, the solid content of dried sludge achieved in the conventional PDB, decanting PDB, and drainage and decanting PDB was 10%, 8%, and 28%, respectively. Finally, after 12 d of drying, the solid content of dried sludge achieved in the conventional PDB, decanting PDB and drainage, and decanting PDB was 14%, 10%, and 47%, respectively.

The results showed that the drainage and decanting configuration of PDB model achieved the highest drained water ratio and the highest solid content of dried sludge with drying time compared to the other configurations. The sludge drying depends on two important factors; filtration and evaporation. The used sludge in this experiment was un-stabilized sludge. Thus, after few days and due to the biological action, part of the sludge raised to the upper surface which resulted in the appearance of trapped water layer in the middle of the tank as seen in Fig. 6. This water didn't filtrate easily because of the clogging of gravel layer by the settling sludge on the surface of gravel layer. Also, this trapped water didn't evaporate because of the floating sludge layer on the tank surface with a thickness of about 8 cm, which prevents the sun rays from reaching

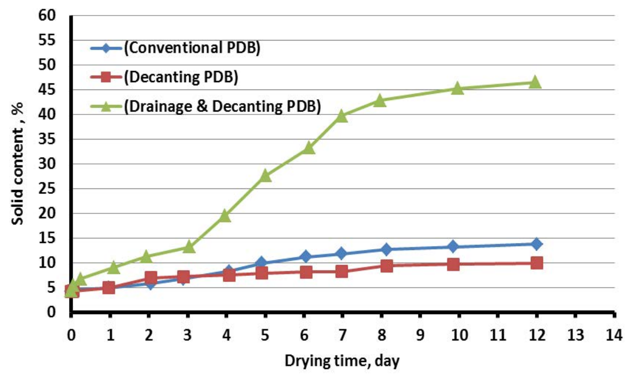

Fig. 5. Relation between drying time and dried sludge solid content for different configurations of PDB.

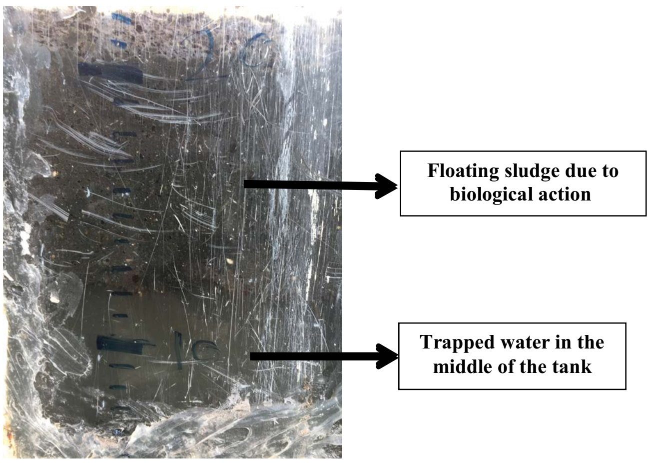

Fig. 6. Formation of water trapped between two sludge layers.

this water [6,21,25,26]. This explains the high efficiency of the drainage and decanting paved drying bed (MPDB) model in accelerating the drainage action of water in shorter time compared to the other configurations. This can be attributed to the use of two drainage pipes; one in the bottom channel that received the gravity of filtered water during the 1st days and the other in the corner of the bed for draining the trapped water formed in the later days.

4.2. Modified PDB comparing to the CSDB

Fig. 7 shows the relation between drying time and drained water ratio for the MPDB compared to the CSDB. After 1 h of drying, the drained water ratio achieved in the MPDB and the CSDB was 22% and 6%, respectively. After 1 d of drying, the drained water ratio increased to 55% and 33% in the MPDB and the CSDB, respectively. After 5 d of drying, the drained water ratio increased to 88% and 62% in the MPDB and the CSDB, respectively. Finally, after 12 d of drying, the drained water ratio increased to 95% and 76% in the MPDB and the CSDB, respectively.

Fig. 8 shows the relation between drying time and dried sludge solid content for the MPDB compared to the CSDB. After 1 d of drying, the solid content of dried sludge achieved in the MPDB and the CSDB was 9.1%, and 6.3%, respectively. After 5 d of drying, the solid content of dried sludge achieved in the MPDB and the CSDB was 28%, and 11%, respectively. Finally, after 12 d of drying, the solid

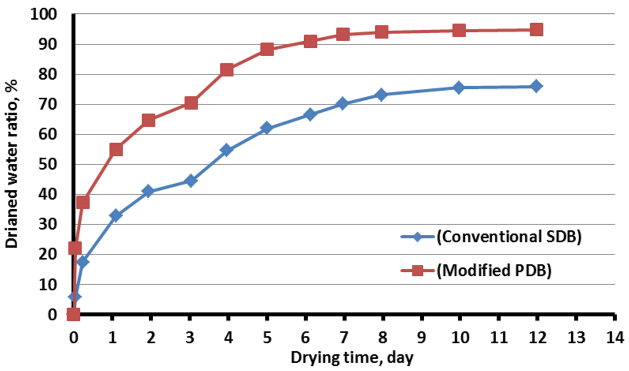

Fig. 7. Relation between drying time and drained water ratio for MPDB compared to CSDB.

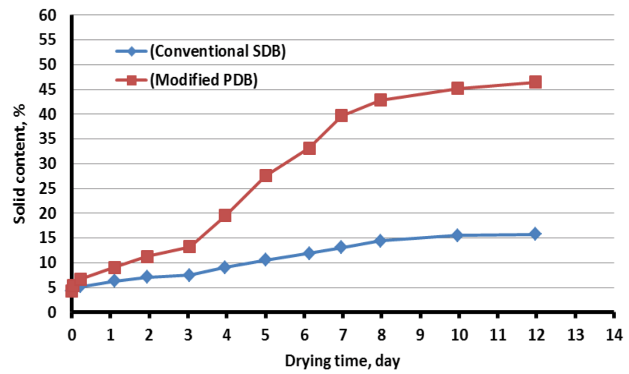

Fig. 8. Relation between drying time and dried sludge solid content for MPDB compared to CSDB.

content of dried sludge increased to 47% and 16% in the MPDB and the CSDB, respectively. The results in the present study are similar to the results in Lampreia [28].

The results demonstrated that, the ratio of drained water was high on the first 5 d then started to decrease. This complies with the results in Al-Nozaily et al. [13] and Lampreia [28], which found that the filtration is the main factor for sludge drying compared to the evaporation of water. Also, the results showed that, the MPDB is more efficient than CSDB in the ratio of drained water and achieving higher solid content in less time, this is similar to the results in [1]. The maximum solid content achieved by the CSDB was 16% after 12 d of drying, whereas the same solid content achieved by the MPDB occurred after only 3.5 d of drying. This means that the modification occurred in the conventional PDB has greatly accelerated the rate of drained water from the bed.

The filtration mechanism that occurred in both CSDB and MPDB can be explained as follows:

4.2.1. Nature of filter layer

The filtration layer used in the CSDB is 20 cm sand layer with a grain size of 0.5–1 mm. The sludge layer spreads out directly over the sand layer which results in the acceleration of clogging the filter due to the accumulation of solids in the voids of the top sand layer leading to a decrease in the drained water ratio after 3–5 d of drying. On the other hand, the used filter in the MPDB consists of two layers; the inner layer of the geo-textile membrane around the drainage pipe (which works as the sand layer in the CSDB), and the outer layer of fine gravel with a thickness of about 20 cm and grain size of 5–10 mm. In the MPDB, the sludge passes through the gravel filter before entering the geo-textile membrane, which helps trap a large proportion of solids between the voids of gravel before it reaches the geo-textile membrane and closes it.

4.2.2. Drainage capacity of trapped water

As explained earlier in the first stage, a layer of water is trapped between the two sludge layers. This layer in the CSDB cannot be evaporated or filtered easily while in the MPDB it was easy to be drained through the drainage pipe located in the corner of the bed which was working as a decanting pipe. Moreover, the performance of the MPDB is greatly improved comparing to the CSDB in achieving the highest rates of draining water and the highest dried solids content during the shortest possible time.

4.3. Studying the effect of applied sludge layer height

Fig. 9 shows the relation between drying time and drained water ratio for different initial sludge layer depth. The three MPDB models had the same type of sludge but the depth of the sludge layer was 30, 50, and 72 cm respectively. After 1 d of drying, the drained water ratio achieved 20%, 37%, and 18% for the depth of 30, 50, and 72 cm, respectively. After 5 d of drying, the drained water ratio increased to 78%, 86%, and 46% in the three models, respectively. After 12 d of drying, the drained water ratio reached 88%,

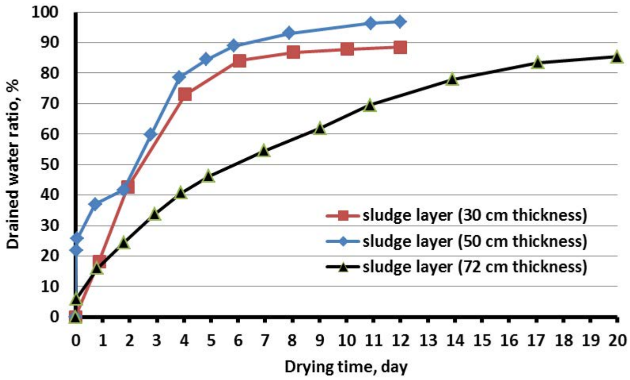

Fig. 9. Relation between drying time and drained water ratio at varied sludge layer height (30, 50, and 72 cm).

97%, and 74% in the three models, respectively. These results agree with the results in Ifeanyi [8] and Mehrdadi et al. [29]. An extended drying test was conducted for the model with an initial sludge depth of 72 cm and the drained water ratio reached 85% after 20 d.

It was found that the sludge height of 50 cm gives better results than the height of 30 cm due to the higher rate of water exit from the filtration middle. Moreover, the sludge concentration and the percentage of total initial solids in the sludge with 50 cm depth are less than 30 cm. So, a clogging of the filtration middle (gravel filter) with a depth of 30 cm of sludge occurs faster than 50 cm. The higher the level of the water above the filtration middle, the faster the rate of water exit. This happened with a depth of sludge 50 cm compared to 30 cm due to the sludge pressure on the filter. So, the water is filtered faster through the pores of the gravel but it did not happen with the 72 cm sludge height. This is contrary to the theory of filtration, which occurred to a depth of 50 cm of the sludge which may be attributed to the small height (30 cm) of the filtration middle (gravel filter) compared to the height of the sludge (72 cm). Thus, the area of water exit from the filter is small compared to the height of the sludge (72 cm). So, the accumulation rate of solid on the filtration middle is higher. Therefore, the filter clogging occurs quickly, thus the flow rate decreases. To achieve a higher water flow rate than the filter with a sludge depth of 72 cm, the filter height should be increased to 72 cm instead of 30 cm. Also, the reason for the lower rate of water exit at a height of 72 cm compared to 50 cm is that the density of the sludge and the total initial solids in the sludge with a height of 72 cm is higher than 50 cm, and this is shown in Table 1.

Fig. 10 shows the effect of sludge layer depth on the solid content plotted vs. the drying time. After 1 d of drying, the solid content of dried sludge achieved in the three models was 7%, 5%, and 6.5% for the depth of 30, 50, and 72 cm, respectively. After 5 d of drying, the solid content of dried sludge increased to 23%, 18%, and 9%, respectively. After 12 d of drying, the solid content of dried sludge increased to 33%, 52%, and 16%, respectively. An extended drying test was conducted for the model with an initial sludge depth of 72 cm and the solid content of dried sludge increased to 28% after 20 d, which is less than those achieved in the case of 30 and 50 cm for only 12 d from drying. From the obtained result, it is recommended that the height of the sludge layer inside the MPDB should not exceed 50 cm. Because when using a depth of 72 cm from the sludge, it was found that it will take a longer period of time (several weeks) to reach the required solids content for dried sludge, and therefore the rate of dried sludge is small. To obtain the required rate of dried sludge, the number of drying beds or drying bed area should increase. In other words, more lands will be needed and this will be expensive (non-economic). From the obtained results, we did not test depths greater than 72 cm for sludge.

Al-Nozaily et al. [13] used sludge from the thickener tank and the sludge depth was 20 cm. They conducted the test for drying period 7–12 d to achieve sludge cake containing 25% dry solid content. These values are less than those reported by Metcalf and Eddy [3] of 10–15 d. Their results could achieve dry solids content ranging from 56% to 90%. Al-Malack et al. [14] used sludge depth in the range 20–30 cm. In their experiments, the drying period was 10–15 d to achieve sludge cake containing 60%–70% dry solid content and the sludge loading rate was 100–300 kg dry solids/m^2/y. Lamperia [28] studied the influence of sludge depth on the drying time of anaerobic digested sludge with constant solids content. It was found, for all depths, that the sludge initially drained at the same rate until virtually all the free water was exhausted. Thinner sludge applications, therefore (20–35 cm) reached the end of their drainage phase sooner as for the percentage of solid content, it varied between 18% and 32% depending on the initial solids concentration. Several attempts [30] have been made to determine the optimal sludge depth and the results reported a range of depths from 200 to 350 mm. However, these results are highly dependent on sludge characteristics that vary significantly, and therefore it is suggested that each plant goes through continual optimization studies to determine these depths. The above-mentioned recommendations regarding sludge layer height complies with ref. [21] who recommended that the optimum depth of sludge can be determined by

Table 1
Characteristics of the sludge used for different sludge depths (30, 50, and 72 cm)

Depth, cm	Sludge volume, L	Sludge density, kg/L	Tso, mg/L	Solid %	Water content	Water volume, L	Supernatant TSS, mg/L
30	210	0.91	48,675	0.053	0.95	180.9	450.0
50	410	0.86	28,950	0.034	0.97	340	500.0
72	630	0.91	48,765	0.054	0.95	542.6	500.0

Table 2
Summary table of results for all stages

		Drained water ratio, %			Solids content, %		
	Duration, days	1	5	12	1	5	12
Stage (1)	Conventional PDB	15	61	73	5	10	14
	Decanting PDB	15	49	60	5	8	10
	Drainage and decanting PDB	55	88	95	9	28	47
Stage (2)	Modified paved drying bed (MPDB)	55	88	95	9.1	28	47
	Conventional sand drying bed (CSDB)	33	62	76	6.3	11	16
Stage (3)	Sludge layer 30cm	20	78	88	7	23	33
	Sludge layer 50 cm	37	86	97	5	18	52
	Sludge layer 72 cm	18	46	74	6.5	9	16
Stage (4)	Sludge type (WAS)	54	93	97	7.6	31	55
	Sludge type (CPAS)	38	85	97	5.2	19	52
	Sludge type (CPTF)	20	52	59	8.2	13	15
	Sludge type (PS)	22	67	85	3.2	7.5	15

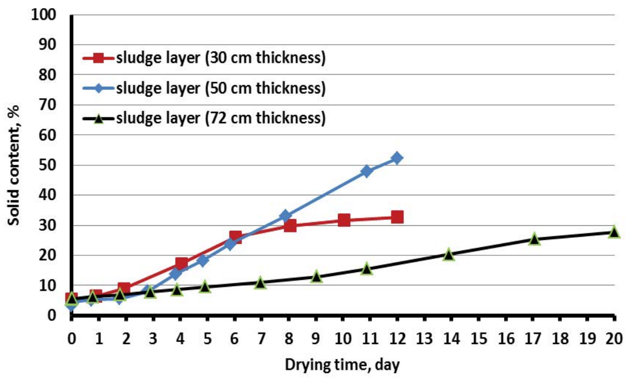

Fig. 10. Relation between drying time and dried sludge solid content at varied heights of sludge layer (30, 50, and 72 cm).

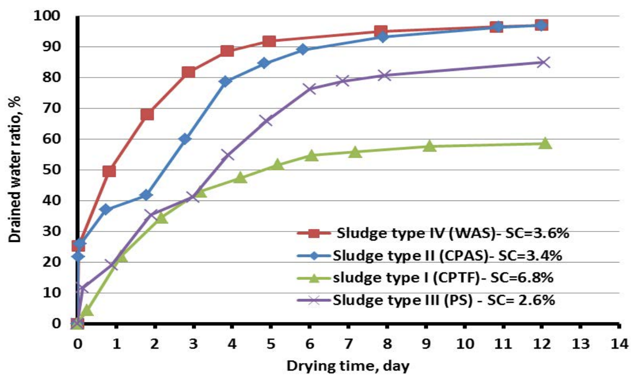

Fig. 11. Relation between drying time and drained water ratio for different types of sludge.

experience. In general, this depth may range from 20 to 45 cm while the typical depth in CSDBs is 30 cm sludge layer, also Table 2 shows summary results for all stages.

4.4. Studying the effect of applied sludge type

Four different types of sludge were used for studying the effect of sludge type on the drying time and the sludge dried solid content using the modified PDB. Fig. 11 shows the relation between drying time and drained water ratio for the four different types of sludge having the same height (50 cm). After 1 d of drying, the achieved drained water ratio was 54%, 38%, 20%, and 22% for sludge type WAS, CPAS, CPTF, and PS, respectively. After 5 d of drying, the drained water ratio increased to 93%, 85%, 52%, and 67% for the four types respectively. These results comply with Ifeanyi [8]. After 12 d of drying, the drained water ratio reached 97%, 97%, 59%, and 85% for the four types, respectively. From the obtained results, it is clear that sludge type WAS and CPAS have the highest drained water ratio compared to the other two types. These results comply with the estimation of the drainable water portion proposed by Wang et al. [6]. They estimated that 60% of the water is drainable and up to 85% of the water of secondary sludge can be lost by drainage. Also Wang et al. [6] stated that “in general, the higher the initial water content, the larger the fraction of drainable water.”

Fig. 12 shows the relation between drying time and dried sludge solids content for the four different types of sludge. After 1 d of drying, the solid content of dried sludge increased to 7.6%, 5.2%, 8.2%, and 3.2% for sludge type WAS, CPAS, CPTF, and PS, respectively. After 5 d of drying, the solid content of dried sludge increased to 31%, 19%, 13%, and 7.5% for the four types, respectively. After 12 d of drying, the solid content of dried sludge increased to 55%, 52%, 15%, and 15% for the four types, respectively. These results agree with the results of Masmoudi et al. [31]. Ceronio et al. [32] determined the drainage time for different types of sewage sludge and reported that the extended aeration sludge required the shortest time for drainage. Additionally, they reported that the increase in initial solid concentration of applied sludge results in decreasing of the filtered water collected for the same type of sludge. Radaideh et al. [22] also found that drying of extended aeration sludge took almost half the time of the drying of anaerobic digested

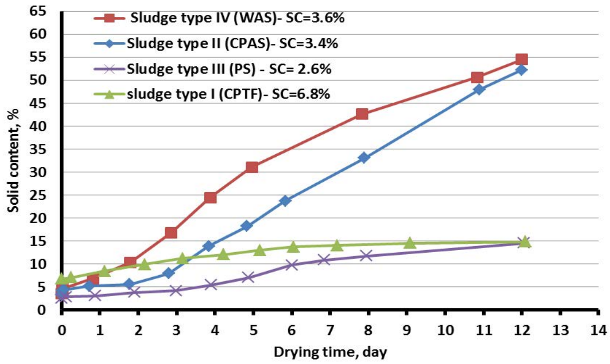

Fig. 12. Relation between drying time and dried sludge solid content for different types of sludge.

sludge for the same operating conditions in the lab and full-scale experiments.

4.5. Effect of solid loading rate

Solid loading rate (So.L.R) is one of the most important parameters used for the design of drying beds. Also, land unavailability limits the application of sludge drying beds. The solid loading rate can be calculated using Eq. (1) below:

$$\text{So.L.R} = \left(\frac{S_0 \times V}{\mu \cdot A}\right)\left(\frac{365}{t}\right) \tag{1}$$

where So.L.R is the solid loading rate (kg/m^2/y), S_0 is the initial solid content (kg/m^3), V is the volume of applied sludge (m^3), A is the area of bed (m^2), and t is the cycle time (d) which is given as:

$$t = t_d \times 1.25 \tag{2}$$

where t_d is the time to reach sludge solid content of 20% (d) (this 25% was used to add the required time for filling and removing of dry sludge from the beds).

For phase I and II, the So.L.R for achieving 20% dry sludge solid content was 191.4, 97, 597.8, and 224.9 (kg/m^2/y) for the conventional PDB, decanting PDB, and drainage and decanting PDB and CSDB, respectively. The So.L.R for CSDB complies with recommendation of [33] for solid loading as he suggested solid loading in the range of 100–300 (kg/m^2/y) for open drying bed and 150–400 (kg/m^2/y) for covered drying beds. Also, the results comply with [34,35]. The drainage and decanting PDB gives the highest So.L.R as it was equal three times of the conventional PDB and 2.5 the values for CSDB.

For phase III, the So.L.R was 661, 694, and 664 (kg/m^2/y) for 30, 50, and 70 cm sludge layer height, respectively. These values were almost the same because So.L.R depends mainly on sludge type [6], that was also investigated by calculating So.L.R for Phase IV and was found to be 1,084; 694; 177; and 438 (kg/m^2/y) for WAS, CPAS, PS, and CPTF, respectively. These results comply with the results of Aboulfotoh [36] who ordered the solid loading rate of different types of sludge in the following decreasing order (WAS, CPAS, and CPTF) which also complies with Metcalf and Eddy Inc., [9] and WEF [37].

5. Conclusion

Based on the obtained results from the present study, it was concluded that:

- Drainage and decanting configuration PDB model, (using two drainage pipes; one in bottom channel of the tank and the other pipe in the corner), achieved the highest drained water ratio and the highest solid content of dried sludge with drying time comparing to the other configurations.
- The maximum dried solid content was achieved by the CSDB and it was 16% after 12 d of drying, whereas the same solid content was achieved by the MPDB after only 3.5 d of drying. The solid content increased to 47% after 12 d of drying.
- The height of the sludge layer inside the MPDB should not exceed 50 cm.
- Sludge type (WAS) and (CPAS) have the highest drained water ratio and dried sludge solid content of about 52%–55% compared to the other types of sludge for 50 cm sludge layer height and for 12 d of drying time.
- The modified PDB achieved the highest So.L.R (598 kg/m^2 y) to obtain 20% dried solid content compared to the conventional PDB (191 kg/m^2 y) and CSDB (225 kg/m^2 y).

Symbols

So.L.R	—	Solid loading rate
S_0	—	Initial solid content
V	—	Volume of applied sludge
A	—	Area of bed
T	—	Cycle time
T_d	—	Time to reach sludge solid content
μ	—	Viscosity

Abbreviations

CSDB	—	Conventional sand drying bed
PDB	—	Paved drying bed
CPTF	—	Thickened combined primary sludge and trickling filter humus
CPAS	—	Thickened combined primary and waste activated sludge
PS	—	Un-thickened primary sludge
WAS	—	Thickened waste activated sludge
TS	—	Total solids
CSDB	—	Conventional sludge drying bed
DPDB	—	Decanting Paved drying Bed
MPDB	—	Modified paved drying bed
SC	—	Solid content
DSC	—	Dried sludge solid content
DWR	—	Drained water ratio
So.L.R	—	Solid loading rate

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