EVALUATION OF THE SLUDGE DRYING BEDS AT SANA’A WASTEWATER TREATMENT PLANT

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ABSTRACT

In the Republic of Yemen the availability of solar radiation throughout the whole year makes the use of the sand sludge drying beds (SDB) an attractive technology, for drying sludge resulted from the wastewater treatment. SDB are simple to operate, low cost where the land is available, and requires minimal operation attention. At Sana’a Waste Water Treatment Plant (SWWTP), the excess sludge out of the extended aeration – activated sludge system is pumped to the SDB. The assumption of the designer to desludge at 25% DS has caused adherence of sand to the sludge and the need to be replaced as well the dried sludge become unattractive to farmers. These problems force the operator to extend the drying period till reach a dryness of 60% which entails to increase the drying time till it reaches 20 days instead of 10 days. Moreover, the operator has applied cement mortar blocks support in order to facilitate the desludging by the mechanical equipment (POB-CAT). These ideas resulted into a bigger problem of an accumulation of sludge inside the aeration tanks and thickeners causing overflow of sludge with effluent, which also mean that SDB has not been optimized. This study aimed at investigating possible factors to provide less drying time such as sand type, blocks spacing, Geo-Web support instead of blocks support and the polymer addition. A pilot plant was constructed using cement mortar blocks consisting of two units each of which at a size of “4.6*2.3*1.25m” as “L,W,D”, one of which is used as a control unit similar to the existing drying beds at the SWWTP, while the experimental unit is used to investigate the effect of different factors through six exps. The initial solid contents of the raw applied sludge ranged between 2.0%- 3.5% depending on the situation in the thickener tank at the start of each experiment during the operation of the pilot plant. Interestingly, the drying time in the pilot plant ranged 7-10 days. According to statistical analysis, using t-test (t ≤0.05 significant difference) using Sa’adah coarse sand at second layer has no significant effect on final solids content they were 56.56±2.2% and 67.28±3.26% at Exp.-2. Increasing of blocks spacing by 10 cm during Exp.-3, produced better at same final drying time of 8 days with dry solid content of 89.56±0.54% and 47.44±2.2% for experimental and control units, respectively.
Using of Geo-Web support in Exp.-4, at same drying time of 10 days with dry solid content of 85.8±0.26% and 79.5±3.12% for experimental and control units, respectively. Moreover Exp.-5 produced high dry solid content of 80.7±0.67% and 25.7±3.08% for Geo-web and control units, respectively with less drying time of 8 days. Polymer addition in Exp.- 6 at same drying time of 10 days, achieved a dry solid content of 85.3±2.27%, and 87.6±1.2% at experimental and control units, respectively. Applying 4 scenarios for scale up assuming efficiency of 100, 90, 80 and 70% with 3 scenarios for final dry solid contents of 25, 40, 60% DS the results revealed that the available 36 SDB are insufficient for drying the sludge to 60%DS. This recommends either extension of additional SDBs or introducing mechanical drying units in case of difficulty to have enough area in the field. It is expected that the mechanical drying units will help speed up drying during the monsoon period. According to the water mass balance, the percolation was the main dominant factor for sludge drying compared to the evaporation of water. The averages were 65% and 35% for percolation and evaporation, respectively. Moreover, 70% of the percolated water took place during first two days. The spacing between blocks is enough for water percolation and the increase of blocks spacing has a considerable effect on drying time and dry solid content percentage.

1. INTRODUCTION

The availability of solar radiation throughout the whole year in most part of Yemen makes the use of the sand sludge drying beds (SDBs) an attractive technology for drying the sludge resulted from the wastewater treatment. Sludge produced during the wastewater treatment is estimated as 80 percent of Biochemical Oxygen Demand (BOD) load (Howard Humphreys 1995). In the case of mechanical treatment, the sludge is produced on daily basis and treated by thickeners and then dried in drying beds as the case in Sana’a wastewater treatment (Al-Nozaily et al., 2005). Generally, the Advantages of sludge drying beds (SDB) are that it Require lower operational skill and attention, low capital cost if the land is available, low energy consumption, low chemical consumption. While the Disadvantages of SDB are the lack of enough engineering design approach; It requires more land compared to the mechanical methods; It is suitable to dry only stabilized sludge; it is climate dependent; and sand bed losses during de-sludging requires replacement. SDBs allow for dewatering through two main mechanisms namely, percolation and evaporation. Conventional sand drying beds are rectangular and contain layers of sand and gravel which overlay an under drain system for percolation collection. The Sana’a Waste water treatment plant SWWTP was operational as an Activated Sludge –Extended Aeration Treatment since May 2000 to treat an average of 50,000 m3/d. The design BOD was assumed as 500 mgBOD/L while at the start of operation it was found 1100mg/L (Al-Nozaily et al., 2005), which increase the BOD loading by more than two times.
The Sana’a drying beds have been designed on the criteria that it would take 10 days retention time on the beds to achieve a performance of 25% dry solid (DS) content of the sludge with a maximum depth of 20cm and initial solid content of 3.5 %, while the actual drying time was on average 20 days to achieve 60% dry solid content (Al-Nozaily et al., 2005). This longer drying time causes accumulation of sludge. This research is aimed at studying the existing situation of the SDB at Sana’a WWTP and the possible improvement to optimize the SDBs operational and design parameters to achieve better performance in drying the sludge. A pilot plant was situated at the Sana’a wastewater treatment plant to study the effect of the following parameters on drying time: sand type and grain size, blocks spacing, Geo-Web support instead of blocks support; polymer addition. The existing 36 Sludge drying beds (SDBs) are provided each 27.5m × 55m in size. The Sludge drying beds are designed for a maximum sludge depth of 200mm of raw sludge (Howard Humphrys, 1995; Consul Aqua Humburg,2000). In a typical sand drying bed, sludge is placed on the bed in a 200 to300 mm layer and allowed to dry. Sludge dewater by drainage through the sludge mass and supporting sand and by evaporation from the surface exposed to the air (Fig. 1). Since most of the water leaves the sludge by drainage, thus the provision of an adequate underdrainage system is essential (Metcalf and Eddy 2003; Stout 2002). Sludge drying beds may be open to the atmosphere or can be constructed with roof to protect them from rain and (in cold climate) from frost. By covering the bed it is also possible to use solar energy to heat up the sludge during the drying period and thus to eliminate pathogens. This ‘solar pasteurization’ is particularly important if the sludge is to be used in agriculture (Van Haandel & Lettinga 1994). The top course sand should consist of at least 6 to 9 inches (Illinois Recommended Standards 1997) or 9 to 12 in (Metcalf and Eddy 2003) or 250 to 450 mm (Mullick 1987) of clean, washed, coarse sand. The effective size (Deff) of the sand should be in the range of 0.8 to 1.5 mm (Illinois Recommended Standards 1997) or 0.3 to 0.75mm (Metcalf and Eddy 2003) or 0.3 to 1.2mm (Mullick 1987). With uniformity coefficient (UC) < 4 (Metcalf and Eddy 2003) or < 5 (Mullick 1987). The finished sand surface should be level (Illinois Recommended Standards 1997). According to Arceivala (1981) sand sizes are similar to those used in coarse sand filter.
1.1 Design of sludge drying beds

The design of sand drying beds involves only the computation of the bed area. This may be done on per capita basis or on solid loading rate basis. When data conforming to the local environmental conditions is not available, the following data may be used:

- **Solid-loading rate**: 50 to 150 kg of dry solids per square meter per year.
- **Per capita requirement of sand bed area**: (1.6 to 2.3 m$^2$ for digested primary and activated sludge).

The main factors that affecting the overall drying time of sludge include the following:

1. **Extent of free drainage**: The greater the fraction of total drainable water, the less the moisture left to be evaporated.
2. **Climatic factors insofar as they affect**: a) Evaporation rate from the sludge surface. This rate is slow and generally controls the overall drying time. b) Moisture added to the sludge by rainfall.
3. **Permissible moisture content in the outgoing sludge**: The overall drying time can be computed by using a model given by Arceivala (1980) in which a material balance of all incoming and outgoing moisture masses is made. The model is applicable to cases where the evaporation time controls the overall drying time. Figure 2 shows briefly, a model for a given mass of sludge spread over a unit area that has been exposed to rainfall the moisture to be evaporated is given by:
**Fig. 2**: A model for estimating overall drying time (Source Arceivala 1981; 1992)

\[ t = \frac{\left( (1-f_i) q_i + (1-f_r) q_r - q_d \right)}{(f_e E_w)} \]  

(1-1) 


\( t \) = required drying time, days  
\( E_w \) = evaporation rate from free water surface, mass/area/time or mm/month  
\( f_e \) = reduction factor to account for reduced evaporation rate from sludge surface  
\( q_i \) = moisture initially present in sludge mass/area  
\( q_r \) = moisture received through rainfall, mass/area  
\( q_d \) = moisture remaining in dried sludge, mass/area  
\( f_i \) and \( f_r \) = fraction of \( q_i \) and \( q_r \), respectively, that is drained from the bed. Thus, (1-\( f_i \)) and (1-\( f_r \)) are the fraction remaining in the sludge.

The typical range of experimentally observed values, the coefficients for aerobic and anaerobic digested sewage sludge which can be applied to sand drying beds at depth of 15 to 30 cm are given in (table 1). Aerobic sludges are those from extended aeration plants (Arceivala 1981; 1992).
Table 1: Typical values of coefficients for aerobically treated sludge (Source: Arceivala 1981; 1992; 1995)

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Aerobically treated sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_i$</td>
<td>0.8-0.9</td>
</tr>
<tr>
<td>$f_r$</td>
<td>0.75</td>
</tr>
<tr>
<td>$f_c$</td>
<td>0.78</td>
</tr>
</tbody>
</table>

2. Methodology

2.1 Field study:

The SWWTP drying beds are considered as a vital component in drying sludge. It has not been optimized in term of operation. This study tried to investigate the possible alternative methods to provide efficient drying time. Sludge dewatering has been monitored through 6 Exps conducted during the period June to October 2005. Each Exp. Include control unit representing the design of SWWTP drying beds by Consul Aqua Hamburg (2002).

The experimental unit was tested Appling several factors during the six exps described in table 2:

<table>
<thead>
<tr>
<th>Exp</th>
<th>Pilot Plant Exps details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental Unit</td>
</tr>
<tr>
<td>1</td>
<td>Using Sa’adah Sand-2rd layer</td>
</tr>
<tr>
<td>2</td>
<td>Using Sa’adah Sand-2nd layer</td>
</tr>
<tr>
<td>3</td>
<td>Increasing spacing of cement mortar blocks from $\approx 11\text{cm}$ to $\approx 21\text{cm}$</td>
</tr>
<tr>
<td>4</td>
<td>Geo-Web support</td>
</tr>
<tr>
<td>5</td>
<td>Geo-Web support</td>
</tr>
<tr>
<td>6</td>
<td>Polymer addition</td>
</tr>
</tbody>
</table>

1. The first and second Exps was designed to study the effect of sand type by using a coarse Sa’adah sand (rounded particles) instead of coarse sand from crushed basalt at second layer of control unit.
2. The third Exp. was designed to the study the effect of cement mortar blocks spacing by increasing of blocks spacing to $21 \pm 1\text{cm}$ (increasing filtration area up to $4.98\text{m}^2$ instead of $11\pm 1\text{cm}$ (with filtration area of
4.14 m\(^2\)) at control unit. The rainfall was occurred at this Exp and the quantity of rainfall was measured by using special pan.

3. The fourth and fifth Exp was designed to study the effect of Geo-Web support instead of blocks support.

4. The sixth Exp was designed to study the effect of polymer addition with manual mixing. Exps details are summarized in Fig. 3

<table>
<thead>
<tr>
<th>Exp Number</th>
<th>Control unit</th>
<th>Sa’adah coarse sand</th>
<th>Experimental unit</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crushed basalt coarse sand</td>
<td></td>
<td></td>
<td>Effect of sand type at second layer</td>
</tr>
<tr>
<td>2</td>
<td>Crushed basalt coarse sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>≈ 11 cm blocks spacing</td>
<td></td>
<td>≈ 21 cm blocks spacing</td>
<td>Effect of cement blocks spacing</td>
</tr>
<tr>
<td>4</td>
<td>Cement Blocks support</td>
<td></td>
<td>Geo-Web Support</td>
<td>The effect of Geo-Web support instead of cement blocks</td>
</tr>
<tr>
<td>5</td>
<td>Cement Blocks support</td>
<td></td>
<td>Geo-Web Support</td>
<td></td>
</tr>
</tbody>
</table>
The control unit which was constructed has five sieved sand gravel layers from top to bottom as the following specification.

1. The first layer has a thickness of 200mm of S'a’adah sand (rounded particles) ranged 0.4-0.8mm placed between blocks support which has a spacing 11±1cm
2. The second layer has a thickness of 150 mm of coarse sand (crushed basalt angular particles) with particles size ranged 0.8-1.6mm
3. The third layer has a thickness of 150mm of fine gravel (crushed basalt) with particles size ranged between 1.6-3.2mm
4. The fourth layer that surrounding the drainage pipe has a thickness of 550-600 mm of medium gravel (crushed basalt) with particles size ranged 3.2-6.3mm
5. The fifth layer that located under the drainage pipe has a thickness of 150mm thickness of fine gravel (crushed basalt) with particles size ranged 1.6-3.2mm.

For each Exp, sludge was pumped from the thickener tank to both units until the sludge thickness reached 20cm. Time needed to pump the sludge to reach this thickness was about 2.5-5 minutes for each unit. The sludge was sampled immediately from both units after loading onto the beds. The dewatered sludge and percolating flow were monitored during the whole dewatering period. The samples taken from different parts of the unit to make a good representative of the whole unit. Dewatered sludge samples were collected every day until the end of each Exp. Several points are selected randomly for each Exp. The samples from these selected points were then mixed. New three samples were then taken from this mixture weighted. The three samples were dried in oven at 105 °C for 24 hours to determine the dry solid content. Percolating flow was monitored and the daily flow rate was determined.

2.2 Sampling location:

The location of pilot plant was in the SWWTP beside of thickeners tanks and sludge sampling from thickener tank are shown in fig.(4)
2.3 Pilot plant construction:

A pilot plant was constructed in the field using cement mortar blocks walls and divided into two equal units with the dimension (4.6*2.3*1.25m) each. It was constructed above the ground level. One unit was used as a control unit while the other was used as an Experimental unit which was used with applying different factors during the six Experiments (fig. 5).
**Installation of High density Poly Ethylene (HDPE) Membrane:**

The installation of HDPE Membranes was done as shown in fig. (6).

The purpose of this membrane is to prevent water leakage

**Drainage System:**

The drainage system consisting of perforated Polyethylene chloride (PVC) pipe was provided to enhance the collection of water drained from the boxes. The internal diameter of the pipe is 150mm. The drainage pipe was drilled with holes of 10mm in diameter. The holes were drilled in a zigzag manner along the whole length of the pipe located in the box. A schematic diagram (Fig. 7) illustrates the pipe and the dimensions. The holes are made only in the upper surface of the pipe. The slop of pipe was one (1%) percent. The pipe wrapped in geotextile fabric. The geotextile fabric is needed to prevent the filter media from entering into the pipe. The pipe laid on 15cm of coarse sand layer (d=1.6-3.2mm).

![Fig. 6: Installation of HDPE membranes](image1)

![Fig. 7: Perforated pipe](image2)

**2.4 Selection of proper characteristics for sand as a drying bed:**

A trial experimental has been done by using an imhoff cone filled halfway (500ml) with sand have grain size ranged between 2-4mm and filled the remainder to 1 liter with sludge. After that we observed that the sludge passed through the filter to beaker that placed under cone tip, therefore we use the sand particles ranged
between 0.4 to 0.8mm as sand filter to prevent the sludge infiltration through the filter layers and finally clog the drain system.

2.5 Exps 1 and 2. Determination of the effect of sand layer on sludge drying time

According to the design of the existing sludge drying beds, The pilot plant experimental and control units were filled with a gravel and sand as follows (Fig. 8):

1- First layer of 20cm depth with fine sand at particle size of d= 0.4-0.8mm
2- Second layer of 15cm depth with coarse sand at particle size of : d = 0.8 - 1.6 mm. Sand type was Crushed basalt in control unit and  natural circular sand (Sa’adah sand)
3- Third layer of 15cm depth with: fine gravel at d = 1.6 – 3.2 gravel type was Crushed basalt in control unit and experimental unit.
4- Drainage layer: The drainage media consisting of gravel surrounding the drain pipe, extending 400-450mm above the top of the drain pipe with particles size (3.2- 6.3mm). The pipe wrapped in geotextile fabric. The geotextile fabric is needed to prevent the filter media from entering into the pipe.
5- Under-drain layer: The under drain (under drain pipe) layer consisting of 15cm of fine gravel with particle size (1.6-3.2mm).

(a) Plan of pilot plant
(b) Section A-A
2.6 Experiment 3: determination of the effect of blocks spacing on drying time
In exp. three the test was to determine the effect of blocks support spacing on sludge drying. The blocks spacing increased in experimental unit as shown in fig. (9).

During this Exp the rainfall for 1 hr at 5 pm after 5 hours from sludge application. The rainfall was measured by using a special pan and the result recorded in this Exp.

**Fig. 9: Pilot plant units with blocks support**

### 2.7 Experiment 4and 5: determination of the effect of Geo-web support on drying time

In this Exp the Geo-web cellular confinement system was installed in a sludge drying bed in the top sand layer of experimental unit at Exp 4 and 5. The gravel and sand layers are similar to the control unit **Geoweb specification:** the Geoweb specification are listed in fig (10) with its shape in Fig (11)

<table>
<thead>
<tr>
<th>Geoweb® GW20V</th>
<th>Nominal Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>289 cm² (44.8 in²)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell Details</th>
<th>Cell Depth</th>
<th>Nominal Dimensions ±10%</th>
<th>Density per m² (yd²)</th>
<th>Nominal Area ±1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW20V</td>
<td>200 mm (8 in)</td>
<td>224 mm (8.8 in)</td>
<td>259 mm (10.2 in)</td>
<td>34.6 (28.9)</td>
</tr>
</tbody>
</table>
Fig. 10: Geoweb specification (Adapted from: www.prestogeo.com)

The advantages of geo-web adapted from (www.prestogeo.com) are:
- Directly supports end loaders allowing them to drive directly on the sludge drying bed without destroying the integrity of the filtration media.
- Prevents lateral slippage or shear of the filtration sand.
- Reduction in filtration media replacement costs. One to two inches of sand are sacrificed in the sludge removal process.
- Loading and cleaning time is significantly reduced.

While the blocks support are used for experimental unit in Exp 4 and 5 the sand and gravel layers stay same to the previous Exps with the same blocks spacing.

Fig. 11: Exp 4and5 Geo-web support shape

2.8 Experiment 6: determination of the effect of polymer addition on drying time

In this Exp organic polymer was added to sludge in experimental unit. Consideration shall be given to providing a means of decanting the supernatant of sludge placed on the sludge drying beds. More effective decanting of supernatant may be accomplished with polymer treatment of the sludge (Illinois Recommended Standards 1997). The organic polymer dose added to the sludge was 70 mg/l of sludge (Al-Mohanish, 2000). Manual mixing was accrued to mix sludge with polymer due to an unavailable mechanical mixer.
3. Result and discussion:

3.1 Percolation and evaporation water mass balance

Mass balance of all Exp.(1-6) on percolation and evaporation:
Water content at $t_{\text{final}}$ = water content at $t_0$ + rainfall water – percolation water - Evaporation water. There is no considerable different in drying time between experimental unit and control unit. The percolation and evaporation percentages were 60 and 40 for experimental and control units, respectively (Fig. 12)

![Water balance diagram](image)

Remaining water: water that available in the sludge at specific time
Evaporation water: water that removed form the sludge by evaporation at specific time
Percolation water: water that removed from the sludge by percolation at specific time.

Figure 12: Water balance during the pilot plant

Percolated water starts between one and four hours after sludge loading onto the beds. Percolated water took place marginally at first two days the percentages were 73%, 73%, 59% and 69% for experimental unit-Exps 3-6 and 72%, 76%, 44% and 68% for control unit-Exps 3-6. The evaporation percentages at first two days were 40%, 44% and 50% for Exps 3, 4 and 6 for experimental unit and 40%, 43% and 57% for Exps 3, 4 and 6. The percolated water of Exp 3 was greater than of other Exps this related to rainfall water that increase percolated water at this Exp. The decrease of percolate flow of Exp 6 is due to high initial solid content for sludge that applied at this Exp. The evaporation water percentages were between 27.4 and 47.7 during different Exps, while the percolation percents were between 52.3 and 72.6. (Table 3)
Table 3: The effect of the factors on evaporation and percolation at Exps 1-6

<table>
<thead>
<tr>
<th>Exp</th>
<th>Factor</th>
<th>experimental unit</th>
<th>Control unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Percol %</td>
<td>Evap %</td>
</tr>
<tr>
<td>1st (22.5-29.5)</td>
<td>sand type</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2nd (5.6-12.6)</td>
<td>sand type</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3rd (9.7-17.7)</td>
<td>Blocks spacing</td>
<td>72.6</td>
<td>27.4</td>
</tr>
<tr>
<td>4th (3.8-13.8)</td>
<td>Geo-web support</td>
<td>65.6</td>
<td>34.4</td>
</tr>
<tr>
<td>5th (22.8-30.8)</td>
<td>Geo-web support</td>
<td>63.7</td>
<td>36.3</td>
</tr>
<tr>
<td>6th (20.9-30.9)</td>
<td>Polymer addition</td>
<td>61.9</td>
<td>38.1</td>
</tr>
</tbody>
</table>

Note: During Exp. 1 and 2 at the experimental unit the percolation flow could not be monitored because a leakage occurred between the drainage pipe and HDPE membrane.

From table (3) it can be observed that there is no considerable difference in evaporated water between experimental and control units due to exposing the pilot plant to similar situations except in exp. 5 where the difference was high and the evaporation water was 36.3% and 47.7% for experimental and control units, respectively. Using of Geo-web support at exp 4 and 5 has a considerable effect on percolate water especially at Exp 5. The values were 61.9 and 60.4% for experimental and control units, respectively. This related to filer area at experimental unit about 10 m$^2$, while the filter area was 4.14 m$^2$ for experimental unit. The effect of increasing the cement block spacing in exp 3 was significant on dry solids content percentage, which was 89.6% compared with control unit (47.4%). In spite of the rainfall occurred during this Exp, a great difference in percolation water was achieved as 72.6%, 71.3% for experimental and control units, respectively, this mean that the increase of filter area (block spacing) from 4.14 m$^2$ to 5.98 m$^2$ has a significant effect on percolation water especially during the rainfall precipitation this can get a feasibility applying the Geoweb support during rainfall season. There’s no considerable effect for polymer addition on percolate water they were 61.9 and 60.4 for experimental and control units, respectively. This is in conflict with Al-Mohanish (2000) who supported the use of polymer. the reason probably due to the small scale of pilot plant.
3.2 Pilot plant sludge drying characteristics:

The sludge characteristics before and after pilot plant operation for Exps 1 to 6 are listed in tables (4 and 5).

**Table 4. Experimental units Pilot plant sludge drying characteristics during Exps**

<table>
<thead>
<tr>
<th>Exp</th>
<th>Raw sludge depth m</th>
<th>Raw sludge volume m³</th>
<th>Sand Filter area m²</th>
<th>Initial Dry solid content %</th>
<th>Rain mm</th>
<th>Dry solid content at the end %</th>
<th>Drying time day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; (22.5-29.5)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>2.061</td>
<td>-</td>
<td>90.46</td>
<td>7</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; (5.6-12.6)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>2.230</td>
<td>-</td>
<td>56.57*</td>
<td>7</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; (9.7-17.7)</td>
<td>0.2</td>
<td>2.116</td>
<td>5.98</td>
<td>2.735</td>
<td>10</td>
<td>89.56</td>
<td>8</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; (3.8-13.8)</td>
<td>0.2</td>
<td>2.116</td>
<td>10</td>
<td>2.528</td>
<td>-</td>
<td>85.77</td>
<td>10</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; (22.8-30.8)</td>
<td>0.2</td>
<td>2.116</td>
<td>10</td>
<td>2.199</td>
<td>-</td>
<td>80.71</td>
<td>8</td>
</tr>
<tr>
<td>6&lt;sup&gt;th&lt;/sup&gt; (20.9-30.9)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>3.494</td>
<td>-</td>
<td>87.58</td>
<td>10</td>
</tr>
</tbody>
</table>

*Cloudy period

**Table 5: Control units Pilot plant sludge drying characteristics during Exps 1-6**

<table>
<thead>
<tr>
<th>cycle</th>
<th>Raw sludge depth m</th>
<th>Raw sludge volume m³</th>
<th>Sand Filter area m²</th>
<th>Initial Dry Solid content %</th>
<th>Rain mm</th>
<th>Dry Solid content at the end %</th>
<th>Drying time day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; (22.5-29.5)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>2.011</td>
<td>-</td>
<td>92.92</td>
<td>7</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; (5.6-12.6)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>2.210</td>
<td>-</td>
<td>67.28</td>
<td>7</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; (9.7-17.7)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>2.740</td>
<td>10</td>
<td>47.44</td>
<td>8</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; (3.8-13.8)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>2.512</td>
<td>-</td>
<td>79.53</td>
<td>10</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; (22.8-3.9)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>2.454</td>
<td>-</td>
<td>25.71</td>
<td>12</td>
</tr>
<tr>
<td>6&lt;sup&gt;th&lt;/sup&gt; (20.9-30.9)</td>
<td>0.2</td>
<td>2.116</td>
<td>4.14</td>
<td>3.499</td>
<td>-</td>
<td>85.26</td>
<td>10</td>
</tr>
</tbody>
</table>

From tables (4 and 5) the following points can be discussed:

The drying time during all Exps ranged 7 -12 days. These values are less than those reported by Metcalf and Eddy (2003) of 10 – 15 days. The dry solids content achieved were 56% to 90% which is higher than 40% DS that was recommended
by Metcalf and Eddy (2003). There’s no significant difference in final dry solids content at Exp 1 the values were 90.46 and 92.92 for experimental unit and control respectively. There’s a significant difference (according to t-test) in final dry solids content at Exp 2 the values were 56.57 ±2.2 and 67.28 ±3.26 for experimental and control units, respectively. The increase of filtration area has a significant effect (according to t-test) on final solids content at Exp 3 they were 89.56% ± 0.54% and 47.44% ± 2.19% for experimental and control units, respectively. Using of geo-web support in Exp 4 and 5 has a significant effect (according to t-test) on final dry solids content as well as drying time especially at Exp 5 they were 80.71% ±0.68% and 25.71%±3.08% DS content and 8 and 12 days drying time for experimental and control units, respectively. The polymer addition in Exp 6 has no considerable effect (according to t-test) on final solids content as well as drying time at Exp 6 they were 87.58%± 1.19% and 85.26% ±2.27% for experimental and control units, respectively for same drying time (10 days).

### 3.3 Comparison between actual and calculated drying time

The theoretical drying time can be computed as following (table 6):

- Applied sludge over 1 m² area = 200 Kg
- Initial solid content = 2.01%DS (97.99% water)

**q_i =** At 97.99 % water content, the water content in the applied sludge of 200kg is 195.98 kg and solids will 4.02 Kg.

**Final water content = 7.1% (92.9% Dry cake)**

**q_d =** Weight of water in dried sludge cake = 0.071 (4.02/0.929) = 0.307 Kg

- $f_i = 0.8$ (0.8-0.9)
- $f_t = 0.73$
- $f_c = 0.78$

- $q_r = $ Rainfall in month of May = 0mm
- $E_w = $ Evaporation rate in month of May = 298.22mm/month (Kg/m²-month)

The drying time over a unit area of m²

$$t = \frac{(1- f_i)q_i + (1- f_t) q_r - q_d}{f_c E_w}$$

$$= \frac{(1- 0.8)195.98 + (1- 0.73) kg X 0.0 - 0.307 kg}{(0.78) (298.22 Kg/month)}$$

$$= 0.167184 \text{ month} X 31 \text{ day/month} = 5.2 \text{ days}$$
Table 6: Actual and theoretical drying time for pilot plant

<table>
<thead>
<tr>
<th>Exp</th>
<th>Month</th>
<th>Evaporation mm/month</th>
<th>Rainfall During Exps mm/month</th>
<th>Control Unit</th>
<th>Experimental unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Theoretical drying time day</td>
<td>Actual drying time day</td>
</tr>
<tr>
<td>1st</td>
<td>May</td>
<td>298.22</td>
<td>0.0</td>
<td>7.8</td>
<td>7</td>
</tr>
<tr>
<td>2nd</td>
<td>June</td>
<td>292.5</td>
<td>0.9</td>
<td>7.5</td>
<td>7</td>
</tr>
<tr>
<td>3rd</td>
<td>July</td>
<td>263.19</td>
<td>9.8</td>
<td>8.3</td>
<td>8</td>
</tr>
<tr>
<td>4th</td>
<td>Augu</td>
<td>261.33</td>
<td>35.1</td>
<td>10.1</td>
<td>10.2</td>
</tr>
<tr>
<td>5th</td>
<td>Augu</td>
<td>261.33</td>
<td>35.1</td>
<td>8.2</td>
<td>12</td>
</tr>
<tr>
<td>6th</td>
<td>Sept.</td>
<td>283.20</td>
<td>0.0</td>
<td>7.7</td>
<td>10</td>
</tr>
</tbody>
</table>

# Civil Aviation & Meteorology Authority (2003)
* Using Penman equation for evaporation from open surface

The values of theoretical drying time differ from actual drying, the reason related to coefficients in Arceivala formula, nature of sludge, and the metrological data (temperature, rainfall, wind speed, relative humidity, sunshine and evaporation) doesn’t represent the actual during the field experimental work.
The filter area doesn’t represent the whole area of the drying bed due to decreases by block support at most Exps.

3.4 Sludge volume calculation:
The design criteria of designer (Howard Humphreys 1995) when design Sana’a sludge drying beds are:
Flow rate = 50,000 m$^3$/d
BOD = 500 mg/l
Wet sludge depth = 20cm
Initial solid content of the sludge after thickening to be pumped to drying beds = 3.5%
Drying period 10 days to achieve sludge cake containing 25% dry solid content
The quantity of sludge which will be produced at the treatment works was estimated as 80% of BOD load (by the designers Howard Humphreys 1995) as following:

\[ \text{BOD Load} = \frac{50,000 \text{m}^3/\text{d} \times 500 \text{mg/l}}{1000 \times 1000} = 25 \text{ ton/day} \]
Dry sludge production per day = 0.8 kg sludge / kg BOD * 25 ton BOD/d = 20 ton dry sludge / day

Daily volume of sludge cake at 25% solid = \( \frac{20 \text{ton/d}}{0.25} \) = 80 ton sludge cake/day

Daily liquid sludge containing 3.5% solid = \( \frac{20 \text{ton/d}}{0.035} \) = 571.43 m³

Volume of sludge per each drying bed: 55 X 27.5 X 0.2 = 302.5

Number of drying beds filled per day: \( \frac{571.43}{302.5} \) = 1.89 ≈ 2 beds/day

Number of drying beds needed per period of drying = 10 days * 2 beds/day = 20 drying beds

**The actual quantity of sludge during the research period using the same assumption that used by the designer:**

Flow rate = 50,000 m³/day

BOD = 1100 mg/l

BOD load = \( \frac{50,000 \text{m}^3/\text{d} \times 1100 \text{mg/d}}{1000 \times 1000} \) = 55 ton/day

Dry sludge = 0.8 kg sludge / kg BOD * 55 ton BOD/d = 44 ton dry sludge / day

Daily volume of sludge cake at 25% solid per day = \( \frac{44 \text{ton/d}}{0.25} \) = 176 ton sludge cake / d

Daily liquid sludge at 3.5% solid per day = \( \frac{44 \text{ton/d}}{0.035} \) = 1257 m³

Volume of sludge per each drying bed: 55 X 27.5 X 0.2 = 302.5

Number of drying beds filled per day: \( \frac{1257 \text{m}^3}{302.5 \text{m}^3} \) = 4.2 beds/day

Number of drying beds needed = 10 days * 4.2 beds/day = 42 drying beds per drying period.

1. The actual drying time at the treatment plant is 20 days to achieve around 60% DS.
2. The designer Howard Humphreys (1995) assumes that the sludge will be removed after 10 days at 25% dry solid content which is difficult to perform desludging. The sludge is adhered to the sand grains which will take out sand and need resanding or/and it will clog the filter when it is removed using mechanical equipment.
3. In Exp. 6 applying initial solid content of 3.5% the drying time was 10 days with 80% final dry solid content. This is a higher achievement of drying.
beds performance compared to the design values that were stated by Howard Humphreys (1995) as the final dry solid content are about 25%.

4. The sludge drying beds are overloaded according to the present quantity of sludge calculated.

5. The system is organically overloaded. This make the aeration system capacity not sufficient to supply the oxygen required to stabilize the sludge. The sludge discharges to the thickeners and, eventually, to drying beds is high in volume and drainability is low.

standardization will be applied (to equalize DS content and then determine the drying time needed to achieve this DS content), also different scenarios for different DS content such as 25% DS that adapted by designer (Howard, Humphreys 1995), 40% DS that reported by Metcalf and Eddy (2003); Aqua Hamburg (2002) and 60 that adapted by SWWTP with different efficiencies of scale up (transferring from pilot plant scale to full scale that present at SWWTP (55*27.5m) to determine the suitable percentages for sludge removing that will obtain an enough capacity for existing sludge drying beds (44 drying beds) with different efficiencies.

**Scale up of experimental unit when desludging at 25% dry solids content:**
According to all experiments scale up, the sludge drying beds are sufficient for drying sludge up to 25% DS content except Exp 2 at 70% efficiency and Exp 5 at 70% and 80% efficiency.

**Scale up of experimental unit when desludging at 40% dry solids content**
regarding to Exps 3 scale up the sludge drying beds are sufficient for drying sludge up to 40% DS content, also it will be sufficient according Exp 1, 2 and 4 at 100% and 90 efficiency and Exp 5 at 100% efficiency and Exp.6 at efficiency 100%,90% and 80%.

**Scale up of experimental unit when desludging at 60% dry solids content:**
regarding to experimental Exps 3,6 scale up the sludge drying beds are sufficient for drying sludge up to60% DS content at efficiency 100% and 90% and Exp 1 at efficiency 100%, otherwise it will no sufficient.

**_Sludge productivity for control unit:_**
In table (7), the sludge productivity for control unit can summarized

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Exp -1-</th>
<th>Exp -2-</th>
<th>Exp -3-</th>
<th>Exp -4-</th>
<th>Exp -5-</th>
<th>Exp -6-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater flow to the WWTP m3/d</td>
<td>37000</td>
<td>37000</td>
<td>37000</td>
<td>37000</td>
<td>37000</td>
<td>37000</td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>---------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>BOD (mg/l)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily sludge production (DS-load) (kg DS/d)</td>
<td>32560</td>
<td>32560</td>
<td>32560</td>
<td>32560</td>
<td>32560</td>
<td>32560</td>
</tr>
<tr>
<td>Initial solid content %</td>
<td>2.011</td>
<td>2.21</td>
<td>2.74</td>
<td>2.512</td>
<td>2.454</td>
<td>3.499</td>
</tr>
<tr>
<td>Daily sludge production (input volume) (m3/d)</td>
<td>1619.1</td>
<td>1473.3</td>
<td>1188.3</td>
<td>1296.2</td>
<td>1326.8</td>
<td>930.6</td>
</tr>
<tr>
<td>Required drying time (d)</td>
<td>7.00</td>
<td>7.00</td>
<td>8.00</td>
<td>10.00</td>
<td>12.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Required drying time including half day for filling and desludging (d)</td>
<td>7.50</td>
<td>7.50</td>
<td>8.50</td>
<td>10.50</td>
<td>12.50</td>
<td>10.50</td>
</tr>
<tr>
<td>Fillings per year</td>
<td>49</td>
<td>49</td>
<td>43</td>
<td>35</td>
<td>29</td>
<td>35</td>
</tr>
<tr>
<td>Adopted sludge loading rate (kg DS/m2.a)</td>
<td>196</td>
<td>215</td>
<td>235</td>
<td>175</td>
<td>143</td>
<td>243</td>
</tr>
<tr>
<td>Total required area (m2)</td>
<td>60716</td>
<td>55249</td>
<td>50504</td>
<td>68049</td>
<td>82926</td>
<td>48854</td>
</tr>
<tr>
<td>Total available area (m2)</td>
<td>54450</td>
<td>54450</td>
<td>54450</td>
<td>54450</td>
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<td>54450</td>
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<tr>
<td>Total number of available sludge drying beds</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Total number of required sludge drying beds</td>
<td>40</td>
<td>37</td>
<td>33</td>
<td>45</td>
<td>55</td>
<td>32</td>
</tr>
<tr>
<td>DS percentages after drying %</td>
<td>92.92</td>
<td>67.28</td>
<td>47.44</td>
<td>79.53</td>
<td>81.1</td>
<td>85.26</td>
</tr>
<tr>
<td>DS concentration after drying kg DS/m3</td>
<td>929.2</td>
<td>672.8</td>
<td>474.4</td>
<td>795.3</td>
<td>811</td>
<td>852.6</td>
</tr>
<tr>
<td>Daily DS volume after drying m3/d</td>
<td>35.04</td>
<td>48.39</td>
<td>68.63</td>
<td>40.94</td>
<td>40.15</td>
<td>38.19</td>
</tr>
</tbody>
</table>

From table (7) It can be observed that the DS content are not in equal values at different drying time at end of Exps. This makes comparison among them not possible, therefore we make standardization as in experimental unit with different efficiencies of scale up (transferring from pilot plant (4.6*2.3m) scale to full scale that present at SWWTP (55*27.5m) to determine the suitable percentages for sludge removing that will obtain an enough capacity for existing sludge drying beds (44 drying beds) with different efficiencies

- Increasing the blocks spacing (filter area) has a significant effect on drying time especially at rainfall season which can filtrate the excess water that came form rainfall precipitation, therefore we can conclude that using of
geo-web support which provided the higher filtration area at rainfall season produce a sufficient area for excess water that come from rainfall to passes through filter.

- A special arrangement during rainfall can be done for existing sludge drying beds to not extend the drying time by partially or completely covering the sludge drying beds during rainfall season.
- The sludge drying time were between 7 to 12 days at control unit which was designed according to the existing sludge drying beds at SWWTP, which represent around 50% of the actual drying time at SWWTP (20 days) to reach 60% DS content.
- Sludge loading rate when desludging at 25% DS content ranged between 178 and 283 kg DS/m².a (drying time 7-9 d) for 70% efficiency of scale up which is higher than 150 kgDS/m².a that was recommended by Mullick (1987) for thickened sludge.
- Sludge loading rate when desludging at 40% DS content ranged between 161 and 213 kg DS/m².a (drying time 8-12 d) for 70% efficiency of scale up, which is higher than 150 kgDS/m².a that was recommended by Mullick (1987) for thickened sludge.
- Sludge loading rate when desludging at 60% DS content ranged between 140 to 182 kg DS/m².a (drying time 10-14 d) for 70% efficiency of scale up.

In Table (8) the design criteria comparison is listed

<table>
<thead>
<tr>
<th>Table 8: Different design criteria for Sana’a sludge drying beds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Wastewater flow to the WWTP m³/d</td>
</tr>
<tr>
<td>BOD (mg/l)</td>
</tr>
<tr>
<td>Daily sludge production (DS-load) (kg DS/d)</td>
</tr>
<tr>
<td>Initial solid content %</td>
</tr>
<tr>
<td>Daily sludge production (input volume) (m³/d)</td>
</tr>
<tr>
<td>Required drying time including half day for filling and desludging</td>
</tr>
<tr>
<td>(d)</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>Fillings per year</td>
</tr>
<tr>
<td>Adopted sludge loading rate (kg DS/m2.a)</td>
</tr>
<tr>
<td>Selected depth m</td>
</tr>
<tr>
<td>Total required area (d)</td>
</tr>
<tr>
<td>Total available area m2)</td>
</tr>
<tr>
<td>Total number of available sludge drying beds</td>
</tr>
<tr>
<td>Total number of required sludge drying beds</td>
</tr>
<tr>
<td>DS percentages after drying %</td>
</tr>
<tr>
<td>DS concentration after drying kg DS/m3</td>
</tr>
<tr>
<td>Daily DS volume after drying m3/d</td>
</tr>
</tbody>
</table>

4. **CONCLUSIONS AND RECOMMENDATIONS**

4.1 **Conclusions:**

The reasons of higher drying time at SWWTP were:

- Using angular particles and coarse sand at the upper layer of sand filter, which may allow passing the sludge down to the lower layers that may cause clogging.
- The BOB-CAT equipment used to desludging may cause compact the lower layers of sand and gravel, which may result in clogging the filter.
- Inconsistency of sludge distribution over the SDB which might keep wet sludge at some places with bigger thickness.

Therefore, several experiments at different factors on a precise way of sieved sand and gravel layers with manual operation has been conducted concluding the following:

1. The waste water treatment plant is presently organically overloaded mainly due to the increase of BOD and suspended solids influent concentrations by two to three times higher than the design values.
2. Using a natural (rounded particles) Sa’adah sand (d=0.4-0.8mm) at upper filter layer of the sludge drying beds has perform better than using crushed basalt (angular particles), which being at existing sludge drying beds has an effect on preventing sludge passes through filter layer and finally cause clogging drainage system which in terms cause ponding of the water with the sludge at the surface.

Most of drainage occurred during the first two days. This is in line with Mullick (1987).

3. After the sludge is applied on the beds. The average percentage was around 70% from total percolated water.

4. The removal of water by percolation was the main dominant factor for sludge drying compared to the evaporated water. The averages were 65% and 35% for percolation and evaporation, respectively.

5. The sludge drying time were between 7 to 12 days at control unit which was designed according to the existing sludge drying beds at SWWTP, which represent around 50% of the actual drying time at SWWTP (20 days) to reach 60% DS content, which reflect that the operation is at low performance that could well be due to clogging of the sand bed which would need to be replaced. In addition the pumps of sludge is non consistent due to pumping of higher depth in some places which needs more time up to 20 days. Rainfall can also be the reason for more drying time.

6. Using blocks support has no significant effect on drying time compared to more surface filtration area. Nevertheless, using of block support has benefit desludging by the mechanical equipment, which is faster and cheaper than by labors. This indicates that the available surface area between blocks is already enough for the drainage water.

7. Increasing the blocks spacing (filtration area) has a significant effect on drying time especially at rainfall season which can filtrate the excess water that came from rainfall precipitation, therefore we can conclude that using of geo-web support which provided the higher filtration area at rainfall season produce a sufficient area for excess water that come from rainfall to pass through filter.

8. The polymer addition has no considerable effect on overall drying time probably due to the small scale of pilot plant.

9. At up scaling assumption with different efficiencies (70-100%), the available sludge drying beds at SWWTP (36 drying beds) can be:
   - Assuming desludging at 25% DS content: the available sludge drying beds will be enough for drying the sludge quantity that produced from SWWTP in most experimental Exps at all scenarios-scale up, at most efficiencies (scale up) according to experimental unit and control unit.
   - Assuming desludging at 40% DS content: Assuming the experiment the available sludge drying beds are enough for drying the sludge quantity, that produced from SWWTP when the blocks spacing
increased at (experiment 3) according to experimental unit, also it can be sufficient according to exp. 1 and 6 at efficiency 80-100% and exp. 2 and 3 at efficiency 90 and 100% according to control unit.

- Assuming desludging at 60% DS content: the available sludge drying beds are insufficient for sludge drying which procured from SWWTP, when the sludge removed from the sludge drying beds at 60% DS content according to experimental unit and control unit.

4.2 Recommendations:

1. Particular care must be given to sand quality. Sand particles should have a diameter of (0.4-0.8 mm) and should be of spherical shape to avoid clogging of filter.

2. Replacement of the top 2 cm sand filter every 2-3 Exp's after every desludging is recommended to prevent clogging and performed of layer.

3. The spacing between blocks is suitable for water percolation and the increase of blocks spacing has a considerable effect on drying time and dry solid content percentage especially during the rainfall period.

4. Increase the spacing between the blocks is recommend to the extent that it has efficient drying time and prevents the mechanical equipment (BOB-CAT) tiers from falling in the sand layer between blocks.

5. Using of Geo-Web support is expected to have a considerable effect on drying time. Therefore applying of Geo-Web Support on the one full scale drying beds to give more clear results on the effect of Geo-Web on drying time.

6. Farther research is needed for the following factors:
   - Studying the effect of sludge depth on sludge drying time
   - Studying the effect of sludge scratching on drying time.
   - Studying the effect of initial dry solid content on drying time.
   - Studying the effect of sludge drying beds covering from rainfall on drying time.
   - Studying the effect of sand depth on drying time.

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