GSTF Journal on Agricultural Engineering (JAE) Vol.2 No.1, 2015

# Evaluation of Soil Compaction and Sealant Application for Compacted Earthen Liners

Amir M. González-Delgado, Manoj K. Shukla, Blair Stringam, and Mehran Parsheh

***Abstract*-The open earthen pond system is a cost effective system for the production of microalgae and aquaculture products. Studies are required in the development of compacted earthen liners as cost-effective lining technologies to avoid negative impacts on water resources and human health. The objective of this study was to determine the effect of different levels of compaction and application of a polyacrylamide polymer as a soil sealant on the hydraulic conductivity of soil. Three soils collected from the existing pond sites were packed into aluminum cores (5 cm diameter), proctor molds (10 cm diameter) and stock pots (60 cm diameter) prior to saturated hydraulic conductivity ($K_s$) determination using the constant head method. A negative relationship was obtained between $K_s$ and compaction for sandy loam, sandy clay loam and loam soils. The application of the soil sealant to compacted soil cores, proctor molds and stock pots did not decrease the $K_s$ to the value of 1 x $10^{-9}$ m/s or lower to meet the regulatory criteria of compacted clay liners. The dry bulk density versus $K_s$ curves indicate that sandy loam and sandy clay loam soils should be compacted to 1.82 and 1.69 g/cm$^3$, respectively in soil cores and 2.40 and 1.59 g/cm$^3$ in soil molds respectively to meet the regulatory criteria. The puddling experiments with sandy loam and loam soils in the stock pot also showed decreases in soil hydraulic conductivity as finer particles settle out of suspension in the soil pores. These experiments showed that sandy clay loam and loam soil can be compacted to decrease the $K_s$ below the regularity criteria for clay liners. More experiments particularly in small ponds are needed to validate the results of the laboratory experiments.***

***Keywords: saturated hydraulic conductivity; bulk density; soil texture; microalgae; evaporation ponds***

## I. INTRODUCTION

Microalgae are photosynthetic organisms with commercial and industrial applications. Different chemical compounds derived from microalgae cultures are used for cosmetics, dietary supplements and food sources. Microalgae extracts are present in face and skin care products [1]. Alternative protein sources and supplements such as pigments, antioxidants, β-carotene and fatty acids are produced from algae culture systems [2]. Microalgae are known as a natural food source of aquatic organisms, therefore algal biomass is mostly used to produce animal feed supplements for aquaculture. The microalgae biomass is commonly used for molluscs, shrimp and fish production and improvement of quality products [3]. Also, microalgae have been recognized as an alternative renewable energy source by the biofuel industry because of their high lipid content and rapid biomass production [4].

There are two microalgae culture systems used for large scale biomass production. These systems are known as closed photobioreactor systems and open pond production systems [5]. However, the majority of microalgae production occurs in open pond systems due to the low cost of construction and operation compared with photobioreactors [1, 3, 6, 7]. Microalgae, are also commonly produced in artificial ponds known as raceway ponds [3]. Raceway ponds are shallow closed loop oval channels that are circulated with a paddlewheel. The paddlewheel circulation enhances the microalgae culture and the shallow depth maximizes solar energy absorption for photosynthesis. Most of these ponds are lined, with the liner making up the bulk of the cost of building the pond [8]. As this industry continues to grow, it would be critical to evaluate lower cost alternatives to these liners. However, large scale adoption of low cost liners for microalgae culture should be preceded with careful evaluation of environmental and human health risks.

Coarse textured soils with high hydraulic conductivity are not suitable for building unlined ponds [9]. Lining materials are required to prevent the loss of

DOI: 10.5176/2345-7848_2.1.13

water and pollutants from the bottom of the pond. Otherwise human health and water resources may be negatively impacted [10]. Currently, artificial ponds are lined with concrete or compacted clay or they may be lined with plastic liners (geo-membranes and geosynthetic clay liners) [11, 12]. Concrete and plastic liners are impervious materials that are effective against seepage. However they may not be cost-effective for some projects due to their high installation and maintenance costs [13]. Geo-membranes are 0.75 mm to 2 mm thick flexible plastic membranes that are water impermeable. Geosynthetic clay liners are made of a dry layer of bentonite-clay between two geomembranes with a total thickness of 5 to 10 mm. Compacted clay liners are made of a layer of clay compacted to a $K_s$ of $1 \times 10^{-9}$ m/s or lower and usually have a thickness of 0.9 m to meet the U.S. Environmental Protection Agency (USEPA) regulations [14, 15].

Compacted clay liners are less expensive than other lining technologies and are used in the production of microalgae and aquaculture products. The application of polyacrylamide polymers as a lining technology to control water seepage is also being evaluated [16, 17]. Previous studies reported that polyacrylamide polymers have the capacity of reducing the hydraulic conductivity by sealing the soil pores [18, 19]. Studies are needed to evaluate the sealing capacity of polyacrylamide polymers in order to develop cost-effective lining technologies.

The main objective of this study was to determine the effect of different levels of compaction and polyacrylamide polymer application treatments (soil sealant) on the $K_s$ of soils. The other objective was to evaluate the decrease in the soil $K_s$ by puddling treatments. The experimental site for the potential development of open ponds is Sapphire Energy Integrated Algal Biorefinery (IABR) located in Columbus, New Mexico. This study is expected to provide useful information on treatments that likely will assist in the selection of a treatment or treatments for earthen liners in southwestern New Mexico and in areas with similar soils.

## II. METHODS AND MATERIALS

### A. *Collection of soil samples*

Undisturbed soil core and loose soil samples were collected from Sapphire Energy IABR site located at Columbus, NM. Six undisturbed soil core samples were collected from the bottom of a previously drained pond (the pond) at a depth of 0-5 cm. The exposed bottom of the pond allowed for the collection of samples to evaluate the existing physical soil properties at the pond. The undisturbed soil cores were covered with clear plastic wrap to prevent desiccation and soil loss. The soil core method was used to collect the undisturbed soil samples and the soil bulk densities were determined using the method described by Blake and Hartge [20]. The bulk density of soil throughout the report refers to the dry soil bulk density. The soil surrounding the impounded cores at the time of extraction was collected in plastic Ziploc bags to determine the moisture content and texture.

Two soil types were identified by reviewing the soil survey of Luna County, New Mexico and used to coordinate the collection of soil samples. Loose soil samples were collected using a soil auger from 0-25 cm and 25-55 cm depths, respectively at a second soil sampling site located approximately 300 m north of the pond. The collection of deeper loose soil samples was not possible with a soil auger because of the existence of a gravelly material that inhibited the digging with a soil auger. The third soil sampling site was located approximately 2,000 m northeast of the pond. Using a shovel, three loose soil samples were collected from 0-17 cm depth and were stored in plastic bags. The fourth soil sampling site was located approximately 1,500 m southeast of the pond and loose soil samples were collected from 0-17 cm depth.

After identifying the dominant soil texture, additional loose and undisturbed soil core samples were collected from the third sampling location (northeast site) during a second sampling event. Twelve 3-gallon buckets were filled with loose soil collected with a shovel from 0-17 cm and 17-40 cm depths. Also, two undisturbed soil core samples were collected at each of the 0-5 cm and 40-45 cm depths. The buckets were covered with plastic bags and secured to prevent contamination and loss of soil during their transportation.

### B. *Soil moisture content and Soil texture*

A representative sample was obtained from each of the loose soil samples collected from the field to determine the soil moisture content immediately after returning from the sampling sites. The moisture content of the samples were determined with the soil moisture content method defined by Gardner [21]. Pre-weighed metal cans were used to dry the soil samples in an oven for 24 hours at $105^0$ C. The difference in weight before and after drying was obtained to calculate the water loss during the drying. The ratio of water mass lost during drying and dry soil mass gave the gravimetric moisture content of the soil.

The remaining soil samples were spread on a table, large soil clods were hand crushed and the soil was air dried for three days. The air-dried soil was run through a 2 mm sieve (Dual Manufacturing Co., Chicago, Ill). Organic material, debris, and stones were removed from the soil samples. Soil clods (> 2 mm) were broken down with a rubber mallet, and the material was sieved again. The soil material < 2 mm was stored in plastic bags to conduct soil texture analyses. The hydrometer method was used to determine the soil texture and identify the soil types in the experimental site [22]. A hydrometer (Fisher Scientific Inc., Pittsburgh, PA) was used to measure the density of the soil suspension that is influenced by the soil particle size [23].

### C. Saturated Hydraulic Conductivity

In this study, treatments were applied at three different scales using aluminum cores, proctor molds and stock pots because it is reported that soil hydraulic conductivity is a function of the sample support [24]. Aluminum cores were 5 cm long and 5 cm in diameter, proctor molds were 10 cm long and 10 cm in diameter, and stock pot was 55 cm long and 60 cm diameter. Metal cores were used to repack the soil to conduct $K_s$ experiments. The bottom of each metal core was covered with cheesecloth to prevent the loss of soil during saturation and during $K_s$ experiments. The weight of the metal cores were recorded prior to and after repacking them with each soil type identified by hydrometer method. The same procedure was used to repack the soil in proctor molds and stock pot. After repacking, soil cores and molds were water-saturated from the bottom by placing them in a plastic water pan and slowly raising the head of water in the pan. The repacked soil cores and molds were saturated from the bottom because it is easier and more efficient to remove most of the air from the soil pores and obtain more complete saturation. The hydraulic head was kept small and water inside the core was allowed to move via capillary rise. The time allowed for saturation was at least 12 hours.

The $K_s$ for the soil cores and molds was determined by the constant head method [25] as follows

$$K_S = \frac{Q}{\left(\frac{h+L}{L}\right) x\ A} \qquad (1)$$

where $Q$ is the volumetric rate of flow ($m^3/s$), $A$ is the cross-sectional area ($m^2$), $h$ is the constant head (m) applied during the experiment and $L$ is the height (m) of the soil column. The area (A) for the metal cores, molds and the 160-quart stock pot were 19.63, 7.85 and 2,826 $cm^2$, respectively.

An empty metal core of the same diameter was attached at the top of each soil core to provide space for maintaining a constant head of water on top of the soil. Circular filter papers were placed on top of the soil samples to prevent erosion/disturbance of the soil surface. Each soil core and mold was placed on top of an iron wire mesh which was glued to the top of a funnel. A 100 ml graduated cylinder was placed under the funnel to collect all the water that ran out of the bottom of the funnel. A constant water head of 5 cm was maintained on top of the soil. The plastic Marriott bottle continuously supplied an equal amount of water into the core that came out of the bottom of the core to maintain a constant head of 5 cm of water at the top of the soil in each core. The effluents were collected in graduated cylinders at specific time intervals until three to six consistent readings were obtained with only small differences in effluent volume (< 2ml) for a given time interval. Four replications were made for each soil types identified in the study area. A similar procedure was followed for proctor molds; however, a constant head of 10 cm was maintained on top of the soil in each proctor mold and 16 cm on top of 30 cm of soil in the stock pot.

### D. Saturated hydraulic conductivity experiments with soil sealant

Four soil cores for each soil type were used to evaluate the reductions in the soil $K_s$ by soil sealant (Seepage Control Inc., Chandler, AZ) application. The $K_s$ of the soil were determined before and after adding one ml of soil sealant. A volume of one ml of soil sealant was added to the soil samples based on the recommended application rate of 3.78 liters (1 gal) of soil sealant per 7,560 liters (2,000 gal) of water (0.0005 L/L). The $K_s$ experiments were started 24 hours after applying the soil sealant to the cores under a constant head of five cm of water. Additional experiments were conducted with the same soil cores with five mL of soil sealant application. The recommended amount of soil sealant is much smaller than one mL but one mL was the minimum measurable with the graduated dropper to approximate the recommended application rate of 50 mL for 100 mL of water present in the soil cores. The experiments conducted with 5 mL of soil sealant represent 100 times more sealant application than the recommended application rate.

The circular filter papers were removed from the soil cores to maximize the interaction of soil sealant with the soil. The volume of soil sealant added to the samples was measured with a graduated dropper. After adding the soil sealant, water developed a whitish color that slowly vanished over time. This is probably due to the settlement of the chemical and subsequent filling of the pores. At the cessation of the experiments, a greasy soil surface was observed.

### *E. Compaction of soil cores and proctor molds*

The effect of compaction on $K_s$ was evaluated on four soil cores for each soil. The $K_s$ of the soil was determined under three successively increasing compactions. The compaction was created by using a standard two inch (five cm) proctor hammer. Before manual compaction, soil cores were drained to near field capacity soil moisture content. At the end of each compaction, the volume of soil in each core was determined to calculate the new dry bulk density. Compacted cores were subsequently saturated from the bottom prior to the determination of the $K_s$. As the last step of the $K_s$ determination, one mL and five mL of soil sealant were added to each of the compacted soil cores. Similar experiments were conducted using repacked proctor molds. The $K_s$ was determined at the end of each of the four successive compaction treatments.

### *F. Puddling treatments*

A 160-quart stock pot was modified to work as a permeameter. The soils were repacked separately in the stock pot to simulate puddling experiments similar to that in a paddy field. First, holes were drilled through the bottom of the 160-quart stock pot and a plastic tray with a hole in the center was attached below the bottom of the pot. A funnel with a valve to turn the flow from the bottom of the pot on or off was attached. This arrangement ensured that water flowed free out of the bottom of the pot and allowed for easy determination of the rate of flow through the soil. A layer of gravel approximately four cm thick was placed at the bottom of the pot and a circular metallic mesh was placed on the top of the gravel. Cheesecloth was placed on the metallic mesh to prevent soil loss during the puddling experiments. The $K_s$ experiments were conducted after saturating the soil from the top. After saturation was accomplished, 16 cm of water head was maintained on the soil surface, and the effluent was collected from the bottom of the pot using a 1000 ml graduated cylinder.

After completing the first hydraulic conductivity experiment, the soil in the stock pot was puddled with a standard proctor hand compaction hammer (Humboldt MFG. Co., Schiller Park, Ill.). The puddling depth was about 10 cm. The wet soil was worked similarly to the way manual puddling is done on a paddy field. At the end of a puddling treatment, the soil suspension was left to settle for about 24 hours and water contained much less suspended particles (more clear) than immediately after puddling. Puddling operations were repeated three times, and the $K_s$ was determined 24 hours after the cessation of each test. The water coming out of the bottom of the stock pot during $K_s$ tests were mostly clear and contained little sediment.

After conducting four $K_s$ experiments with each soil type, 58 mL of soil sealant was added to the stock pot and after 24 hours, the $K_s$ was determined again. The stock pot was subsequently drained to collect soil samples with a push-probe. The collected soil samples were used to determine the vertical variation of bulk density of the soil in the stock pot that showed bulk density was higher in the bottom half of the stock pot. It was difficult to collect an intact sample from the upper puddled layer (no data are presented).

## III. RESULTS AND DISCUSSION

### *A. Particle Size Distribution and Soil texture*

Determining the texture of different soils found at the experimental site is important for evaluating the potential of earthen liners and the viability of compaction treatments. Areas with soils containing a fine textured clay are suitable for the development of earthen liners [14]. The soil particle size analyses identified three types of soil textures present throughout the study site. The soil types were identified based on their percentages of sand, clay, and silt contents and using USDA soil textual classification (Table 1).

TABLE I. LOCATION AND DEPTH OF UNDISTURBED AND LOOSE SOIL SAMPLES WITH THEIR RESPECTIVE PERCENTAGE OF SOIL PARTICLE SIZE AND SOIL TEXTURE.

| Location | Depth (cm) | n[a] | Sand (%)[b] | Clay (%)[b] | Silt (%)[b] | Soil Texture |
|---|---|---|---|---|---|---|
| Pond[c] | 0-5 | 6 | 43.29 ± 0.88 | 36.59 ± 0.94 | 20.12 ± 0.11 | Clay loam |
| North | 0-25 | 3 | 55.12 ± 0.34 | 16.40 ± 0.64 | 28.48 ± 0.78 | Sandy loam |
| North | 25-55 | 3 | 53.84 ± 0.00 | 27.25 ± 0.48 | 18.91 ± 0.48 | Sandy clay loam |
| Northeast | 0-12 | 6 | 57.85 ± 0.41 | 13.36 ± 0.92 | 28.78 ± 1.08 | Sandy loam |
| Northeast | 0-17 | 3 | 58.21 ± 1.78 | 13.36 ± 2.78 | 28.42 ± 1.00 | Sandy loam |
| Northeast[d] | 0-17 | 3 | 59.06 ± 1.09 | 12.21 ± 0.54 | 28.72 ± 0.94 | Sandy loam |
| Northeast[d] | 17-40 | 3 | 42.40 ± 0.00 | 28.21 ± 0.54 | 29.38 ± 0.54 | Loam |
| Southeast | 0-20 | 3 | 69.83 ± 0.94 | 9.92 ± 0.19 | 20.24 ± 0.77 | Sandy loam |

[a] n; number of soil particle size analysis.
[b] Mean ± Standard Error of sand, clay and silt.
[c] Samples collected from pond bottom.
[d] Samples collected during the second sampling event.

The soil type identified at the surface (0-25 cm depth) was sandy loam at each sampling site. Sandy clay loam was present at the 25-55 cm depth in the northern site and loam was the soil type identified at the17-40 cm depth in the northeastern site. The particle size analysis of soil samples collected from the bottom of the pond classified the soil as clay loam. Because there is no information on the addition of clay material, it seems the compaction treatment of the soil on the pond bottom during construction caused a breakdown of sand and coarse silt-sized particles and changed the soil texture.

Sandy loam and sandy clay loam soils were chosen for compaction treatments to determine $K_s$ of soil in repacked cores, proctor molds, and stock pot. Sandy clay loam was chosen because sandy clay loam and loam are expected to provide similar values of conductivity under compaction that exceeds natural soil compaction. The texture analysis (Table 1) also showed no statistically significant difference in clay content between sandy clay loam and loam. Because loam has slightly higher silt plus clay contents than sandy clay loam, loam was selected in place of sandy clay loam for puddling treatments where dispersion and subsequent settlement of finer particles are important.

### *B. Hydraulic properties of undisturbed soil in the pond*

Under a constant head of 5 cm, only one of the six undisturbed cores, collected from the pond bottom, conducted water through it during the Ks experiments. During pond construction, clay layers were found in some areas near the pond. Although the clay layer is not contiguous, compaction of the soil along with likely texture modifications by heavy machinery could be the reason that no water came out of the cores during hydraulic conductivity tests. The only core that was permeable had a bulk density of 1.35 g/cm3 and a Ks of 2.83 x 10-7 m/s. The average bulk density values for all the undisturbed soil cores collected from the pond bottom was 1.44 ± 0.10 g/cm3.

### *C. Hydraulic properties of undisturbed soil cores*

The bulk density of the undisturbed sandy loam sample collected at the northeastern site was 1.21 g/cm$^3$ and $K_s$ of 3.25 x 10$^{-5}$ m/s. One of the two undisturbed loam samples collected from 20-25 cm depth transmitted water when hydraulic conductivity experiments were performed. The bulk density and $K_s$ values for this undisturbed core sample were 1.51 g/cm$^3$ and 2.22 x 10$^{-6}$ m/s, respectively. The average bulk density value for the two undisturbed loam soil cores were 1.59 ± 0.07 g/cm$^3$. The high soil dry bulk density was due to the weight of the stones and gravels included in the dry soil weight. Because gravels and stones can have large pores around them, hydraulic conductivity of this system can be high in spite of the high bulk density.

### *D. Hydraulic properties of soil cores treated with Sealant*

The effect of compaction was evaluated in soil cores repacked with sandy loam and sandy clay loam soils, separately. At the end of the third $K_s$ test on each soil core, two different concentrations of soil sealant were applied to the cores, and $K_s$ was determined 24 hours after the application of the soil sealant.

There was no outstanding change in $K_s$ values between the third hydraulic conductivity test and the tests conducted after applying 1 mL and 5 mL of soil sealant, for both soils. The final average $K_s$ values without soil sealant for sandy loam and sandy clay loam were $2.17 \times 10^{-7} \pm 1.47 \times 10^{-7}$ m/s and $4.88 \times 10^{-8} \pm 2.45 \times 10^{-8}$ m/s, respectively. The $K_s$ values for sandy loam and sandy clay loam after the application of 5 mL of soil sealant were $1.99 \times 10^{-7} \pm 1.11 \times 10^{-7}$ m/s and $9.86 \times 10^{-8} \pm 5.14 \times 10^{-8}$ m/s, respectively. The $K_s$ value for both soils before and after the application of soil sealant at final compactions remained within their standard deviations, and no significant differences were observed. These experiments do not show the usefulness of the soil sealant for decreasing hydraulic conductivity even at rates much higher than those recommended by the manufacturer. Therefore, experiments should be conducted in the field to assess the true potential of the soil sealant.

The experiments in Fig. 1 with soil sealant were conducted at the highest level of compaction (highest bulk density) of the soil cores. To be sure that the effect of soil sealant on reductions in $K_s$ were not related to the high bulk density of soil in the cores (Fig. 1), more experiments were performed by packing the cores with both soils at or close to the natural bulk density of soils in the field. There was only a slight reduction in the $K_s$ for both soils after applying 1 mL of soil sealant (Fig. 2). The application of 5 mL of soil sealant did not change the $K_s$ of the soils. The final average $K_s$ values for sandy loam and sandy clay loam were $5.71 \times 10^{-6} \pm 7.07 \times 10^{-7}$ m/s and $7.88 \times 10^{-6} \pm 6.18 \times 10^{-7}$ m/s, respectively.

The current recommended application rate for the study site is 0.20 L of soil sealant/m$^2$ (0.005 gal/ft$^2$). The soil sealant's manufacturer recommends an application rate of 3.78 liters (1 gal) of soil sealant per 7,560 liters (2,000 gal) of water. Soil in the cores (Fig. 1 and Fig. 2) had a surface area of 19.63 cm$^2$ (0.021 ft$^2$), and the volume of ponded water was 98.13 cm$^3$ (0.0259 gal). Thus, based on any of the above recommendations, the cores should have been treated with $4.35 \times 10^{-3}$ L/m$^2$ ($1.06 \times 10^{-4}$ gal/ft$^2$) and 0.05 mL ($1.30 \times 10^{-5}$ gal/gal). However, soil cores were treated with 1 mL and 5 mL of soil sealant because of the ease of measuring and to determine if there were appreciable reductions in the hydraulic conductivity of the soil. The amount of 1 mL and 5 mL of soil sealant were 2.50 and 12.52 times greater than the application rate used in the study site. The data in Fig. 2 indicate that $K_s$ decreased with increasing amounts of soil sealant, but it is highly unlikely that addition of amounts greater than 5 mL of soil sealant will be enough to reduce the $K_s$ to USEPA levels; moreover costs associated with soil sealant may make its application impractical. Although laboratory experiments conducted by Young et al. [18] showed $K_s$ reduction in the soil with increasing concentration of polyacrylamide polymer that promoted the clogging of soil pores.

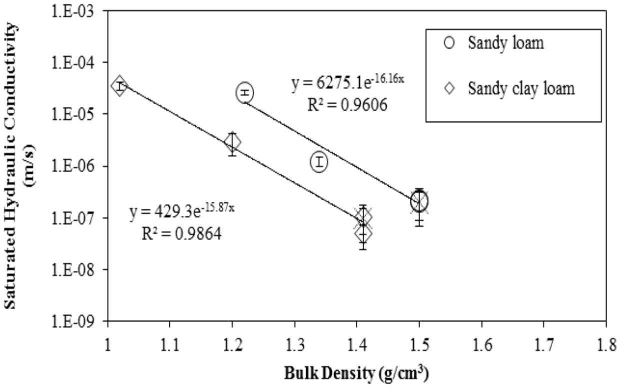


Fig. 1. Saturated hydraulic conductivity of soil cores compacted at different levels and subsequently treated with 1 mL and 5 mL of Soil Sealant after the third compaction. Experiments conducted with the soil sealant are marked with the dashed-X symbols. The vertical axis has a logarithmic scale, and error bars are included for each data point. Error bars represent standard error.

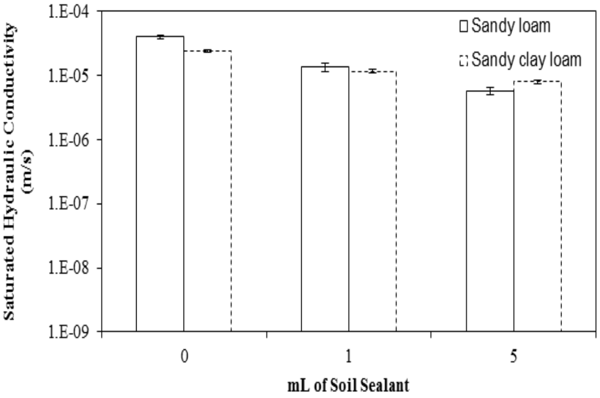


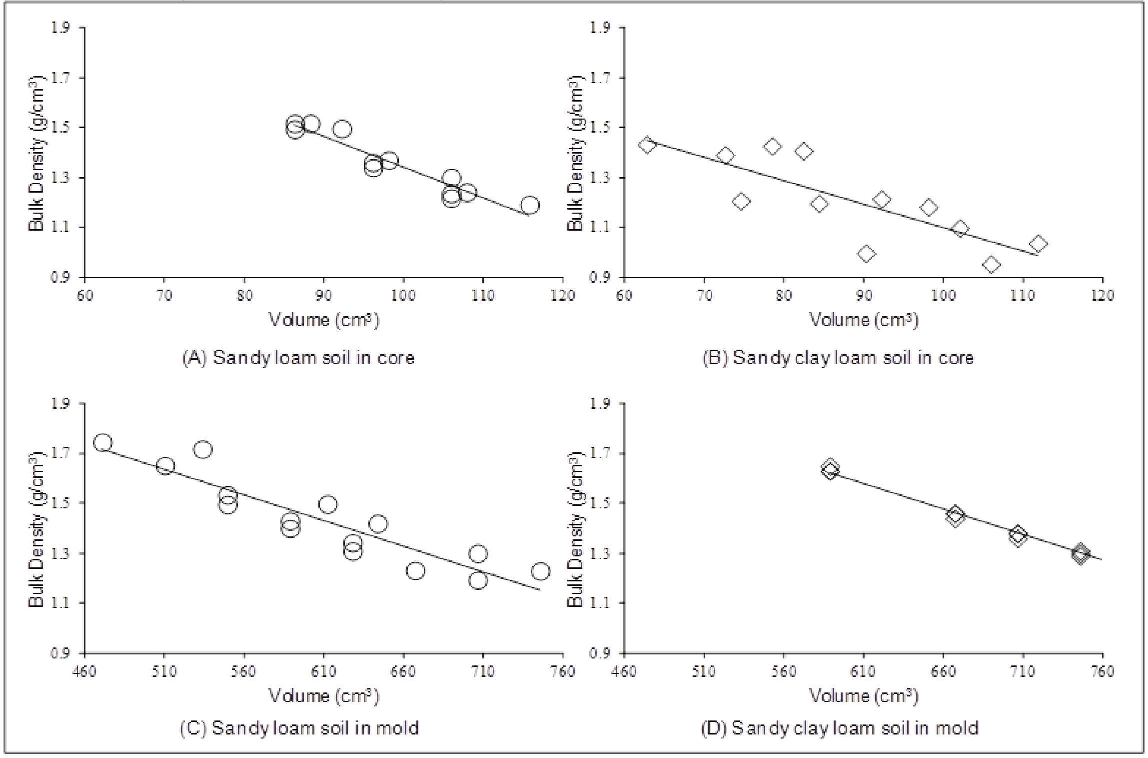
Fig. 2. Saturated hydraulic conductivity of soil cores determined 24 hours after the application of 0 mL, 1 mL and 5 mL of soil sealant. Error bars represent standard error.

## E. *Relationships between compaction and soil volume*

The soil was repacked in cores and each core was slightly compacted by using a standard proctor hammer

(2 inch diameter) prior to the saturation to determine hydraulic conductivity. Soil in each core was subsequently drained below field capacity prior to the next compaction obtained by hammering the soil four times with the proctor hammer. The change in volume of the soil in each core was recorded at the end of each compaction treatment (Fig. 3A and Fig 3B). Each core was saturated again and the hydraulic conductivity tests were repeated. The procedure was repeated for each core and soil four times. Soil volume decreased with increasing compaction, and the average decrease in soil volume was 19% for sandy loam soil and 28% for sandy clay loam. The relative compaction expressed as the ratio of initial bulk density and final bulk density (not the maximum bulk density) was 72% for sandy loam soil and 73% for sandy clay loam soil at a soil water content below field capacity (below 0.33 bars or 4.8 psi).

A similar decrease in soil volume with increasing compaction also was observed in proctor molds. Average decreases in the soil volume were 29% for sandy loam soil and 25% for sandy clay loam soil (Fig. 3C and Fig. 3D). The relative compaction expressed as the ratio of the initial bulk density and the final bulk density were 71% for sandy loam and 75% for sandy clay loam soils.



(A) Sandy loam soil in core

(B) Sandy clay loam soil in core

(C) Sandy loam soil in mold

(D) Sandy clay loam soil in mold

Fig. 3. The relationship between soil bulk density and soil volume after compaction using a standard 2 inch proctor hammer in soil cores (A and B) and proctor molds (C and D) for sandy loam and sandy clay loam soils.

### *F. Relationships between hydraulic conductivity and bulk density*

It is evident from Fig. 1 that for both soil types, $K_s$ decreased with increasing soil bulk density in soil cores. The $K_s$ for sandy clay loam soil was consistently lower than for those obtained for sandy loam soil at each level of compaction. A negative exponential relationship between $K_s$ and compaction was obtained for both soils. Previous studies have reported a similar relationship between $K_s$ and compaction [26, 27, 10]. The exponential relationship suggests that the sandy loam and sandy clay loam should be compacted to 1.82 and 1.69 g/cm$^3$, respectively to meet the USEPA limit of 1 x 10$^{-9}$ m/s for compacted clay liners.

Six proctor molds, three of them repacked with sandy loam and three with sandy clay loam soils, were used to determine the effect of compaction on the $K_s$ (Fig. 4). In general, with increasing bulk density, $K_s$ decreased in proctor molds. A decrease in the $K_s$ of proctor molds packed with sandy clay loam soil was clearly evident, and at a bulk density of about 1.4 g/cm$^3$, the average $K_s$ value was $3.04 \times 10^{-7} \pm 5.04 \times 10^{-8}$ m/s. However, the $K_s$ for proctor molds packed with sandy loam soil was $1.62 \times 10^{-6} \pm 1.01 \times 10^{-6}$ m/s at a bulk density of 1.72 g/cm$^3$.

The compaction process decreases the movement of water through the porous media as a result of reduction of soil pore size and pore connectivity [28, 29]. Fig. 4 presents a negative exponential relationship between $K_s$ and compaction for both soils in proctor molds. The exponential relationship suggests that the sandy loam soil should be compacted to 2.4 g/cm$^3$ and sandy clay loam to 1.59 g/cm$^3$ to meet the USEPA limit of $1 \times 10^{-9}$ m/s for compacted clay liners. It is highly unlikely that sandy loam soil can be compacted to 2.4 g/cm$^3$ to yield USEPA specified $K_s$ for compacted clay liners. There is a potential of utilizing the sandy clay loam soil present in the area and compacting it further to yield a USEPA specified $K_s$ for compacted clay liners. This is further supported by laboratory work where repacked sandy clay loam soil molds did not transmit water when compacted to a bulk density ≥ 1.45 g/cm$^3$.

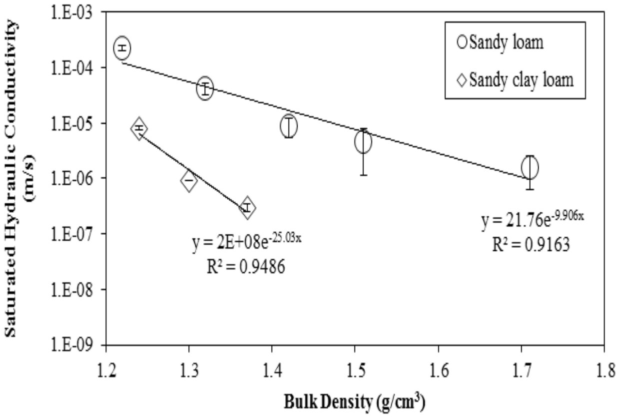


Fig. 4. Saturated hydraulic conductivity of soil molds for different bulk densities. The vertical axis has a logarithmic scale and error bars are included for each data point. Error bars represent standard error.

### G. *Puddling treatments*

The puddling treatments that simulate a paddy field situation were conducted with sandy loam and loam soils because these two represent the most contrasting soil textures. The bulk densities of the sandy loam and loam soils packed to conduct puddling experiments were 1.25 g/cm$^3$ and 1.07 g/cm$^3$, respectively. During puddling, the soil at and below the depth of puddling is usually compacted, and the fine soil particles within the puddling depth get dispersed and become suspended. At the termination of puddling operations, the suspended particles began to settle slowly, further clogging the pores and decreasing the hydraulic conductivity of the puddled layer (Fig. 5). Rezaei et al. [30] have also reported soil aggregate breakdown due to puddling in a paddy field with attendant reduction of macropore but increase of micropore volumes. The elimination of soil aggregates and modification of soil pores through the puddling treatment contributed to the formation of a blocked soil surface that decreased the $K_s$. Also they reported that the bulk density increased with depth for each puddling intensity level.

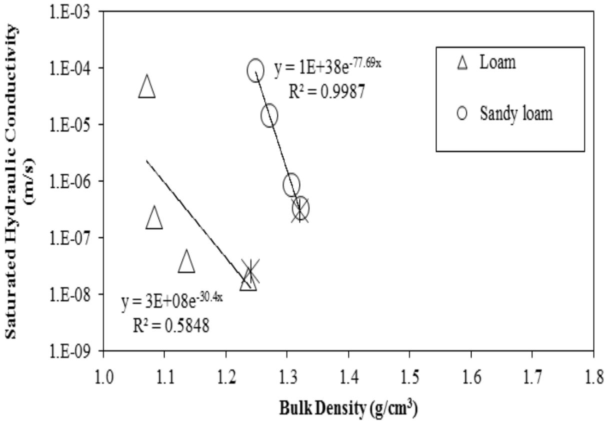


Fig. 5. Saturated hydraulic conductivity of soil after puddling treatments to simulate paddy field conditions under different bulk densities. The saturated hydraulic conductivity of the porous media also was determined after 24 hours of adding 58 mL of soil sealant at the end of the last paddy field simulation. Experiments conducted with the soil sealant are marked with the dashed-X symbols. The vertical axis has a logarithmic scale.

The puddling treatments with sandy loam and loam soils showed a decreasing trend for $K_s$ with increasing compaction. Lower $K_s$ values were obtained from loam than from sandy loam for each bulk density. The lowest $K_s$ obtained at the end of the last puddling was $1.90 \times 10^{-8}$ m/s for loam soil that was compacted to a bulk density of 1.24 g/cm$^3$. This clearly indicates that larger amounts of finer particles clog the soil pores and further decrease the hydraulic conductivity of the soil.

Similar to other experiments conducted in soil cores, soil sealant was also applied to the stock pot at the end of the fourth $K_s$ experiment. The stock pot had a cross-sectional area of 2,826 $cm^2$ (3.14 $ft^2$). Based on the recommended application rate used on the existing pond site in Columbus, NM, 58 mL of soil sealant was added to the stock pot. The $K_s$ experiments conducted about 24 hours later showed that the $K_s$ did not change substantially (Fig. 5). The final $K_s$ value for the soil sealant application was only 13% smaller in sandy loam soil; however, the value was almost 28% higher in loam soil. These experiments further demonstrate that application of soil sealant alone will not decrease the $K_s$ to the USEPA mandated limit for compacted clay liners. The puddling experiments of Fig. 5 were conducted when water was ponded on the soil surface. Because the average bulk density of the puddled loam soil was only 1.24 $g/cm^3$ and $K_s$ was 1.90 x $10^{-8}$ m/s, there is a possibility that further increases in compaction by conducting a puddling treatment when soil water content is below the field capacity may decrease the $K_s$ to the EPA mandated limit. Previous studies have shown that puddling treatment can increase or decrease the bulk density depending on the soil moisture content [31, 32]. The cohesion between soil aggregates is greater when the soil is at a moisture content below saturation. Therefore, the puddling of soils at moisture content below saturation produces higher soil bulk density values than those at saturated moisture content. Ahmad [33] reported that the bulk density increased with decreasing water-soil ratio after conducting a study to determine the influence of water-soil ratio on puddling efficiency.

## IV. CONCLUSION

The soil texture analysis showed three different types of soils present in the study area. The soil near the surface at all of the sampling locations was classified as sandy loam while soil at deeper depths (below 17 cm) was sandy clay loam or loam. Experiments in soil cores, proctor molds, and stock pot (three different scales) did not support the use of soil sealant for decreasing $K_s$ to USEPA mandated criteria for compacted clay liners. Although soil sealant did not seem to decrease the $K_s$ of the soil, field experiments should be conducted before ruling out the sealing potential of the soil sealant. As compaction increased, hydraulic conductivity of the soil decreased, and a negative exponential relationship were obtained between $K_s$ and compaction for both soils. The exponential relationship suggested the sandy loam and sandy clay loam should be compacted to 1.82 and 1.69 $g/cm^3$, respectively in soil cores and 2.40 and 1.59 $g/cm^3$, respectively in soil molds, to meet the USEPA limit. The puddling experiments with sandy loam and loam soils showed a decreasing trend for $K_s$ with increasing compaction. Puddling in loam produced consistently lower $K_s$ values than sandy loam. The lowest $K_s$ obtained at the end of the puddling was 1.90 x $10^{-8}$ m/s for loam soil with a bulk density (compaction) of 1.24 $g/cm^3$. These results indicate that with a further increase in the bulk density, puddling treatment has the potential to reduce the hydraulic conductivity of the soil to the USEPA-specified limit. The results were derived from experiments conducted with soil samples without gravel therefore experiments under field conditions will be required to evaluate the effect of gravel on the $K_s$ of compacted porous media. The three types of soils present in the experimental site contain enough clay content for the development of compacted earthen liners for open ponds, therefore, it could be useful to conduct $K_s$ experiments under different compaction treatments after mixing these soil types in the field.

## ACKNOWLEDGEMENT

Authors thank New Mexico State University (NMSU) Agricultural Experiment Station, Las Cruces, NM, USA for support. Sincere thanks are for Sapphire Energy Inc., Las Cruces, NM, USA for providing the financial support and valuable assistance during sampling.

## REFERENCES

[1] P. Spolaore, C. Joannis-Cassan, E. Duran, and A. Isambert, “Commercial applications of microalgae,” Journal of Bioscience and Bioengineering, 2006, vol. 101: pp. 87-96.

[2] T.M. Mata, A.A. Martins, and N.S. Caetano, “Microalgae for biodiesel production and other applications: A review,” Renewable & Sustainable Energy Reviews, 2010, vol. 14: pp. 217-232.

[3] L. Brennan, and P. Owende, “Biofuels from microalgae-a review of technologies for production, processing, and extractions of biofuels and co-products,” Renewable & Sustainable Energy Reviews, 2010, vol. 14: pp. 557-577.

[4] I. Priyadarshani, and B. Rath, “Commercial and industrial applications of micro algae – a review,” Journal of Algal Biomass Utilization, 2012, vol. 3: pp. 89-100.

[5] D. Chaumont, “Biotechnology of algal biomass production - a review of systems for outdoor mass-culture,” Journal of Applied Phycology, 1993, vol. 5: pp. 593-604.

[6] R. Slade, and A. Bauen, "Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects," Biomass & Bioenergy, 2013, vol. 53: pp. 29-38.

[7] P. Letcher, S. Lopez, R. Schmieder, P.A. Lee, C. Behnke, M. Powell, and R. McBride, "Characterization of amoeboaphelidium protococcarum, an algal parasite new to the cryptomycota isolated from an outdoor algal pond used for the production of biofuel", PLOS ONE, 2013, 82 e56232. DOI: 10.1371/journal.pone.0056232.

[8] R.C. McBride, and D.S. Merrick, "Catalyzing innovation. Innovation in open pond algae agriculture for biofuel production," 2014, vol. 10(3) DOI:10.1089/Ind.2013.1614.

[9] E.R. Venteris, R.C. McBride, A.M. Coleman, R.L. Skaggs, and M.S.Wigmosta, "Siting algae cultivation facilities for biofuel production in the United States: trade-offs between growth rate, site constructability, water availability, and infrastructure," Environmental Science and Technology, 2014, vol. 48 (6): pp.3559-3566.

[10] A.M. Gonzalez-Delgado, M.K. Shukla, A.L. Ulery, A.S. Bawazir, and P.V. Brady, "Saturated hydraulic conductivity of self-sealing lining materials for desalination evaporation ponds," Desalination and Water Treatment, 2011, vol 29: 187-195.

[11] T.J. Lundquist, I.C. Woertz, N.W.T. Quinn, and J.R. Benemann, "A realistic technology and engineering assessment of algae biofuel production," Energy Biosciences Institute. University of California Berkeley. 2010.

[12] Y. Chisti, "Biodiesel from microalgae," Biotechnology Advances, 2007, vol. 25: pp. 294–306.

[13] O. Sivrikaya, "Models of compacted fine-grained soils used as mineral liner for solid waste," Environmental Geology, 2008, vol. 53: pp. 1585-1595.

[14] C.H. Benson, and J.M. Trast, "Hydraulic conductivity of thirteen compacted clays," Clays and Clay Minerals, 1995, vol. 43: pp. 669-681.

[15] J.P. Giroud, K. BaduTweneboah, and K.L. Soderman, "Comparison of leachate flow through compacted clay liners and geosynthetic clay liners in landfill liner systems," Geosynthetics International, 1997, vol. 4: pp. 391-431.

[16] R.E. Sojka, D.L. Bjorneberg, J.A. Entry, R.D. Lentz, and W.J. Orts, "Polyacrylamide in agriculture and environmental land management," Advances in Agronomy, 2007, vol. 92: pp. 75-162.

[17] B.T. Story, M.A. Urynowicz, and G.F. Vance, "Field demonstration of polyacrylamide in an unlined irrigation canal," Journal of Irrigation and Drainage Engineering-ASCE, 2013, vol. 139: pp. 399-404.

[18] M.H. Young, E.A. Moran, Z. Yu, J. Zhu, and D.M. Smith, "Reducing saturated hydraulic conductivity of sandy soils with polyacrylamide," Soil Science Society of America Journal, 2009, vol. 73: pp. 13-20.

[19] J. Zhu , and M.H. Young, "Sensitivity of unlined canal seepage to hydraulic properties of polyacrylamide-treated soil," Soil Science Society of America Journal, 2009, vol. 73: pp. 695-703.

[20] G.R. Blake, and K.H. Hartge, "Bulk density, In A. Klute (Ed), Methods of Soil Analysis," Part I, ASA Monograph No. 9, Madison, WI, 1986, pp. 363-375.

[21] W.H. Gardner, "Water content. In A. Klute (Ed), Methods of Soil Analysis," Part I, ASA Monograph No. 9, Madison, WI, 1986, pp. 493-544.

[22] G.W. Gee, and J.W. Bauder, "Particle size analysis, In A. Klute (Ed), Methods of Soil Analysis," Part I, ASA Monograph No. 9, Madison, WI, 1986, pp. 337-382.

[23] J.M. Keller, and G.W. Gee, "Comparison of American society of testing materials and soil science society of America: Hydrometer methods for particle-size analysis'" Soil Science Society of America Journal, 2006, vol. 70: pp. 1094-1100.

[24] M.K. Shukla, "Introduction to soil hydrology. In M.K. Shukla (Ed), Soil hydrology, land use and agriculture: Measurement and modeling," CAB International, Wallingford, U.K., 2011, pp. 1-23.

[25] A. Klute, and C. Dirksen, "Hydraulic conductivity and diffusivity: Laboratory methods, In A. Klute (Ed), Methods of Soil Analysis," Part I, ASA Monograph No. 9, Madison, WI, 1986, pp. 687-734.

[26] S. Assouline, "Modeling the relationship between soil bulk density and the hydraulic conductivity function," Vadose Zone Journal, 2006, vol. 5: pp. 697-705.

[27] B.K. Behera, "Effect of puddling on puddled soil characteristics and performance of self-propelled transplanter in rice crop, In B. P. Varshney (Ed)," Agricultural Engineering International: the CIGR Ejournal, 2009, vol. 10: pp. 1-18.

[28] D. Dec, J. Dorner, O. Becker-Fazekas, and R. Horn, R "Effect of bulk density on hydraulic properties of homogenized and structured soils," Revista De La Ciencia Del Suelo Y Nutricion Vegetal, 2008, vol. 8: pp. 1-13.

[29] J. Lipiec, and R. Hatano, "Quantification of compaction effects on soil physical properties and crop growth," Geoderma, 2003, vol. 116: pp. 107-136.

[30] M. Rezaei, R. Tabatabaekoloor, S.R. Mousavi Seyedi, and N. Aghili Nategh, "Effects of puddling intensity on the in-situ engineering properties of paddy field soil," American Journal of Agricultural Economics, 2012, vol. 3: pp. 22-26.

[31] G.B. Bodman, and J. Rubin, "Soil puddling," Soil Science Society of America Journal, 1949, vol. 13: pp. 27-36.

[32] P.K. Sharma, and S.K. De Datta, "Effects of puddling on soil physical properties and processes," Advances in Soil Science, 1986, vol. 5: pp. 139-178.

[33] D. Ahmad, "Puddling efficiency for rice root growth in a cohesive soil," Pertanika Journal of Science & Technology, 1993, vol. 1: pp. 93-102.

## AUTHORS' PROFILE

**Dr. Amir M. González-Delgado** received his B.Sc. degree from Universidad Metropolitana, San Juan, PR, U.S. in 2004 and M.Sc. degree from University of Texas at El Paso, El Paso, TX, U.S. in 2006, both in environmental science. He received his Ph.D. degree in plant and environmental science with emphasis in soil physics from New Mexico State University, Las Cruces, NM, U.S. in 2011. He is working as a Post-doctoral Researcher at New Mexico State University, Las Cruces, NM, US.

**Dr. Manoj K. Shukla** received his B.Sc. degree in agricultural engineering in 1981 and M.Sc. degree in soil and water engineering from JN. Agricultural University, India. He received his Ph.D. degree in soil physics from University of Agricultural Sciences, Vienna, Austria in 1998. Dr. Shukla is a Professor of environmental soil physics at New Mexico State University, Las Cruces, NM, US.

**Dr. Blair Stringam** received his B.Sc. degree in agricultural engineering from University of Alberta, Alberta, Canada in 1988. He received his M.Sc. degree in agricultural and irrigation engineering in 1992 and Ph.D. degree in biological and agricultural engineering from Utah State University, Logan, UT, U.S. He is an Associate Professor in the Plant and Environmental Science Department of New Mexico State University, Las Cruces, NM, US.

**Dr. Mehran Parsheh** received his M.Sc. degree in mechanical engineering from Chalmers University of Technology, Gothenburg, Sweden and Ph.D. degree in mechanical engineering and fluid dynamics from Royal Institute of Technology, Stockolm, Sweden. He works as a Principal Engineer for Sapphire Energy Inc.