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Full Length Research Paper

Design, Fabrication and Testing of a Constant Head Permeameter

Ajayi A. S.[1], Okafor Michael[2], Sekiteri P.A.[3] and Ibrahim Rasheed[1]

[1]Department of Agricultural and Bio-Environmental Engineering Technology, Auchi Polytechnic, Auchi, Edo State, Nigeria.
[2]Department of Civil Engineering Technology, Auchi Polytechnic, Auchi, Edo State, Nigeria.
[3]Department of Mechanical Engineering Technology, Auchi Polytechnic, Auchi, Edo State, Nigeria.
*Corresponding author E-mail: ajayistan@gmail.com; Tel: +2348039714411

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ABSTRACT: Hydraulic conductivity describes how easily a fluid is transported through a porous medium. The permeability of soils is a very important feature which plays the crucial role in issues connected with the flow of ground water and the migration of pollutions. The laboratory device used to measure hydraulic conductivity is a 'permeameter'. This laboratory device is not readily available, probably due to its cost, there is a need to initiate and develop a design that will meet the demands of projects that has to do with the hydraulic conductivity property of soil samples. The improvised constant head permeameter consist of a transparent constant head permeameter box made of Perspex glass material, a rubber water tank, a 0.5hp centrifugal water pump, glass siphons made from Pyrex capillary tubes, plastic funnels, PVC pipes, a metal stand, a graduated movable pin, core sampler holders, and a 4amps step down transformer. The constant head permeameter is designed and able to determine hydraulic conductivity of soil samples with particle sizes within the range of 0.001mm – 2mm. The T-Test result between the improvised and Imported Permeameter mean K_{sat} values was 0.03 which is less than the critical value of 0.05 (5%). It is therefore recommended that a water tight medium should be put in place between the core sampler and the core sampler holder.

Keywords: Design, Testing of a Constant Head Permeameter

INTRODUCTION

Hydraulic conductivity is considered one of the most important parameters within hydrogeological contexts and describes how easily a fluid is transported through a porous medium. The parameter can be estimated using several different methods, where permeameter testing, grain-size distribution analysis and pumping tests are considered the most commonly permeameter used Amer and Ridder (2002). Pumping tests are considered the most accurate method of permeability, because the soil sample in this test represents an undisturbed "in situ" material, but the tests are time-consuming and costly which also depend on soil porosity and configuration of soil pores. Estimation of hydraulic conductivity using empirical formulas based on grain size distribution is a simpler and less expensive method, but it is often difficult to predict the precision of these. Estimation of hydraulic conductivity can also be easily accomplished by permeameter testing in the laboratory. A weakness in estimating the hydraulic conductivity in the laboratory is that the sample material does not represent an undisturbed "in situ" material because the grain structure of the sample is disturbed during the drilling process of the groundwater well and when transported from the well to the laboratory Brady and Weil (2005).

The most common method of permeameter testing is performed using a type of permeameter cell known as a Darcy-cell.

To be able to correctly estimate the hydraulic conductivity of groundwater in a soil one must assume that the sample is fully saturated with water. However, fully saturating a soil sample in the Darcy-cell has proven to be a challenge, as gas bubbles may be trapped in the pore spaces. Extracting the air in the sample by applying vacuum to the cell will make it easier to fully saturate the sand sample. It has however not been possible to apply vacuum on the existing cell at the Department of Geoscience and Petroleum because the existing cell-wall is too weak to withstand the difference in pressure on its inside and outside when vacuum is applied. It is therefore possible to modify the existing apparatus so as to be able to apply vacuum on the cell, to better estimate the hydraulic conductivity in soils (Brady and Weil, 2005).

The soil water movement is of considerable importance to many aspects of agricultural systems. The behaviour of soil water flow systems, such as the flow of water to drains and wells, evaporation from the soil surface, the movement of water to plant roots and many others, are determined by the soil moisture characteristic curve (Ibrahim, 2005).

Hydraulic conductivity (K), also known as coefficient of permeability, is a measure of soil ability to transmit water, while the soil moisture characteristic curve is the relationship between the water content and the soil water potential. In other words, saturated hydraulic conductivity (K_{sat}) is a measure of the ability of soil to conduct water under a unit of hydraulic potential gradient. Hydraulic conductivity of soils depends on several factors such as; fluid viscosity, pore size distribution, grain size distribution, void ratio, degree of soil saturation. It also depends on the soil temperature and the viscosity and density of the water (Edoga, 2010).

Hydraulic conductivity of soil is of the most important physical property of the soil. It is needed to describe how water moves through the soil. This information is useful for studying irrigation, water logging and drainage erosion, soil water balance studies and other soil problems. It is important for studying the sub surface flow and transport problems, estimating the quantity of underground seepage, solving problems involving pumping seepage water from construction excavation, stability analyses of earth structures and earth retaining walls subjected to seepage forces (Edoga, 2010).

The laboratory device used to measure hydraulic conductivity is a 'permeameter'. The two kinds of permeameters commonly used are the 'constant-head' and 'falling-head' permeameter. The constant-head permeameter is used with non cohesive sediments (i.e. sand, gravel), while the falling-head permeameter is used with cohesive sediments with lower conductivity. This laboratory device is not readily available, probably dues to its cost, there is a need to initiate and develop a design that will meet the demands of projects that has to do with the hydraulic conductivity property of soil samples. Therefore, the need for the development and improvisation of a similar model or design by using local materials from our environment, and still achieving similar hydraulic conductivity results as other constant head permeameters, has become necessary (Camp, 2016).

This study is meant to develop, test and evaluate a constant head permeameter that will be used subsequently for determining saturated hydraulic conductivities of soil samples. In the university environment, most research work and knowledge acquisition of hydraulic conductivity are mostly done in the soil science department of agricultural science. Hence, having a second laboratory equipment or setup will reduce stress on that one equipment. This laboratory equipment will be very useful to the department because various students' projects that involve the determination of 'k' values will be solved almost immediately and free of charge.

Also for practical purposes, this laboratory equipment will be readily available to students who are being taught on how to determine the hydraulic conductivities of soil samples. The objective of this study is to design, fabricate and test a constant head permeameter for hydraulic conductivity measurement.

MATERIALS AND METHODS

Description of the study location

Auchi is located between latitude 6^0 70 "00" to 7^0 18 "00" North of the Equator and longitude 6^0 49 "00" East of the Greenwich Meridian. Auchi is the headquarters of Etsako-West Local Government Area of Edo State, Nigeria. The area covers a total land area of 94,562 km^2.

Design considerations

The fabrication of an improvised constant head permeameter was carried based on the principles of the imported permeameter in the department of Civil Engineering Technology, Auchi Polytechnic Auchi**.** This system involved the use of standard glass siphons used to convey water from the plastic core sampler holder onto a pyrex glass burette.

A 0.5hp pump was used to deliver water at a very slow flow rate from the storage tank onto the transparent constant head permeameter box at a height of about 91.44cm.

The whole system used conveyance pipes of 2.54cm internal diameter PVC pipes. Assumptions were that, the inlet pipe has to be the same in internal diameter and surface roughness, in order to achieve that constant water level in the transparent constant head permeameter box (Figures 1, 2 and Plate 1).

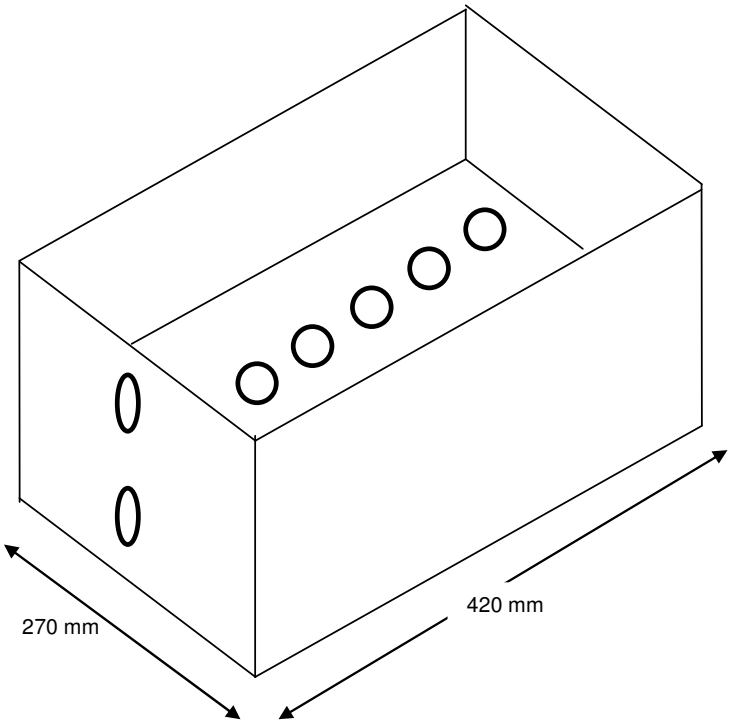

Figure 1: The permeameter box

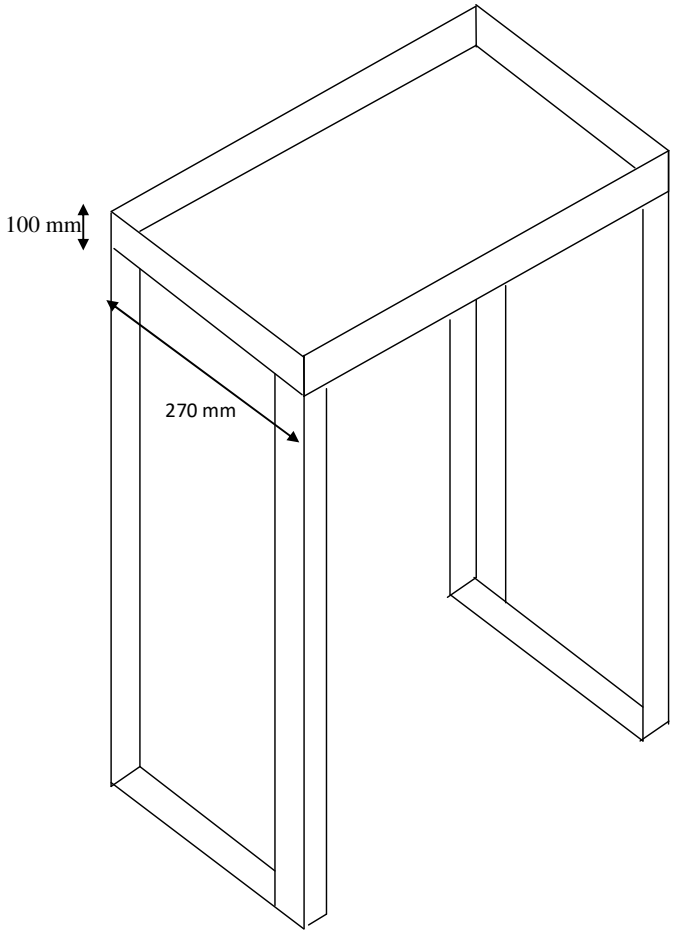

Figure 2: The frame

Plate 1: Permeameter set up

Design calculation

Design of permeameter box

Volume of box

The volume of hopper is determined from the equation.

$$V_h = b \times h \times l$$

Design of frame

Assembling of component parts

The materials and their various sizes as listed in (Table 1) were bought and ready for assembly. The Perspex glass was bought in a flat sheet of 182.88cm x 60.96cm. This flat sheet was then bent with heat from a flame of fire so as to achieve just one seam on the edge of the permeameter box. Then a separate sheet was cut to cover one of the open ends. At a distance ¾ of the entire height of the permeameter box, another layer of the Perspex glass was placed inside to serve as a barrier or support for the core sampler holder. Two holes were then punched at one side of the box – the breadth surface, one at the top and the other at the bottom. The holes were each situated at a little distance from the bottom and about 2.54cm from the top respectively. The top hole was placed that way so as to make the water level high because this is where the outlet pipe was to be fitted. Six holes of about 5.01cm were bored through the Perspex glass layer that was going to serve as a support for the core sampler holder. They were bored equidistant to each other and at equal distances away from the edge of the permeameter box. Smaller holes of about ½ the diameter of the large holes were also bored at equal distances in between the interval of the large holes.

After all these were set, the PVC pipes were cut into different lengths based on the point of use. The drum (storage tank) was also bored at the top and at the bottom of its side. The bottom hole was bored in such a way that it corresponded with the pipe inlet level of the water pump. A pipe was now fitted into the hole with an adaptor fitting to the drum. The pipe extended at a certain distance to the pump. But just before the pump, a non-return valve was coupled with the pipe. Another PVC pipe projecting upwards was fitted from the pump to the permeameter box. The length of this pipe was determined based on the height of the permeameter stand (support). This was now the inlet pipe for water to leave the pump and enter the permeameter box through the bottom hole that was initially bored. Another PVC pipe was fitted with an adaptor from the top hole on the permeameter box to extend up to the tank again. But this time, to the top hole on the tank. The piping here involved

Table 1: Sample sites and notations.

S/N	Plot Location	Sample Notation
1	School of Art and Design	A
2	School of Engineering	B
3	School of Applied Science and Tech	C
4	School of Environmental studies	D
5	School of Business studies	E
6	CEDAP	F
7	Hostel	G
8	Sport complex	H
9	Staff quarters	I
10	Staff Primary School	J

a lot of bends that were taken care of by elbow fittings. This was now the outlet pipe. It was meant to convey the water from the permeameter box back to the drum (tank), giving the system a circulatory process. The core sampler holders were cut at equal heights corresponding to the distance from the Perspex glass support layer to the top of the permeameter box. This was done this way so that the siphon will have a balanced position when in operation (Plate 1).

Testing and evaluation

Three soil samples each were taken from ten different locations around Auchi Polytechnic for testing and evaluating the performance of the improvised permeameter. Table 1 shows the locations where the soil samples were taken. Undisturbed samples were taken from each location at shallow depths using core samplers for bulk density and hydraulic conductivity determination. Samples of disturbed soil particles were collected for textural class analysis.

The core sampler samples were taken to the laboratory and covered with a piece of muslin cloth held in place with a rubber band from the ten locations at a shallow depth and in three replications each. The samples were placed in a shallow bowl with the covered end down, filled with water to a depth just below the top of the samples, and allowed to saturate for 24 hours. The completely saturated soil samples were afterwards removed from the water. Cylindrical core sample holders were also fixed to the samples held in place by the gasket to ensure a tight fitting and to prevent water from passing through the sides of the cylindrical core sampler holder. The water supply to the transparent constant permeameter box was turned on and the samples placed inside the permeameter. A U-tube siphon which is used to connect the water above the soil sample in the sampler holder and the calibrated burette, was filled with water and placed inside the permeameter. As water rose inside the sampler holder, it was transmitted through the U-tube to a measuring burette where the volume 'V' is measured in a given time 't' which is the duration it takes to reach that volume pending on the rate of flow. For accuracy, large volume is used for high flow and small volume for low flow. After the volume has been measured, the siphon is removed and the head of water in the sampler holder and the permeameter are measured (head in and head out) respectively. The data were tabulated and is shown in the Appendix (Table A1). The hydraulic conductivity was calculated using the formula;

$$K = \left(\frac{V}{At}\right)\left(\frac{L}{\Delta H}\right) \quad \text{.....1}$$

Where,

A is the cross sectional area in the sample (cm^2)
L is the length of the sample (cm)
V is the volume of water (cm^3) or (ml)
T is the time it takes to obtain the volume of water (secs)
$\Delta H$is the difference in head (cm)

$$K = \left(\frac{V}{At}\right)\left(\frac{L}{H^{+}-H^{-}}\right) \quad \text{.....2}$$

Where,
H^+ is the head in (cm)
$H^-$is the head out

Bulk density determination

The same soil samples used for the determination of hydraulic conductivity were also used for bulk density determination, except that an oven was introduced to dry the soil sample. Weighing balance was as well used to weigh the samples. The bulk density was determined using the core sampling method. The soil sample was collected from the field using the core sampler with a diameter of 5cm and height 5cm. The samples were oven dried at 110^0C for a period of 24 hours and weighed. The bulk density BD was then computed using a formula given by Smith (1968).

$$BD = \frac{M_d}{V} \quad \text{.....3}$$

Where,
BD = Bulk density (g/cm^3)
M_d= mass of oven dried soil (g)
V = volume of core sampler (cm^3)

Table 2: Textural class and Bulk density of the soils used for the test/

Sample	Sand (g/kg^{-1})	Silt (g/kg^{-1})	Clay (g/kg^{-1})	Textural class USDA	Bulk density (g/cm^3)
A	520	280	200	S.L	0.99
B	720	200	80	S.L	1.12
C	780	100	120	S.L	1.19
D	520	360	120	S.L	1.21
E	540	380	80	S.L	1.08
F	620	160	220	S.C.L	1.18
G	600	220	180	S.L	1.21
H	560	340	100	S.L	1.15
I	620	260	120	S.L	0.98
J	520	380	100	S.L	1.09

Where;
S.L = sandy loam
S.C.L = sandy clay loam

Total porosity

The total porosity of the sampler was determined using the expression below;

$$F = 100\left(1 - \frac{\beta}{2.65}\right) \quad \ldots\ldots 4$$

Where,
β= bulk density (g/cm^3)
2.65 is particle density
F is the porosity

The percentage bulk volume not occupied by solids is the total porosity of that soil. The porosity of a soil is the amount of pore spaces influenced by its physiochemical properties such as percolation, infiltration, aeration and redox status of the soil. The amount of pore spaces (porosity) can be obtained from its density and particle density measurement.

Particle size analysis

For each of the soil sample representing the various plot locations, 50g of the sieved soil was transferred into plastic cups. 100 ml of sodium hexametaphosphate solution was added to the soil and the mixture was shaken in an end to end mechanical shaker for 20 minutes before they were transferred into 1000 ml measuring cylinders. A Hydrometer and thermometer were used to measure the behaviour of each solution and their temperatures were recorded respectively at 40 seconds and 2 hours interval. Blank of the reagents were also run.

Statistical analysis

The calculated saturated hydraulic conductivity (K_{sat}) values from the improvised constant head permeameter, and the Imported Permeameter were analyzed using the T-test Hypothesis. The parameters used in the computation and comparison of the K_{sat} values include the following; average, mean difference and the T-test (T) values.

RESULTS AND DISCUSSION

Textural class and bulk density of sampled soil

Conversion unit:

% to g/kg^{-1} = x 10
g/kg^{-1} to % = ÷ 10

From the Table 2, it can be observed that nine of the sampled soils fell within the sandy loam textural class and with a bulk density range of $0.98g/cm^3$ to $1.21g/cm^3$. The soil sample A6 fell in the sandy clay loam textural class with a bulk density of $1.18g/cm^3$. Bulk density values from literature show that they are in the range of $1.4g/cm^3$ to $1.7g/cm^3$. But the results above show a very different case which could arise as result of the presence of roots and cultivation activities on that particular soil which makes the soil very loose. This can be justified since the soil samples were taken at shallow depth i.e. 0 – 10cm depth.

Saturated hydraulic conductivity

Tables 3 and 4 show the summary of the K_{sat} values obtained from the improvised constant head permeameter, literature (range of values) and Imported Permeameter. The range of values from Table 3 shows that sandy clay loam is from 0.00017cm/s – 0.408cm/s. while that of sandy loam is from 0.00051cm/s – 0.00105cm/s. Table 4 shows that the improvised data results has 0.015cm/s for sandy clay loam and between

Table 3: Hydraulic conductivity data from literature.

Textural class	K_{sat} range (cm/sec)	Mean K_{sat} (cm/sec)
Sandy clay loam	0.158 – 0.447	0.338
Sandy clay loam	0.022	0.022
Sandy loam	0.00067	0.00067
Sandy loam	0.00064 – 0.00131	0.00098
Sandy clay loam	0.00017 – 0.00035	0.00026
Sandy loam	0.00051 – 0.00093	0.00067
Sandy loam	0.000105 – 0.000699	0.00075
Sandy loam	0.000194 – 0.000409	0.00030
Sandy clay loam	0.00031	0.00031

Source: Olorunfem and Fasinmirin, (2011), Musa (2000), Ohize (2019)

Table 4: Hydraulic conductivity data from improvised constant head permeameter and imported Permeameter.

Sample	Saturated Hydraulic conductivity	
	Improvised	Imported
A	0.031	0.16
B	0.059	0.51
C	0.040	0.11
D	0.049	0.35
E	0.038	0.26
F	0.015	0.37
G	0.060	0.55
H	0.047	0.69
I	0.048	0.46
J	0.056	0.29
n	10	10
Mean	0.044	0.375
Mean difference (MD)	0.331	

Table 5: Comparison between improvised, literature and Imported Permeameter K_{sat} values.

Soil type	K_{sat} (cm/sec)		
	Improvised	Literature	Imported Permeameter
Sandy loam	0.048	0.00067	0.38
Sandy clay loam	0.015	0.09	0.37

0.031cm/s – 0.06cm/s for sandy loam. Also the Imported Permeameter data result has 0.37cm/s for sandy clay loam and between 0.11cm/s – 0.69cm/s for sandy loam.

Comparison of saturated hydraulic conductivity

The table above (Table 5) shows a summary of the average of mean K_{sat} values for the two soil types – sandy loam and sandy clay loam, as obtained from the improvised constant head permeameter, Imported Permeameter constant head equipment. The T-Test result between the improvised and literature mean K_{sat} values was 0.8 which is greater than the critical value of 0.05(5%). Hence the hypothesis is accepted and this indicates that there is no significant difference between the K_{sat} values from the improvised constant head permeameter and the K_{sat} values obtained from literature of the same soil type. The T-Test result between the improvised and Imported Permeameter mean K_{sat} values was 0.03 which is less than the critical value of 0.05 (5%). Hence the hypothesis is rejected and this indicates that there is a significant difference between the K_{sat} values from the improvised constant head permeameter and the K_{sat} values obtained from the Imported Permeameter of the same soil type. This difference must have occurred as a result a slight malfunctioning of the Imported Permeameter constant head due to water passage between the core sampler holder and the core sampler. This malfunctioning also might be a recent development as the K_{sat} values obtained from literature

are as far back as 2005 down. Probably, the equipment must have been functioning well then. Details of the T-Test analysis can be seen in the Appendix. Also, from Table 5, K_{sat} value for sandy loam – fine sand fall in the range of 0.001cm/s - 0.003cm/s, while K_{sat} values from the improvised constant head permeameter for sandy loam and sandy clay loam falls in the range of 0.02cm/s – 0.06cm/s (Table 5). It can be observed that there is not much difference in the range of values as this difference could be caused by several factors such as, temperature of water, organic matter content, etc.

Conclusion

The results obtained showed that there was no significant change in the K_{sat} values of the soils from the improvised constant head permeameter and K_{sat} values from past research studies. But there was a slight significant change in the K_{sat} values of the soils from the improvised constant head permeameter and Imported Permeameter constant head permeameter.The constant head permeameter is designed and able to determine hydraulic conductivity of soil samples with particle sizes within the range of 0.001mm – 2mm. There was a basic challenge during the running of the constant head permeameter.
There was challenge of voltage fluctuation as a result of the use of electricity to power the centrifugal water pump. Hence, the following will be recommended:

a. An automatic transformer which will step down the voltage when it is high and step up the voltage when it is low should be put in place.
b. A variable speed water pump can be installed in the system as he revolution of the pump can be controlled.
c. A water tight medium should be put in place between the core sampler and the core sampler holder.

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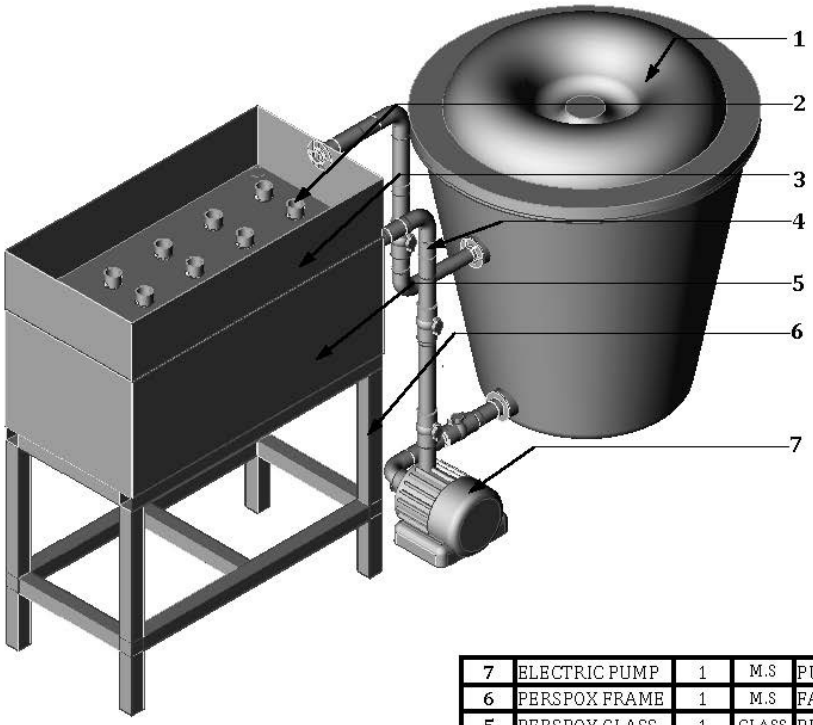
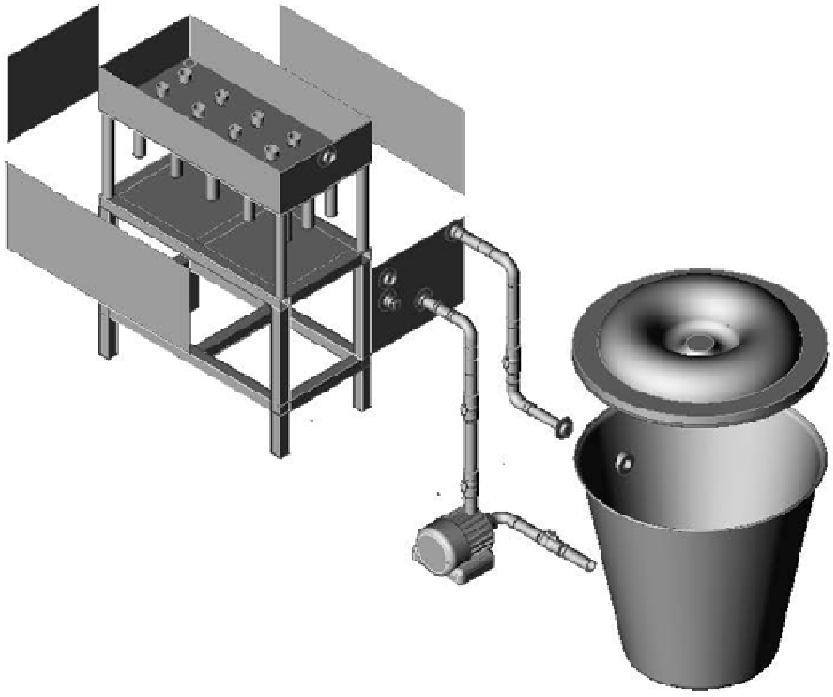
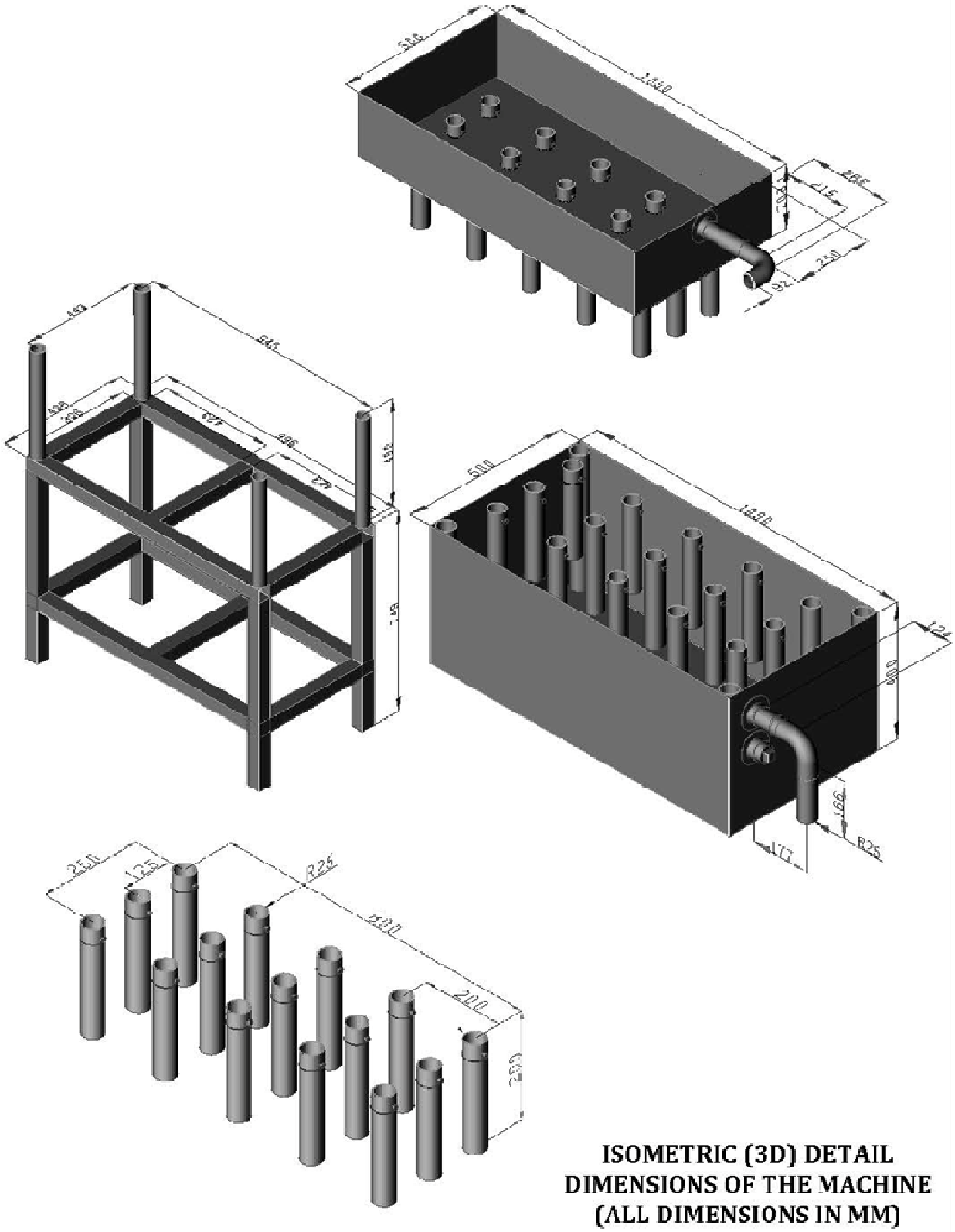
Appendix (Table A1)



ITEM	DESCRIPTION	QTY.	MAT.	REM.
7	ELECTRIC PUMP	1	M.S	PUR
6	PERSPOX FRAME	1	M.S	FAB
5	PERSPOX GLASS	1	GLASS	PUR
4	PVC PIPE	1	RUB	PUR
3	GLASS SIPHON	1	GLASS	PUR
2	OPEN HEAD PIPE	1	M.S	FAB
1	WATER TANK	1	RUB	PUR





ISOMETRIC (3D) DETAIL DIMENSIONS OF THE MACHINE (ALL DIMENSIONS IN MM)