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# ANALYSIS AND APPLICATION OF A NOVEL PLUNGER CUP FOR PERFORMANCE ENHANCEMENT OF POTABLE WATER HANDPUMPS IN INDIA

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**Abstract**
Handpump is an affordable and low-maintenance water extraction equipment. This device has been extensively used throughout the sub-Saharan and Asian countries. The present study includes the loss analysis of potable water handpumps, thereby evaluating the root causes of performance deterioration and development of a novel plunger cup using polylactic acid material (PLA). The present approach attempted to propose certain ideal solutions to mitigate the problems encountered in the use of a manual hand pump. A discharge comparison study of handpumps has been conducted in the Assam village of Sonitpur district investigating various internal and external conditions to address the problem of pressure loss. It was found that the plunger assembly cup wears out due to its continuous reciprocating movement thereby causing the problem. Shore A hardness tests has been conducted for rubber (Buna-N), leather fibre, TPU (thermoplastic polyurethane) and PLA materials. It is found that PLA material gives a higher Shore A value comparatively and is suitably used for the fabrication of the novel plunger cup. The novel plunger assembly cup is developed using 3D print technology. PLA material is found to be more advantageous for use as a plunger cup material in terms of health safety and cost.

***Keywords-***
Shore A hardness, 3D printing technology, potable water handpump, PLA and TPU.

## INTRODUCTION

Handpumps are shallow depth pumps that can be operated with manual human power and utilizes mechanical advantage to move the fluids from underground to greater heights. There are different types of handpump available in the market, most of which are working on the principle of suction-piston-pump system. Handpump is the main source of drinking water in the developing countries (Baumann, E. 2000).The use of handpumps is commonly seen in developing countries such as African and Asian countries. There are a number of handpump manufacturer in India that are capable of manufacturing quality handpumps in a consistent manner. Among these, the leading manufacturer of handpump in India was established in the year 1986. The invention of the handpump can be traced back to the ancient civilization of Mesopotamia (modern-day Iran, Iraq, Turkey, and Syria). Although, it was not a proper handpump still it worth mentioning since it was an important step toward its invention. Shadoof was the first handpump (more accurately) invented by the Egyptians. In India, water well was a very common source of water until handpumps arrived in the Indian Market. Modern handpumps design can be credited to Oscar Carlson who was famous for his Sholapur handpumps followed by India Mark II handpumps. The Mark II handpump has evolved with time continuously with the need and conditions which finally came with minimum effort. Even after the invention of the centrifugal pump, handpump was vastly used because of its inexpensiveness. In a developing country like India where a large part of the population still lives in the rural areas and prefers cheaper devices, the manual handpump provides the best solution for obtaining underground water. It is because of its inexpensive technology, demanding very little complicated maintenance that can be easily carried out by communities for free drinking water (Foster et al 2019). Though there are alternate water-extracting equipment options available in the market, still the manual handpump is considered to be the most inexpensive device for the purpose.

The common problems of handpump are often caused by the malfunctioning of small replaceable parts, owing largely to the degradation of items such as seals (plunger cup), bushings, and bearings (Ottosson eta al 2021). The malfunctioning of the small parts of the handpump often leads to a decrease in the pump discharge. The continuous usage of the handpump causes dysfunctioning of certain associated parts like the plunger cup, valve etc. This may also cause a low discharge thereby increasing the vessel fill-up time. It has been found that the improper working of the plunger cup is the main reason of pressure losses. The plunger cup seals the region between the plunger assembly and the internal cylindrical wall (Chaiya et al 2022). After continuous use, the conventional plunger cup wears out. Wearing out depends on the hardness value of the material. Therefore, replacing the conventional plunger cup material with some hard material is one of the possible solutions (Ottosson et al 2021). After consideration of several factors, two of the possible materials selected were the TPU and PLA for design and development of a novel plunger cup. Major advantage of most types of TPU and almost all types of PLA is that these are biodegradable (Jaso et al 2015).

The present study analyzes the potable water handpumps used usually in India and evaluates the causes of losses. Quantities that have been analyzed include the discharge compression, suction pressure, friction losses, loss due to sudden expansion, plunger cup material friction coefficient, and valve sizing.

Further, the handpump performance has been attempted to be enhanced through design and fabrication of a novel plunger cup using PLA material.

## RESEARCH METHODOLOGY

We have calculated the slip factor to approximate the pressure losses (Heyde M., 1998). The actual rate of discharge normally varies slightly from the theoretical discharge due to failure of the valves to close instantly when the plunger changes direction and to back leakage between the plunger and the cylinder wall during pumping [8]. The slip factor defines the ratio of the difference of the theoretical discharge and actual discharge to the actual discharge.

$$\text{slip} = (Q_t - Q_a) \times \frac{100}{Q_t} \qquad (1)$$

where, $Q_t$ is the product of the cross-section ($A_c$) of the cylinder and the stroke length ($l$) divided by the time taken ($t$).

Pressure losses can be approximated from the reduction of the actual discharge from theoretical discharge. First of all, the slip factor of three different cast iron handpumps is calculated with different duration of usage. The investigation showed that the duration of usage of the plunger cup and the material of the plunger cup was the main factor that resulted in pressure losses in the handpump. In one case, the plunger cup was of leather (duration of usage: 16 months and 5 months) and the other two cases had rubber plunger cups (duration of usage: 4 months and 13 months). The variation of their slip suggested that hardness of the material was important decider for its durability.

Thus, for the plunger cup design requires selection of new material with all the required properties especially with a higher hardness value. Two materials namely, Thermoplastic Polyurethane (TPU) and Polylactic Acid (PLA), with many required features for proper functioning have been considered. The cup is designed using AutoCAD software and its prototype obtained with PLA material in 3D printer. Although, TPU possessed the maximum values of the required properties, it is ignored due to certain limitations posed by the 3D printer (inability to print with flexible fiber).

For analysis of the wear and tear of the piston seal, friction coefficient of the materials has been calculated and compared. Different materials having similar properties are also studied.

### Suction Pressure Calculation

$$P_1 = P_a + \rho g h \qquad (2)$$

Where, $P_1$ is the pipe inlet pressure, $P_a$ is the atmospheric pressure, $\rho$ is water density, $g$ is acceleration due to gravity and $h$ is the water suction head.

**Loss Due to Friction**

The actual discharge can be obtained as

$$Q_a = A_1 V_1 = A_2 V_2 \quad (3)$$

Where, $V_1, V_2$ are inlet and exit velocities, and $A_1, A_2$ are the inlet and exit pipe areas. The frictional head loss is given by equation (4) as

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_f \quad (4)$$

**Loss due to Sudden Expansion**

The head loss due to sudden expansion is given by the following empirical relation as

$$h_L = (1 - \frac{A_1}{A_2})^2 \times \frac{{V_1}^2}{2g} \quad (5)$$

Where, $A_1, A_2$ are the inlet and exit pipe areas, $V_1$ is the inlet velocity and $g$ is acceleration due to gravity

**Plunger Cup Material Comparison**

The net hydraulic force ($F_h$) on the plunger is the product of the net hydraulic pressure ($P$) and the cross-sectional area ($A$) in the horizontal plane:

$$F_h = 0.25 \times \gamma \times H \times \pi \times D^2 \quad (6)$$

As the plunger assembly reciprocates, the static frictional force ($f_s$) between the cylinder and seal-O-ring should be less than or equal to minimum total force $F_{tot,\ min}$ and can be obtained as given in the following equation (7) or (8).

$$f_s \leq F_{tot,\ min} \quad (7)$$

Or,

$$\mu_s N \leq F_{tot,\ min} \quad (8)$$

**Valve Sizing**

The horizontal cross-sectional area of the opening through the valve seat should be equivalent to 40 to 50 percent of the horizontal cross-sectional area of the cylinder opening, therefore

$$\pi\, {d^2}/{4} = 0.5\pi\, {D^2}/{4} \quad (9)$$

The leakage in the manual Indian potable water handpump may be caused due to a number of reasons which may include continuous reciprocating motion of the cup that may change the orientation of the cup; relative displacement of the nuts and bolts due to improper fit; mismatch in the plunger assembly size with respect to cylinder thereby creating a gap between the cylinder walls and the cup; unsynchronized check valve and piston valve; corrosion; improper and untimely maintenance etc.

**Shore Hardness (Durometer) Test**

Before fabrication of the novel plunger cup, the selected materials namely the leather fibre, rubber, PLA and TPU are subjected to the shore hardness test using a durometer to measures the ability of materials resistance to penetration of the spring-loaded needle like indenter. The spring is initially calibrated. The test is also conducted after the cup is fabricated. Conventional materials that are used for manufacturing the plunger cup has maximum 88 Shore A hardness while TPU has a value of 93 Shore A and PLA with 95 Shore A hardness. Other important properties of these materials are high shear strength, oil and grease resistance.

Industrial Engineering Journal
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**Fig.1**. Durometer test on material

**Fig. 2**. Durometer test of cup

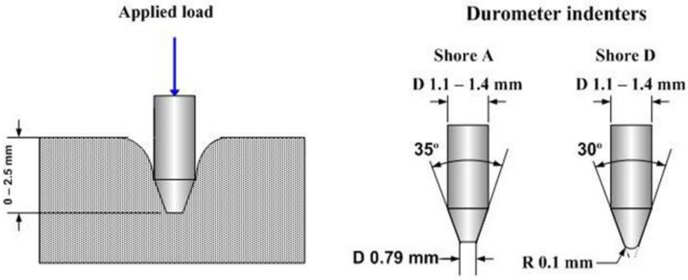


**Fig.3**. Shore hardness test

After considering different factors while prioritizing the hardness value, two materials for designing the plunger cup assembly are considered. They are *Thermoplastic Polyurethane* (TPU) and *Polylactic Acid* (PLA). Although the aim is to extract the plunger cup using the above mentioned materials, but due to the limitation of the 3D printer which cannot print with flexible materials such as TPU, the plunger cup assembly has only been fabricated with PLA. *Thermoplastic Polyurethane* is found suitable for the purpose due to its hardness value and high flexibility. Such materials are created by a polyaddition reaction between diisocynate and one or more diols. It is used for soft engineering plastics or as replacement for the hard rubber. It is a copolymer with a sequence of alternating soft and hard segments.

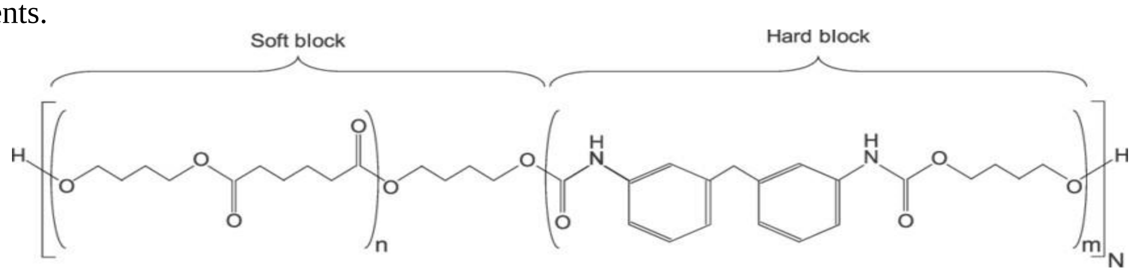


**Fig.4**. Thermoplastic Polyurethane

(*Source: A. Bardin, P. Yves, S. Cerantola, G. Simon, Hydrolytic kinetic model predicting embrittlement in thermoplastic elastomers, 2019)*

Some TPU are biodegradable and others are not, they are non- toxic and safe. PLA has the advantage of being a biodegradable, renewable, hydrolysable and biocompatible in nature. PLA possesses low melting point and low thermal expansion, high strength, and better adhesion property and is heat resisting material. PLA can be used for a number of significant applications including medical and agriculture, packaging industry etc.

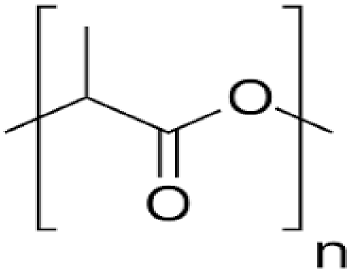

**Fig. 5.** Polylactic Acid

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(*Source: K. Deshmukh, K. Chidambaram, in Biopolymer Composites in Electronics, 2017*)

**RESULTS AND DISCUSSION**

While analysing the potable water handpump, a number of considerations have been made. The final outcome is a result of the use of various physical properties. The handpump efficiency is evaluated using the slip factor. A number of computations are made that include the evaluation of major and minor losses, friction losses, expansion losses etc. For approximating the frictional force impacting the seal-o-ring the hydraulic force and the weight are used. The air leakage loss has been minimized using valve sizing or proper size of the valve w.r.t the cylinder diameter. The slip is limited to 15 percent, preferably 5 percent, which gives a well-designed and maintained pump. Negative slip is possible, and the actual discharge may exceed the theoretical discharge $Q_t$, in terms of swept cylinder volume [8]. We have considered a positive displacement lift pump/suction pump as our experimental equipment. The specifications for the handpump under the present study have been considered from the locally available setup and related calculations are listed in Table 1. The theoretical discharge, $Q_t$ for the present handpump has been computed whose value is shown in Table 1.

**Table 1**. Theoritical discharge calculation for the pump cylinder

| Cylinder | | | |
|---|---|---|---|
| Diameter $(D_c)$ (m) | Area $(A_c)$ $(m^2)$ | Stroke length $(l)$ (m) | Discharge $(Q_t)$ $(m^3/s)$ |
| 0.063 | 0.00312 | 0.3 | $9.35 \times 10^{-4}$ |

Now, for calculation of the actual discharge $Q_a$, we have a bucket of a certain volume $(V_b)$ and fill it up from our experimental handpump. We mark the time required to fill up the handpump, $(t_b)$. The actual discharge can be obtained as given by equation (10).

$$Q_a = \frac{V_{bucket}}{t_b} \quad (10)$$

Table 2 shows the actual discharge of the handpump for a given bucket volume, operated with different cup materials.

**Table 2**. Actual discharge calculations for the constant bucket volume.

| Bucket vol $(V_b)$ $(m^3)$ | Cup material | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | rubber | | leather | | rubber | | rubber | | leather | |
| | $t_b$ (s) | $(Q_a)$ $(m^3/s)$ | $t_b$ (s) | $(Q_a)$ $(m^3/s)$ | $t_b$ (s) | $(Q_a)$ $(m^3/s)$ | $t_b$ (s) | $(Q_a)$ $(m^3/s)$ | $t_b$ (s) | $(Q_a)$ $(m^3/s)$ |
| $10.5 \times 10^{-3}$ | 12 | $8.75 \times 10^{-4}$ | 18 | $5.85 \times 10^{-4}$ | 18 | $5.85 \times 10^{-4}$ | 34 | $3.08 \times 10^{-4}$ | 13 | $8.75 \times 10^{-4}$ |

In Table 2 it can be seen that time taken to fill the same volume of the bucket may be same or different with same or different discharges when operated with same of different cup materials. Using the computed theoretical and actual discharges from Tables 1 and 2 respectively, we obtained the slip values for each actual discharge component as shown in Table 3.

**Table 3.** Evaluation of slip for cup materials with different duration of usage.

| Discharge $(Q_t)$ $(m^3/s)$ | $9.35 \times 10^{-4}$ | | | | |
|---|---|---|---|---|---|
| $(Q_a)$ $(m^3/s)$ | $8.75 \times 10^{-4}$ | $5.85 \times 10^{-4}$ | $5.85 \times 10^{-4}$ | $3.08 \times 10^{-4}$ | $8.1 \times 10^{-4}$ |
| Cup Material | Rubber | Leather | Rubber | Rubber | Leather |
| Usage | New | 16 months | 4 months | 13 months | 5 months |
| Slip % | 6.42 | 37.4 | 37 | 67.4 | 13.3 |

From Table 3, it is observed that the percentage of slip vary with respect to usage duration and types

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of cup material. In Table 3, the slip percentages for the new rubber cup material and the leather material with usage 5 months are lesser than 15% which indicate a properly maintained pump which may be mostly attributed to the use of new and lesser usage of material for the cup. The various losses in the handpump have been computed and listed in Table 4.

**Table 4**. Evaluation of losses in the handpump operation

| Losses | | |
|---|---|---|
| Suction pressure loss (kPa) | Frictional head loss (m) | Sudden expansion loss (m) |
| 199.425 | 0.078 | 0.063 |

In Table 4, the suction pressure has been computed considering the expression given by equation (2) through evaluation of the atmospheric and the static pressures. The frictional head loss is computed using the expressions of (3) and (3a) respectively. For the evaluation of the sudden expansion loss, expression (4) is used after computing the inlet and exit pipe areas and the inlet water velocity.

The net hydraulic force ($F_h$) on the plunger is the product of the net hydraulic pressure (P) and the cross-sectional area (A) in the horizontal plane, i.e. $F = P \times A$ . The net hydraulic pressure ($P$) is the product of the head ($H$) and the specific weight of water, ($\gamma$). Therefore, $P = \gamma H$ and for a circular plunger, its area (A) expressed in terms of plunger diameter (D) is

A = $\boldsymbol{\pi}$×D $^2$/4. The total force acting on the pump is calculated after evaluating the net hydraulic force, ($F_h$) and the force due to the plunger assembly weight ($F_w$). Table 5 shows the total forces acting on the handpump when it is subjected to pushing and pulling forces.

**Table 5**. Evaluation of total forces on a handpump.

| $F_h$ (*Newtons*, N) | $F_w$ (*Newtons*, *N*) | $F_{tot}$ (handle pushed downward) (*Newtons*, *N*) | $F_{tot}$ (handle pulled upward) (*Newtons*, *N*) |
|---|---|---|---|
| 213.953 | 102.122 | 316.075 | 111.831 |

From Table 5, it is seen that during the downward push of the handpump handle, the total force is the sum of the net hydraulic force and the force due to weight of the plunger assembly whereas, in the upward pulling case, the total force is actually the difference between the two forces.

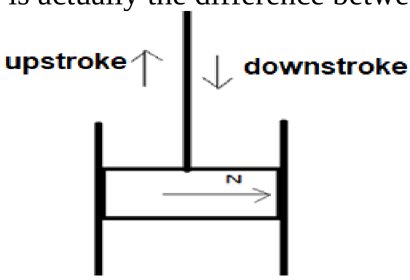



**Fig. 6**. Direction of forces acting on plunger assembly

There are two kinds of seal-o-ring on the basis of material used in their manufacturing. They are leather and rubber piston seals. The friction coefficients for the rubber and leather material are 0.60 and 0.31 respectively considering static friction and 0.58 and 0.50 are the dynamic coefficient values. The static values can be computed when the plunger assembly is yet to reciprocate whereas the dynamic values are obtained during the reciprocating motion of the plunger assembly. Thus, we find that the change in the friction value of the leather and rubber with respect to the cast iron (cylinder inner interface) depends on the coefficient of friction of each material. Moreover, the wear and tear of the piston seal material is directly proportional to friction between the interface.

From the last two statements and the coefficient of friction values and under similar conditions, the wear and tear of rubber will be more than leather material. The designed and fabricated plunger cup is shown in Fig. 7 (a) and (b) and in Figs. 8(a) and (b) respectively.

**Fig.7 (a)** Plunger cup design front view

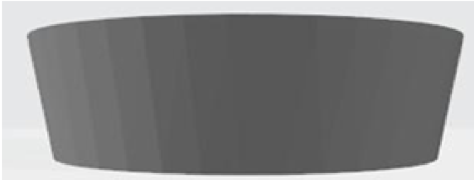
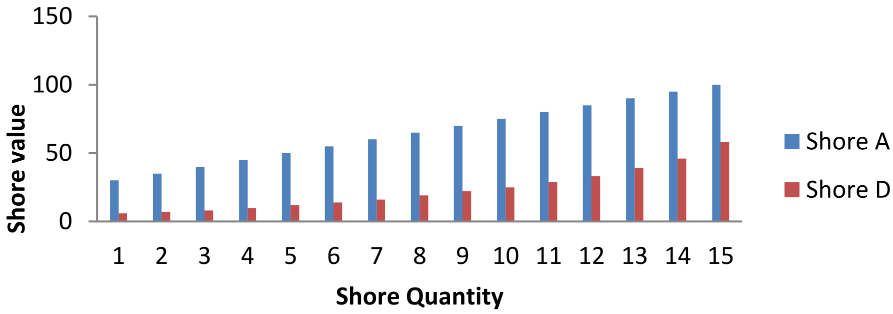


**Fig.7 (b)** Plunger cup design top view

**Fig. 8 (a)** PLA plunger cup front view

**Fig. 8 (b)** PLA plunger cup top view

The value of Shore hardness varies from 0 to 100. The maximum penetration possible is 2.5 to 2.54 mm. This value corresponds to minimum shore hardness value that is 0. No penetration is equivalent to Shore A 100.




Shore hardness conversion between Shore A and Shore D

A rough estimate on the cost effectiveness of PLA material plunger cup has been made The 3D printer TPU Filament and PLA filament cost Rs 1250 for 0.5 Kg spool. The weight of the Plunger Cup is 6.5 g. Thus, the total no. of plunger cups that can be made from 0.5 kg spool = (500/6.5) = 76.92 =76. Therefore, cost of each PLA plunger cup (in terms of the filament cost) comes out to be Rs 16.45. Moreover, this cost has been estimated without consideration of other related expenses such as electricity to run the 3D printer, cost of labour, transportation etc. However, the total cost by addition of all expenses will be less than Rs 30 when mass production is taken into account.

## CONCLUSION

From the slip factor calculations of the different handpumps, it is clear that with different materials of plunger cup and duration of its usage the discharge varies. As the duration of usage of the plunger cup increases, it starts to wear out. This finally results in the reduction of the discharge. The reduction in the discharge also suggests that pressure losses are high. Leather, having a higher value of hardness, wears out slowly in comparison to rubber, which has a lower value of hardness.

The results of the present study and analysis have been summarized in the following:

- By testing hardness values of various materials and considering other properties, we found that TPU and PLA are among the few materials that could suitably replace the conventional plunger cup material.
- The calculation of Shore hardness using Durometer provided the order of hardness as rubber < leather < TPU < PLA. This makes TPU and PLA more durable in comparison to the rubber and leather materials.
- If property-wise TPU and PLA are compared then the mechanical properties of TPU are more favorable than a plunger cup comparison. Since the hardness values of both the material is almost

same (TPU: 93 shore A and PLA: 95 shore A) so the next important mechanical property that becomes the decider is the flexibility of material.

- Since the plunger cup has to adjust itself between the walls of the cylinder and the plunger assembly, it must be enough flexible. Flexibility of TPU is found to be much better.
- From the safety point of usage and biodegradability, PLA is a better choice. All kinds of PLA are biodegradable but all types of TPU aren't.
- PLA is non-toxic though there is no clear evidence regarding the toxicity of TPU. However proper research on their use as a plunger cup considering human health will be remarkable.
- The handpump works as the main source of drinking water for most of the families of rural as well as to some extent in urban and semi urban areas. Hence, the cost effectiveness of the PLA and TPU plunger cup plays an important role. The cost estimate showed that the cost of the PLA plunger cup is not high compared to the leather cup. Moreover, PLA plunger cup will require lesser replacement in comparison to the leather plunger cup.

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