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Development of Abrasive Selection Model/Chart for Palm Frond Broom Peeling Machine Design

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Abstract
A model for predicting the friction required by a palm frond broom peeling machine for effective peeling of palm leaf to broom bristle and a chart for selecting the best abrasive material for this machine's peeling operation were developed in this study using mechanistic modeling method. The model quantified the relationship between the coefficient of friction and other operational parameters of this machine while the abrasives selection chart constitutes a plot of this measured friction parameter against the abrasive materials used in palm frond broom peeling machine fabrication. The values of the coefficient of friction of palm leaf on different abrasive materials used in this plot were determined from experimental study of the effect of moisture content level of naturally withered palm leaves (uninfluenced by external forces) on their coefficient of friction with the abrasives. Results revealed the average moisture content of palm leaf this machine can peel effectively as 6.96% and also that the roughest among the abrasives that approximate the coefficient of friction for a specific design of this peeling machine gives maximum peeling efficiency. Thus, the roughest among the abrasive materials that approximate the coefficient of friction for a specific design of this machine should be selected and used for its fabrication and operation.

Key Words: Abrasive, broom bristle, Chart, friction, Oil palm leaf, peeling, machine design

I. INTRODUCTION

A Broom is an assembled and woven bristles (which may or may not be tied to a handle), used for collection and disposal of dust, trash and debris in places of business, homes and public spaces [1]. Broom has been in existence for centuries and it is the most popular tool used for basic floor cleaning [1, 2]. In addition to cleaning, broom also has religious, ornamental and political applications. Brooms are often found hanging over residential gates and home doors with the bristles facing towards the entrance direction as a symbol of protection against evil spirits and negative energies for all who dwell within while the scented versions of besom brooms are used as craft for indoor decorations [2, 3]. Broom are also used in matrimonial rituals to symbolize a union among African-Americans and as a logo of a registered political party in Nigeria, All Progressive Congress (APC) indicating the party's aim of sweeping out corruption in this nation [4, 5]. Broom bristle are made from a variety of materials which may be organic or synthetic. Organic broom bristle are made from sorghum vulgere (broom corn), birch twigs, oil palm leaves, coconut leaves and other dried stiff grass while synthetic bristles are made of nylon, Poly Vinyl Chloride or tampico [6, 7]. Each bristle variety features different qualities of stiffness, durability and liquid absorbency. Softer fibers are good for push broom bristles in an auto repair shop because they are able to absorb oil or fuel spills in small quantities than the less absorbent and rigid bristle materials [6]. Plastic brooms merely move dirt around while most bristle made from natural stalks absorb dirt, dust and wears very well, and are moisture-resistant [6].

In many developing countries, especially in Nigeria, organic broom compositions are very common, prominent among them is the broom made from oil palm leaf (Fig. 1), due to the abundance of oil palm plant in this region than other organic broom bristle sources.

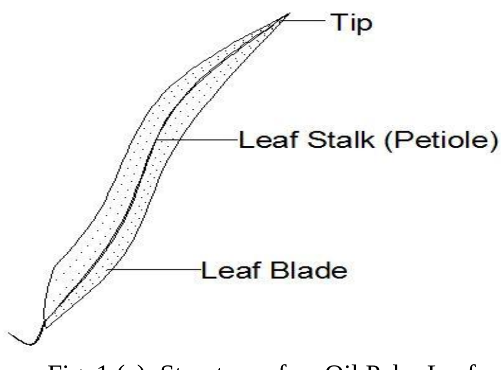

Fig. 1 (a): Structure of an Oil Palm Leaf

Fig. 1 (b): Brooms made from Oil Palm Leaf

Production of broom bristles from oil palm leaves involves harvesting of the leaves from its plant, partial drying of the leaves (for fresh leaves only), detachment (peeling) of the leaf's blade from its petiole (stalk) which constitutes the broom bristle, assembling and weaving of the bristles during which a handle may be attached as desired. Although, the mechanized assembling and weaving operations in broom production from other sources are adoptable in palm leaf broom making, none of the existing technologies is adequate for the peeling process because the palm leaf geometry is not compatible with those of other organic broom bristle sources whose processing have been fully mechanized. Thus, the peeling of palm leaves to broom bristles in this region continued as craft production/manual operation involving scraping off the leaf's blade from its petiole using sharp edged objects such as knife and razor. In order to reduce drudgery and risk involved in this manual peeling process, Nwankwojike [8], designed and developed a palm frond broom peeling machine shown in Fig. 2.

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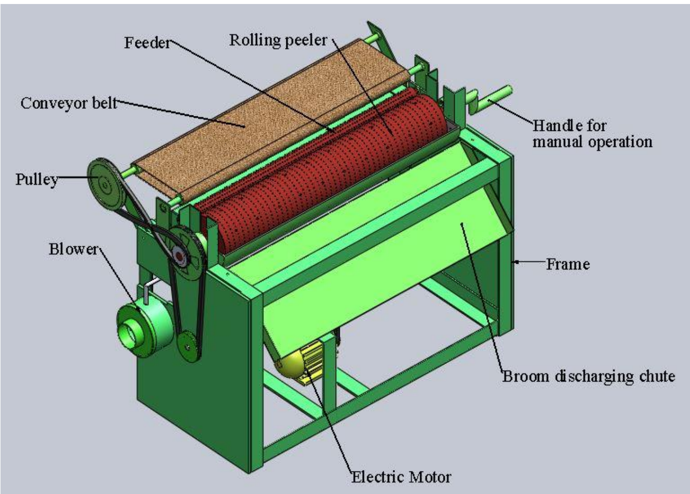

Fig. 2: Palm frond broom peeling machine

This machine produces palm leaf broom bristle by rubbing off the leaf's blade from its petiole (leaf stalk) as the leaf rolls inside a slit between the abrasive surfaces of its rolling and stationary peelers. The leaf is fed into the slit using a conveyor belt and a feeder while the leaf stalk (broom bristle) processed is discharged through its chute. The dust of the leaf blade rubbed off is removed from the peeling slit using a blower connected to the perforated roller of the peeling unit. Thus, the peeling action of this machine depends on the angular velocity of its rolling peeler relative to the stationary peeler and the coefficient of friction between the leaves and the abrasive coated surfaces of the peeing unit. The rolling peeler's speed depends on its drive mountings and transmissions while the coefficient of friction depends on the nature of the abrasive used and moisture content of the palm leaf being peeled. Since the performance of this peeling machine depend on the interaction of these parameters, there is need to establish a procedure for predicting appropriate grit of abrasive cloth or paper for any given palm frond broom machine design in order to ensure its effective operation after fabrication. This requires investigating the effect of moisture content of harvested oil palm leaves on their coefficient of friction with various emery materials and mathematical modeling of the interaction of the peeling friction with other operational parameters of this machine.

The effect of moisture content of palm leaf on its coefficient of friction with different abrasive materials/surfaces in the design and selection of appropriate abrasive material/ grit for palm frond broom peeling machine fabrication is in accord with the works of [9], [10], [11] and [12] which stressed that the knowledge of coefficient of friction of agricultural products on various structural materials/surfaces at different moisture content levels is very important in the analysis and design of post-harvest handling, processing and storage equipment. Development of mathematical model quantifying the friction required for the peeling of palm leaf to bristle in terms of other parameters of this machine is very necessary because it is the predicted value of this friction that will be used in selecting the best material/grit of the abrasive from the experimental data of coefficient of friction of palm leaf on different abrasive materials. This is in line with Mihir [13], which revealed that mathematical modeling helps in the choice of the best system parameters in design. Thus, a model/chart used for the prediction and selection of an appropriate abrasive for a palm frond broom peeling machine during its design was developed in this study.

II. MATERIALS AND METHODS

The mathematical model that quantified the frictional parameter (coefficient of friction) required at the surfaces of the rolling and stationary peelers of palm frond broom peeling machine in terms of other operational parameters was developed using mechanistic modeling approach to ensure its universal application. This model prediction is used for selecting the best grit of abrasive required for any given design of palm frond broom peeling machine from the abrasive selection chart (a plot of coefficient of friction, µ against abrasive cloth/paper types). Mechanistic modeling technique was applied in this study because replication of different sizes of this broom peeling machine entails variation in its design/operational parameters, hence the need for a non-data dependent and physical law based model (mechanistic model) which will provide wide application and realistic predictions. Hence, the application of iterative steps of mechanistic modeling described by [13], [14] and [15] which include system (or sub system) description; choosing of symbols/sign conventions for the process variables; applying fundamental laws of science and other constitutive secondary relations of the interactions between the process variables with some assumptions to obtain the governing equations of the system; Solving and verification of dimensional homogeneity of the derived equation and validation of the model from data collected from the process performance.

The chart for selecting the grits of abrasive clothes or papers required for effective operation of palm frond broom peeling machine was developed by plotting coefficient of friction of palm leaves on different abrasives materials against the abrasive materials investigated. The coefficient of friction was experimentally determined using ten samples of oil palm leaves that withered naturally (usually harvested along with ripe fruit bunch) and different types/grits of abrasives that can peel the palm leaves effectively without breaking the extracted bristle. Withered leaves were used because cutting of fresh palm frond affects the palm fruits yielding capacity of a palm tree adversely and also a broom made from fresh palm leaf requires drying before it can be used for sweeping. Thus, the broom peeling machine was designed to peel this category of partially dry palm leaves. The test was conducted at the Department of Agricultural and Bioresources Engineering Laboratory, Michael Okpara University of Agriculture, Umudike. The leaves were obtained from the oil palm plantation of the same University while the abrasive clothes and papers were bought from Ariara market, Aba in Abia State of Nigeria.

The coefficient of friction of the palm leaves on the abrasive materials were determined using the inclined plane method as described by [16]. Each test involves covering the surface of an adjustable tilting table with an abrasive cloth or paper before placing the palm leaf sample on it, after which the surface was gradually tilted until the leaf is about to slide down. The vertical distance or height of inclination of the surface when the specimen is about to slide was measured and recorded. This test was repeated for all the ten leaves sample with each of abrasive materials, one after another. Each test with a particular leaf/abrasive specimen combination involved three trials with the average reading taken. The coefficient of friction, μ_p between the palm leaves and the abrasives were computed using the following relationship.

$$\mu_p = \frac{h}{l} \tag{1}$$

Where h and l are the vertical (height) and horizontal distances of the inclined surface just before the palm leaf specimen slides.

The moisture content of each palm leaf used in this test was determined using ASTM D4442 standard procedure in which the leaf sample was weighed before and after drying in an oven until no change in its mass was observed [17]. The moisture content was evaluated from the data obtained using the following relation.

$$M_C = \frac{M_I - M_D}{M_D} \tag{2}$$

Where M_C = Moisture content, M_I = Initial mass of sample and M_D = dry-oven mass of sample.

The model/chart prediction capability at varied levels of some operational parameters of an existing palm frond broom peeling machine was evaluated using five different tests. In each test, the number of well peeled broom sticks, m_g and scraps, m_s which consists of those that were not peeled well were counted and used to compute the peeling efficiency, η (%) of the machine from the following relations;

$$\eta(\%) = \frac{m_g}{m_g + m_s} \tag{3}$$

The data obtained from this investigation were tested and compared (at α = 0.05) using Analysis of Variance (ANOVA).

III. MODEL DEVELOPMENT

The description of the palm frond broom peeling machine by [8] as contained in section I above revealed that it peels and discharges the broom bristles using the friction and relative motion of its peelers. The transmissions and mountings of this machine (Fig. 3) shows that the prime mover (electric motor) drives the rolling peeler via the primary driving shaft while the shaft of this peeler drives the conveying unit by means of belt/pulley systems.

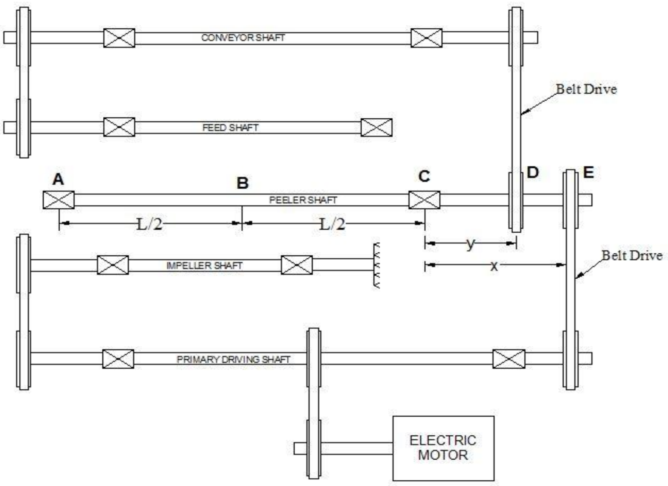

Fig. 3: Transmissions and mountings of palm frond broom peeling machine

Thus, the drive torque, T is used for the motion of the rolling peeler and to overcome the friction between the palm leaf and the abrasives, if power loss to the transmission elements is neglected. Therefore;

$$T = T_f + T_r \qquad (4)$$

Where T_f and T_r constitute torques due to the friction used for the peeling operation (frictional torque) and rotary motion of the roller respectively. The torque developed by the friction between the peelers surfaces as the rolling peeler rotates was determined as Equation (5) from force-distance relation [18, 19].

$$T_f = \mu_p W_1 r \qquad (5)$$

W_1 = Weight of the rolling peeler shaft and roller, N
μ_p = Coefficient of friction of palm leaf on the peeling surfaces
r = Radius of the roller, m

Since the peeler shaft is subjected to both bending and twisting due to its weight and those of the roller and transmission elements mounted on it, T_r is mathematically expressed as Equation (6) based on the relationship between the equivalent torque on a shaft subjected to both bending and twisting forces given by [20, 21].

$$T_r = \sqrt{M_b^2 + M_t^2} \qquad (6)$$

Where *Mb* and *Mt* are maximum bending and twisting moments on this shaft respectively.

Analysis of the force diagram of this rolling peeler shaft (Fig. 4) based on the concept that bending moment is maximum or minimum at a section where resultant shear force is either zero or changes sign [22] revealed the bending moment at point B and twisting moment at point E on this shaft as maximum.

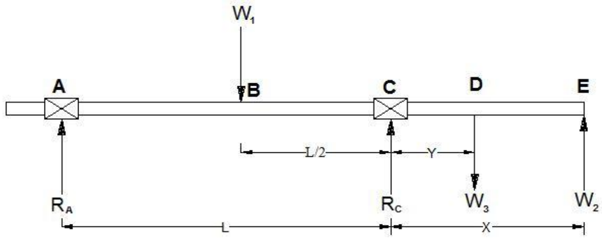

Fig. 4: Force diagram of the rolling peeler shaft

Thus, the maximum bending moment acting on the rolling peeler shaft was quantified as follows;

$$M_b = \frac{R_A L}{2} \qquad (7)$$

Where L is the distance between the shafts bearing supports and R_A, the bearing reaction at point A was quantified as;

$$R_A = \frac{LW_1 + xW_2 - y(W_2 + W_3)}{2L} \qquad (8)$$

Hence;

$$M_b = 0.25LW_1 + 0.5(xW_2 - yW_3) \qquad (9)$$

W_2 = Net reaction due to driven pulley on this shaft, N
W_3 = Net reaction due to driving pulley on this shaft, N
x = Distance between the closest bearing to the drives mounted on this shaft and driven pulley, m
y = Distance between the closest bearing to the drives mounted on this shaft and driving pulley, m

The maximum twisting moment on this shaft was derived from the fundamental relations of belt/pulley drive given by [20] as;

$$M_t = (T_i - T_j)\frac{D_2}{2} \qquad (10)$$

$$T_i = \sigma a - 0.25mD_2^2\omega^2 \qquad (11)$$

$$T_j = \frac{T_i}{\exp\left[\mu cosec\beta\left(3.142 - 0.035\sin^{-1}\left(\frac{D_2 - D_1}{3D_1 + D_2}\right)\right)\right]} \qquad (12)$$

Where;
T_i = Tension on the tight side of the drive belt, N
T_j = Tension on the tight side of the drive belt, N
r = Radius of the peeling roller, m
ω = Angular velocity of rolling peeler, rads^{-1}
μ = Coefficient of friction between the pulley and belt of the primary/rolling peelers shafts drive.
σ = Maximum safe stress of this drive belt, N/mm^2
m = Mass per unit length of this drive belt, kg/m
a = Cross sectional area of this drive belt, mm^2
β = Half of the groove angle of this drive pulley, ^{o}
D_1= Diameter of the peelers driving pulley, m
D_2= Diameter of the peelers driven pulley, m.

Substituting Equations (11) and (12) into (10) gives (13);

$$M_t = 2D_2\sigma a - 0.13\,mD_2^3\omega^2)(1 - \frac{1}{\exp\left[\mu cosec\beta\left(3.142 - 0.035\,sin^{-1}\left(\frac{D_2-D_1}{3D_1+D_2}\right)\right)\right]} \quad (13)$$

Substituting Equations (9) and (13) into (6) gives;

$$T_r = \sqrt{[0.25LW_1 + 0.5xW_2 - 0.5yW_3]^2 + \left[(0.5D_2\sigma a - 0.13\,mD_2^3\omega^2)(1 - \frac{1}{\exp\left[\mu cosec\beta\left(3.142 - 0.035\,sin^{-1}\left(\frac{D_2-D_1}{3D_1+D_2}\right)\right)\right]}\right]^2} \quad (14)$$

Substituting Equations (5) and (14) into (4) gives;

$$T = \sqrt{[0.25LW_1 + 0.5xW_2 - 0.5yW_3]^2 + \left[(0.5D_2\sigma a - 0.13\,mD_2^3\omega^2)(1 - \frac{1}{\exp\left[\mu cosec\beta\left(3.142 - 0.035\,sin^{-1}\left(\frac{D_2-D_1}{3D_1+D_2}\right)\right)\right]}\right]^2} + \mu_p W_1 r \quad (15)$$

This torque relates with its drive power, P as follows [18];

$$P = \omega T \quad (16)$$

Substituting Equations (15) into (16) and solving for μ_p gives;

$$\mu_p = \frac{P\omega - \sqrt{[0.25LW_1 + 0.5xW_2 - 0.5yW_3]^2 + \left[(0.5\sigma a - 0.13\,mD_2^3\omega^2)(1 - \frac{1}{\exp\left[\mu cosec\beta\left(3.142 - 0.035\,sin^{-1}\left(\frac{D_2-D_1}{3D_1+D_2}\right)\right)\right]}\right]^2}}{W_1 r} \quad (17)$$

IV. RESULT AND DISCUSSION

Experimental results revealed that P120, P100, P80, P60, P50, P40, P36, P30 and P24 produced satisfactory peeling without damage to the broom bristles extracted, the extra coarse macrogrit P12, P16 and P20 abrasive broke the bristles after peeling while the very fine macro grit and all the micro grit abrasives (P150 to P2500) did not peel the palm leaves effectively. Table 1 shows the moisture content of palm leaves harvested along with the fruit bunch and their coefficient of friction with the nine abrasives grits that peel the leaves effectively. Analysis of results presented in this table indicates 6.96% as the average moisture content of palm leaves, this design of broom peeling machine can peel effectively. Analysis of Variance of the data presented in Table 1 revealed no significant difference (at α = 0.05) in the coefficient of friction of the palm leaves at this moisture content level on the same abrasive material/grit but significant difference in the coefficient of friction of the leaves on different abrasive materials/grits. The coefficient of friction obtained in this investigation did not follow the usual trend of "the rougher the surface the greater the value of the coefficient of friction" due to varying combination of backing, grit and bond materials of these abrasives. The evaluation of the developed model (Equation 17)/chart (Fig. 5) predictions shown in Table 2, revealed that the roughest abrasive which approximates a coefficient of friction value provides highest peeling efficiency. Thus, the roughest abrasive that approximates a specific coefficient of friction predicted with respect to a given design parameters of the broom peeling machine should be selected for its operation.

V. Conclusion

A model/Chart for selecting best abrasive grit required for the fabrication of palm frond broom peeling machine was developed in this study. Analysis of the developed model/chart predictions revealed that roughest abrasive material associated with specific coefficient of friction predicted for a given design/operational parameters of this broom peeling machine provides maximum peeling efficiency and should be selected among other materials that approximate the same coefficient of friction value for its effective operation.

Table 1: Moisture Content of Withered Palm Leaves and Their Coefficient of Friction with Different Abrasives

S/No.	**Abrasive Materials/Moisture Content/Coefficient of Friction**																	
	P120		**P100**		**P80**		**P60**		**P50**		**P40**		**P36**		**P30**		**P24**	
	M_c (%)	**μ**	**M_c (%)**	**μ**	**M_c (%)**	**μ**	**M_c (%)**	**μ**	**M_c (%)**	**μ**	**M_c (%)**	**μ**	**M_c (%)**	**μ**	**M_c (%)**	**μ**	**M_c (%)**	**μ**
1	6.75	0.75	6.75	0.87	6.75	0.59	6.75	0.88	6.75	0.95	6.75	0.53	6.75	0.43	6.75	0.63	6.75	0.80
2	6.92	0.69	6.92	0.92	6.92	0.69	6.92	0.96	6.92	0.96	6.92	0.51	6.92	0.45	6.92	0.65	6.92	0.84
3	7.04	0.70	7.04	0.91	7.04	0.80	7.04	0.97	7.04	0.94	7.04	0.43	7.04	0.53	7.04	0.70	7.04	0.85
4	7.11	0.63	7.11	0.85	7.11	0.84	7.11	0.87	7.11	0.97	7.11	0.56	7.11	0.52	7.11	0.69	7.11	0.87
5	6.93	0.65	6.93	0.90	6.93	0.85	6.93	0.93	6.93	0.95	6.93	0.47	6.93	0.45	6.93	0.61	6.93	0.79
6	7.01	0.63	7.01	0.95	7.01	0.77	7.01	0.94	7.01	0.98	7.01	0.46	7.01	0.61	7.01	0.75	7.01	0.79
7	7.11	0.71	7.11	0.81	7.11	0.79	7.11	0.82	7.11	0.96	7.11	0.52	7.11	0.47	7.11	0.72	7.11	0.74
8	6.98	0.64	6.98	0.93	6.98	0.72	6.98	0.87	6.98	0.94	6.98	0.47	6.98	0.51	6.98	0.67	6.98	0.75
9	6.75	0.67	6.75	0.91	6.75	0.84	6.75	0.97	6.75	0.97	6.75	0.53	6.75	0.52	6.75	0.69	6.75	0.80
10	7.03	0.70	7.03	0.95	7.03	0.74	7.03	0.97	7.03	0.97	7.03	0.47	7.03	0.51	7.03	0.68	7.03	0.84
Average	**6.96**	**0.68**	**6.96**	**0.90**	**6.96**	**0.76**	**6.96**	**0.92**	**6.96**	**0.96**	**6.96**	**0.50**	**6.96**	**0.50**	**6.96**	**0.68**	**6.96**	**0.78**

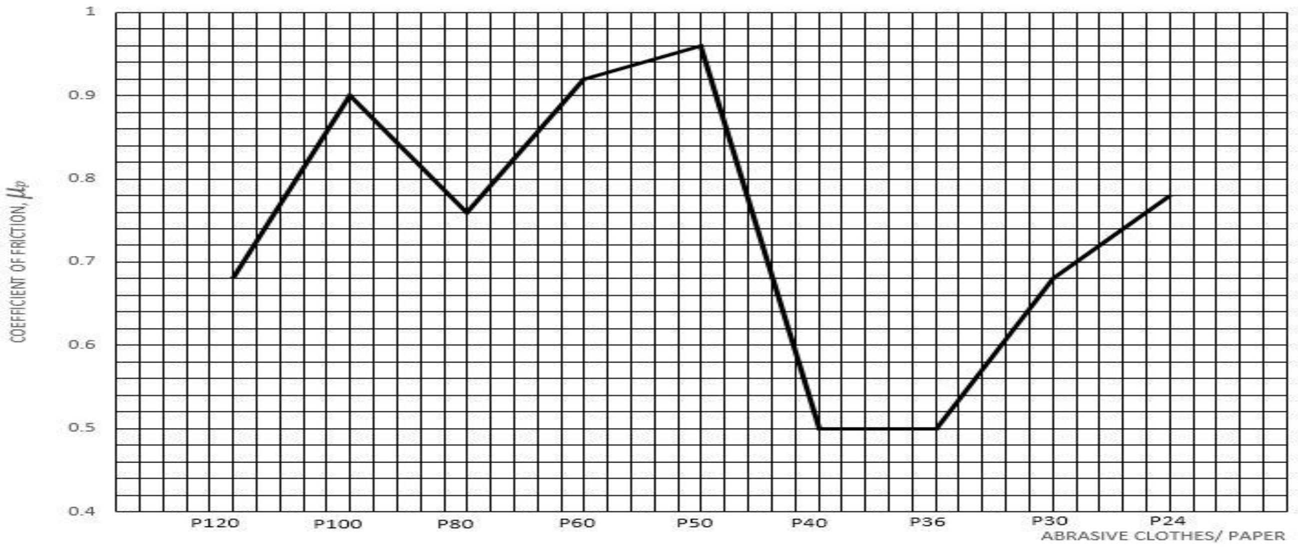

Fig. 5: Abrasive Selection Chart for Palm frond broom peeling machine fabrication

Table 2: Evaluation of the Model/Chart Predictions

Model Parameters /Trials	**I**	**II**	**III**	**IV**	**V**
r (m)	0.08	0.10	0.09	0.12	0.08
m (kg/m)	0.108	0.108	0.108	0.108	0.108
σ (N/mm^2)	2.10	2.10	2.10	2.10	2.1
μ	0.30	0.30	0.30	0.30	0.30
a (mm^2)	81.00	81.00	81.00	81.00	81.00
N (rpm)	793.53	793.53	900.00	600.00	1100.00
D_2 (m)	0.17	0.17	0.22	0.18	0.17
D_1 (m)	0.07	0.07	0.10	0.05	0.07
W_3 (N)	96.91	96.91	140.75	112.5	96.91
L (m)	1.00	0.90	1.20	1.00	1.10
W_1 (N)	50.73	50.45	60.32	73.79	50.73
W_2 (N)	77.86	77.86	101.50	50.7	77.86
x (m)	0.15	0.18	0.13	0.18	0.15
y (m)	0.10	0.10	0.08	0.10	0.10
P (W)	1850.00	1850.00	2650.00	1700.00	2550.00
μ_p	**0.88**	**0.73**	**0.56**	**0.61**	**0.51**
Selected Abrasive	**P40**	**P24**	**P30**	**P30**	**P30**
Peeling Efficiency (%)	**96.03**	**95.50**	**92.30**	**97.30**	**91.60**

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