Empirical Model for Estimating the Physical/Mechanical Properties of Clay/Cement Tiles.

O.S. Olokode, Ph.D.

Department of Mechanical Engineering, University of Agriculture
PMB 2240, Abeokuta, Nigeria.

E-mail: engr_olokode@yahoo.com

ABSTRACT

This paper reports the results of an investigation carried out on the empirical models for estimating the physical/mechanical of clay/cement tiles using "regression equation".

The physical properties measured are percentage water absorption, bulk density and mechanical properties like modulus of rupture and compressive strength of tiles, respectively. Both physical/mechanical properties are dependent variables while independent variable is the value of percentage clay or percentage silica used for the experimental tiles. Experimental results of the properties of tiles produced were found to fulfill or present better values up till percentage clay (X) in mixture of 10-60%, corresponding to percentage silica in mixture of 70-20%, with 20% cement addition are given for percentage water absorption(8.65-14.49%); A=(7.05+0.14(X); bulk density (1.73-2.08g/cm^3; B=(2.15-6.1 × 10^{-3}(X); modulus of rupture (58.22-105.55MPa; M=42.4+3.3X0.052X^2) and compressive strength (21.77 to 45.29MPa; C= 4.53+1.84X - 0.026 X^2), respectively.

(Keywords: clay, cement, tiles, regression, water absorption, bulk density, modulus of rupture, compression, compressive strength)

INTRODUCTION

Tiles are thin slabs used for roofing, flooring, paving, or making drains. They may be made of clays burnt in kilns or concrete. Tiles can be classified according to usage into three kinds namely: roofing tiles, flooring or paving tiles, and wall and drains tiles (Singh, 1979). The manufacturing of ceramics tiles involves careful preparation (Peter Sham 1984) of clay and extrusion process (Adeyemi, 1987 & 1989) to be followed by drying and firing operations (Grimehaw 1971; Stafford 1980) and /or finally glazing operations.

Emphasis has been on ceramics tiles made from clays and other ceramics materials which may be either "glazed" or "unglazed" to acquire specific physical properties and characteristics after firing at appropriate temperature (ASTM, 1985). This work is focused on developing empirical models and making use of experimental data to estimate the physical and mechanical properties of clay/cement tiles and to determine the errors.

The experimental variable and properties of tiles are related together using appropriate mathematical functions to describe the behavior of the system of results. The solution of the problem was then obtained by applying well developed mathematical regression techniques to the models (Hamdy, 1971). The physical properties of tiles, namely percentage water absorption, bulk density, and the mechanical properties of tiles, namely modulus or rupture and compressive strength, are the response variables while the predictor variable is the percentage clay or percentage clay or percentage silica. The physical properties follow a linear relationship while the mechanical properties follow a polynomial quadratic relationship with the predictor variable. A set of linear and quadratic equations are established stating Y (response variables as a function of X) (Younger, 1985) relationship.

MATERIAL METHODS

Theory of Regression Equation

Generally, the average values of the physical properties of tiles can be represented as a linear function represented by:

Y= $\alpha + \beta X + \varepsilon$ **(1)**

Y represents the response variables - % water absorption and bulk density, while X represents the predictor variable - % clay, ε is the error term, while α , β and ε can never be known, so the data in Table (1) are used to obtain numerical estimates, a and b of α and β, and Y becomes the estimated response variable; Younger (1985).

Hence, Y = a + bX **(2)**

By minimizing Equation (2), it leads to the solution of simultaneous linear equations called the normal equations, given by:

$$\sum_{i=1}^{n} Y_i = na + b\sum_{i=1}^{n} X_i \quad \textbf{(3)}$$

$$\sum_{i=1}^{n} X_i Y_i = a\sum_{i=1}^{n} X_i + b\sum_{i=1}^{n} X_i^2 \quad \textbf{(4)}$$

A computer program written in quick-basic was used to solve Equations (3) and (4) and the regression equations are as obtained in Equations (5) and (6) and consequently used to obtain the empirical shown in Figures 1 and 2.

Normal Equations for the Mechanical Properties of Tiles

Generally, the average values of the mechanical properties of tiles tabulated in Table 1 can best be described by quadratic functions as shown in Figures 4 and 5 represented by:

Y = $\alpha + \beta_1 X + \beta_2 X^2 + \varepsilon$ **(5)**

Y represent the response variables – modulus of rupture and compressive strength, and X represent the predictor variable - % Clay, ε is the error term, while $\alpha, \beta_1 and\ \beta_2$ are constants respectively.

Since the exact values of α, β_1, β_2 and ε can never be known, so the data in Table 1 are used to obtain numerical estimates, a, b_1 and b_2 of α , β_1 and β_2 and Y becomes the estimated response variable (Younger, 1985).
Hence:

Y = a + b_1X + b_2X^2 **(6)**

By minimizing Equation (6), it leads to the solution of a set of simultaneous linear equation called the normal equation ns, given by:

$$\sum_{i=1}^{n} Y_i = na + b_1\sum_{i-1}^{n} X_i + b_2\sum_{i=1}^{n} X_i^2 \quad \textbf{(7)}$$

$$\sum_{i=1}^{n} X_i Y_i = a\sum_{i=1}^{n} X_i + b_i\sum_{i=1}^{n} X_i^2 + b_2\sum_{i=1}^{n} X_i^3 \quad \textbf{(8)}$$

$$\sum_{i=1}^{n} X_i^2 Y_i = a\sum_{i=1}^{n} X_i^2 + b_1\sum_{i=1}^{n} X_i^3 + b_2\sum_{i=1}^{n} X_i^4 \quad \textbf{(9)}$$

A computer program in quick basic was used to solve Equations (7) to (9) and the regression equations are obtained in Equations (17) and (18) and consequently used to obtain the figures shown in Figure 3 and 4.

Coefficient of Regression (Correlation Index Coefficient)

The correlation coefficient (James and James, 1976) was computed for each of the properties regression equations, using the relation:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad \textbf{(10)}$$

Where r indicates the degree of linear relationship between X and Y of two random variables; it satisfies -1 ≤ r ≤ 1. And $\bar{X}$ and $\bar{Y}$ are the corresponding means. The correlation coefficient for the experimental values/curves of clay/cement tiles' properties are given in Figures 1- 4.

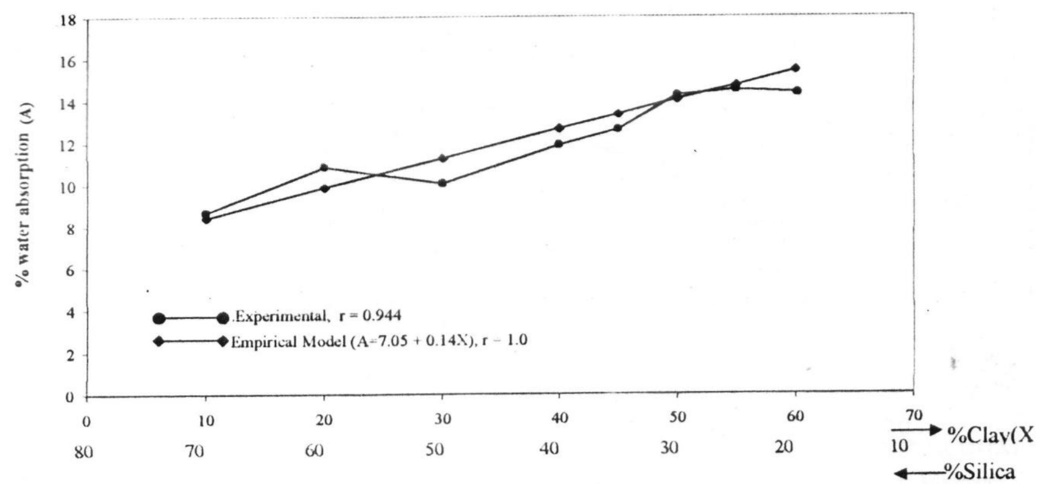

Figure 1: % Water Absorption versus % Clay or % Silica.

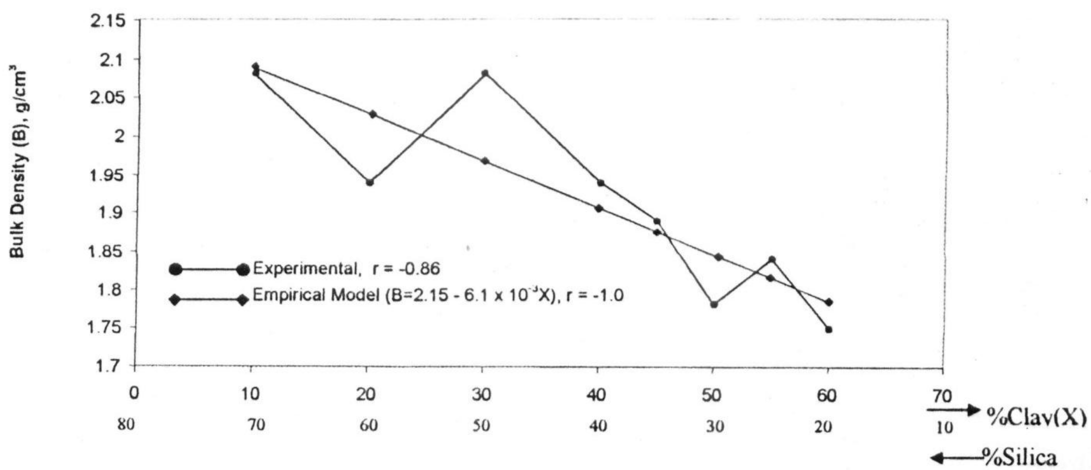

Figure 2: Bulk Density (g/cm^3) versus %Clay or %Silica.

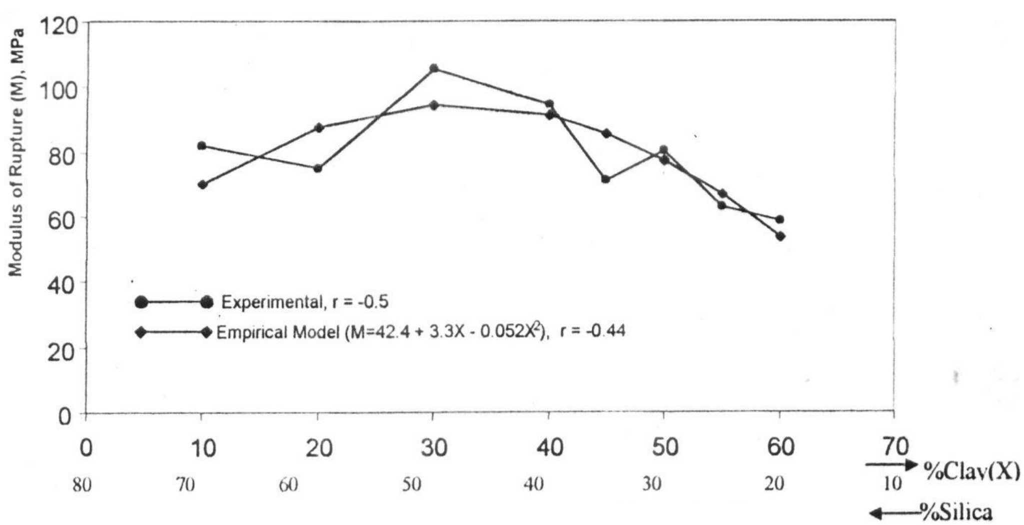

Figure 3: Modulus of Rupture, MPa versus %Clay or %Silica.

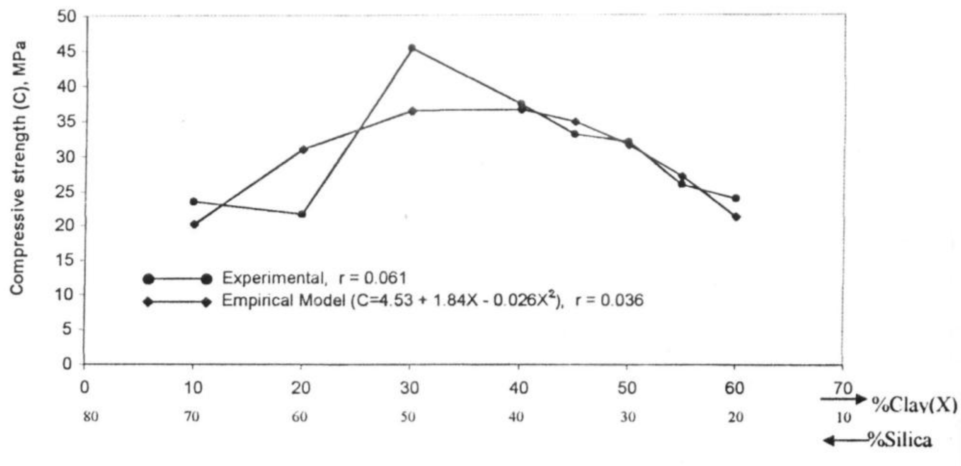

Figure 4: Compressive Strength, MPa versus %Clay or %Silica.

Experimental Work

A vertical hardwood mould was used to manufacture experimental tiles of uniform thickness, and facial dimension of 200mm×200mm pressed in a mould at angle 90º.

The mould is made up of four parts, namely, tiles seat, support wood, mould box, and punch. These parts are easily assembled and dismantled during and after operation. The support plate was used to lift up tiles from the tile seat after it has been manufactured. The punch was used to compress tiles materials in the box during molding. The raw materials used are clays, silica sand (filler) and cement which act as a binder. Each of the mixture was mixed according to the variables under investigation (Table 1). A measured quantity for each tile mixture was placed in the mould box and then pressed using punch with compaction load of 25KN. After molding, the experimental tiles were cured, dried in room temperature of 20-30ºC (Dharmendra et al., 1983).

Experimental Procedures

The experimental test procedures to determine the physical and mechanical properties of tiles specimens were carried in accordance with BS EN 993-1: 2005, BS 1902-38: and the average values are calculated as shown in Table 1.

Water Absorption

Water absorption measurements were carried out according BS EN 12808 – 5: 2008 – Grouts for tiles. Determination of Water Absorption. Fired pellets were soaked in boiling water in a beaker, and left to cool down to room temperature still soaked in water. Excess water was removed from the pellets surface using a moistened cloth prior to weighing. The wet weight (W_w) was then measured. Pellets were left drying in an oven at 110°C overnight, and the dry weight was measured (W_d). Water absorption (WA) was computed as:

$$WA = \frac{W_w - W_d}{W_d} \times 100 \quad \textbf{(11)}$$

Bulk Density

The bulk density of the fired samples was determined by water displacement using Archimedes principle. The experimental set-up allows the weights of the beaker partially filled with water, with and without the pellet immersed in water, to be measured. The difference gives weight of water displacement, according to the Archimedes principle. The weight of water displaced can be easily related to the volume of water displaced, as the density of water is known.

Table 1: Average Properties of Experimental Tiles.

MIXTURES (100%)			PHYSICAL PROPERTIES				MECHANICAL PROPERTIES			
%CLAY	%SILICA	%CEMENT	% WATER ABSORPTION (A)		BULK DENSITY (g/cm^3) (B)		MODULUS OF RUPTURE (MPa)(M)		COMPRESSIVE STRENGTH (MPa)(C)	
			*	**	*	**	*	**	*	**
10	70	20	8.65	8.45	2.08	2.089	81.87	70.20	23.44	20.30
20	60	20	10.85	9.85	1.94	2.028	75.04	87.60	21.77	30.93
30	50	20	10.07	11.25	2.08	1.967	105.55	94.60	45.29	36.33
40	40	20	11.90	12.65	1.94	1.906	94.48	91.20	37.26	36.53
45	35	20	12.61	13.35	1.89	1.876	71.25	85.60	32.98	34.68
50	30	20	14.24	14.05	1.78	1.845	80.29	77.40	31.98	31.53
55	25	20	14.49	14.75	1.84	1.815	62.79	66.60	25.79	27.08
60	20	20	14.24	15.45	1.73	1.784	58.22	53.20	23.89	21.33

Compaction Load = 25KN
Particle Size of sieved Clay and Silica = 1,000 um
% water addition to (clay + silica + cement) = 14%
* Experimental
* Predicted Value

The volume of water immersing in the water using a precision balance. Thus, the bulk density (BD, g/cm^3) is given in terms of sample mass (S_m) and the sample volume (S_v) as:

$$BD = \frac{S_m}{S_v} \qquad \textbf{(12)}$$

Modulus of Rupture Test

The specimens tested were placed horizontally and centrally on the test ring in an overlapping manner. The specimens were then loaded centrally by means of an overhanging wire cord and a hanger hooked on the wire with which the specimens were loaded with unknown values of masses until failure occurred. The modulus of rupture for each specimen was calculated using ASTM (1985).

$$M = 8PL/\pi t^3 \qquad \textbf{(13)}$$

Where, M is the modulus of rupture, P is load at rupture (N), L is distance between supports (mm), t is the average thickness of specimen (mm).

Compressive (Crushing) Test

Each test specimen was placed between the jaws of a manually operated hydraulic press machine. Load was then gradually applied on tiles via a cylindrical metal of 19.5mm diameter and about

30mm in length, until the first line crack was observed. The compressive strength of each specimen was calculated using ASTM (1985).

$C_S = P_C / A_C$ **(14)**

Where, C_S is the compressive strength of the specimen, P_c is the total load on specimen at failure (N) and A_C is the calculated area of the bearing surface on the specimen (mm^2).

RESULTS AND DISCUSSION

Regression Equations

Using the experimental values of tiles properties in Table 1 and a written computer program in quick-basic, the constants 'a' and 'b' in Equations (2), (3), and (4) were determined, and regression equations were obtained respectively for the physical properties as:

% Water Absorption,
$A= 7.05 + 0.14X, 10 \leq X \leq 60, r = 1.0$ **(15)**

Bulk density,
$B= 2.15 - 6.1\times 10^{-3}X, 10 \leq X \leq 60 =-1.0$ **(16)**

Also the constants 'a', 'b_1', and 'b_2', in Equations (6), (7), (8), and (9) were determined, and regression equations were obtained respectively for the mechanical properties as Modulus of rupture

.
$M= 42.4 = 3.3X -0.052X^2$,
$10 \leq X \leq 60, r =-0.44$ **(17)**

Compressive strength,
$C= 4.53 +1.84X - 0.026X^2$,
$10 \leq X \leq 60, r =0.036$ **(18)**

Where 'r' is the coefficient of regression obtained for each of the Equations (15) to (18) is only applicable within the ranges of X (amount of clay quantity in tiles mixture), of 10- 60%.

Water absorption shows a progressive increasing value of clay (Figure 1); this is as a result of clayish affinity for water. The empirical model A = 7.05 + 0.14X have been derived and used to predict the required values of water absorption for a given amount of clay value X.

The consistent closeness of the empirical model and experimental curves showed the validity of the model. The error value computed using Equation (5) for the model is 0.84% for water absorption.

Figure 2 showed reduction in values for bulk density: that is as the amount of clay increases, the amount of Silica decreases in the tiles mixture. The relative density of the clays ranges from 2.00 to 3.1 and that of Silica sand is 2.36. Since Silica is heavier than clays, it is gradually reduced, the bulk density reduces correspondingly.

The empirical model, $B = 2.15 - 6.1 \times 10^{-3}X$ has been derived, and used to predict the required values of bulk density for a given amount of clay value X. The error value of $0.07 g/cm^3$ has been computed using Equation (5) for the model of the bulk density.

Figure 3 and Figure 4 shows that both the modulus of rupture and compressive strength values follows a polynomial (quadratic) relationship with the amount of clays, X. The maximum values of these properties were experimentally obtained at 60%. It was discovered that optimum mechanical properties was obtained when 20% cement was added to 30- 40% clay, 50%-40% silica, under constant 14% water addition and 25KN compaction load with maximum particle size of clay and silica maintained at 1000µm (Table 1).

The empirical models $M= 42.4 + 3.3X - 0.052X^2$ and $C= 4.53 + 1.84X - 0.026X^2$ have been derived, and used to predict the required values of modulus of rupture and compressive strength respectively, for a given amount of clay value X. The errors computed (Younger, 1985) for models are 19MPa and 10MPa for modulus of rupture and compressive strength, respectively.

CONCLUSION

Computational results put the approximate errors (Younger, 1985) in the estimated values of the physical properties of cured clay/cement tiles at ±0.84% and $\pm 0.07 g/cm^3$ for % water absorption and bulk density and that of the mechanical properties at ±(1-19MPa) and ±(1-10MPa) for modulus of rupture and compressive strength, respectively. The empirical data used was for tiles produced from four different clays materials with different clay content, relative density, and grain fineness number (Ohijeagbon, 1995). The variation in properties of clays aforementioned, experimental and computational (approximations) errors are fundamentally responsible for the degree of errors introduced, all other factors remaining constants.

It should, however, be noted that the % cement content used in the data (see Table 1, Average properties of experimental tiles) was 20%. Previous work (Ohijeagbon, 1995) reveals that the average properties of tiles produced with 15% cement addition were almost constant with corresponding values of those produced with 20% cement addition, hence, the model derived in this work are recommended for cement addition in the range 15-20%.

Cement addition less than 15% may not be of much practical significance due to appreciable weakness of strength in tiles produced. Finally, it is interesting to know that it is quite easy to preselect and predict the properties for a brand of tiles to be produced within the range of % clay in mixture of 10 – 60%, corresponding to % silica in mixture of 70 – 20%, with 20% cement addition. At any rate the mixture (100%) is made up of clay, silica, and cement.

ACKNOWLEDGEMENT

This research was undertaken at Imperial College, London, for Dr. O.S. Olokode and was supported by the Commonwealth Scholarships Commission Programme. The author gratefully acknowledges the Material Department of Imperial College for providing the equipment used and extends his thanks to Mr. Richard Sweency and Dr. Mahmood Adrakani for their experimental assistance.

REFERENCES

1. Adeyemi, M.B. 1987. “Experimental Determination of Extrusion Pressures and Properties of Lateritic Bricks made using a Continuous Horizontal Extrusion Process”. *Int. J. of Dev. Tech*. 5: 39-47.

2. Adeyemi, M.B. 1989. “Effects of Extrusion Die-Geometry on the Extrusion Pressure and Mechanical Propitiates of Clay Bricks made by Horizontal Extrusion Process”. *Nig. J. for Tech. Dev*. 1(2):122-127.

3. ASTM. 1985. *Annual Book of ASTM Standards.* 15(02):382 – 383.

4. ASTM. 1985. *Annual Book of ASTM Standards*. 15(02):452 – 455.

5. ASTM. 1985. *Annual Book of ASTM Standards*. 15(02):98.

6. BS.EN. 993 – 1:2005, BS 1902 – 3.8. 1995. Licensed Copy: na na, University of Sheffield, Tha June 2916: 24: 35 BST 2006, Uncontrolled Copy @BS I.

7. BS EN 12808 – 5. 2008. Grouts for tiles. Determination of Water Absorption.

8. Dharmendra K., S.K. Jam, A.K. Bhargawa. 1983. *Materials Science and Manufacturing Process*. Vikas Int. Students Edition, Vikas: New Delhi, India.

9. Grimehaw, R.W. 1971. *The Chemistry and Physics of Clays*. Ernest Benn Publishers: London, UK.

10. Hamdy, A.T. 1971. *Operations Research*. Macmillian Publishing: New York, NY.

11. James and James. 1976. *Mathematical Dictionary. Fourth Edition*. Van Nostrand Reinhold: New York, NY.

12. Ohijeagbon, I.O. 1995. “Manufacturing of Tiles using Cement and Clays”. M.Eng. Thesis. University of Ilorin: Ilorin, Nigeria.

13. Peter Sham, M. 1984. “Understanding Clay Recognition and Processing”. Volunteers in Technical Assistance (VITA): USA.

14. Singh, S. 1979. *Engineering Materials*. Vikas Publishing House: New Delhi, India.

15. Stafford, C.E. 1980. *Modern Industrial Ceramics. 1st Edition*. Bobbs Nerril Co.: New York, NY.

16. Younger, M.S. 1985. *A First Course in Linear Regression, 2nd Edition*. Duxbury Press: Boston. MA.

ABOUT THE AUTHOR

Dr. (Engr) O.S. Olokode, is a Lecturer in the Department of Mechanical Engineering, Federal University of Agriculture, Abeokuta, Nigeria. Dr. Olokode is a registered member of Institute of Materials, Metals and Mining (IOM3) in London.
He is also a member of Nigerian Society of Engineers. He holds a Ph.D. degree in Material Engineering with specialization in Ceramics and Nanotechnology.

SUGGESTED CITATION

Olokode, O.S. 2011. "Empirical Model for Estimating the Physical/Mechanical properties of Clay/Cement Tiles". *Pacific Journal of Science and Technology*. 12(1):81-88.