Field Data Based Mathematical Model for Stirrup Making Activity in Civil Construction

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Abstract

Stirrup or lateral tie is one of the essential element of reinforce cement concrete in civil construction. These stirrups are used for strengthening columns and beams, avoiding buckling of long slender column and avoiding sagging of horizontal beam. The detailed study of present manual stirrup making activity indicates that the process suffers from various draw back like lack of accuracy, low production rate and resulting in to severe fatigue in the operator. The construction operator not only subjects his hands to hours of repetitive motion but also some times suffers internal injury to his body organ that is disorder carpel tunnel syndrome.

In order to remove above draw backs authors have determine an appropriate sample size for the activity and formulated various field data based mathematical models (FDBM) such as multivariable linear model, polynomial model, exponential model, logarithmic model, on the basis of gathered field data by applying theories of experimentation. The formulated model can use to optimize the human energy of worker, production rates and inaccuracy of stirrups.

Keywords:* *Stirrup, Dimensional Analysis, field data based mathematical models (FDBM).

INTRODUCTION

Stirrup or lateral-tie is one of the necessary elements of reinforced cement concrete which is used for strengthening columns and beams [1]. Stirrups are used in the pillars and beams to increase its strength. The framework is made up by the mild steel rods and then the concrete mortar material is filled in it which provides the strength to the construction. The basic functions of the stirrups are(1) To hold and support horizontal and vertical plain mild steel or torr-steel bar.(2)To provide reinforcement and rigidity to columns and beams.(3)To take shear force in horizontal beams structures as well as vertical columns.(4)To avoid buckling of long slender column or to avoid sagging of horizontal beam. The hooked ends of the stirrup also provide proper anchorage which in turn safeguards the structure against horizontal forces occurring due to wind, earthquake etc. The stirrups are made out of 6 mm, 8 mm, 10 mm in plain m.s. or torr-steel bar in various shapes such as rectangular, square. These stirrups are presently made manually. Fig.1.1 shows schematic of stirrup.

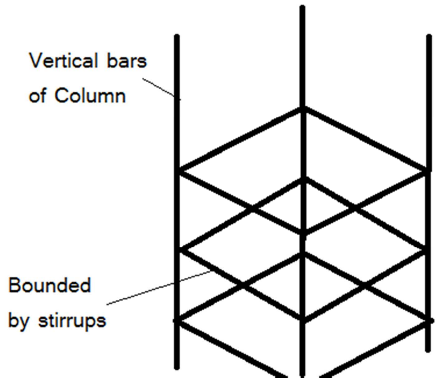

Fig 1. Stirrup holding bars of column

PARAMETERS AFFECTING THE ACTIVITY

The parameter which affects the production rate and accuracy of an activity and human energy of worker were selected. At preliminary stage, more parameters were selected based upon the material, anthropometry of person and environmental parameters. Later on to reduce the variables in number, some variables are clubbed together while some variables which was seemed to be uncontrollable or least affecting, that parameter was rejected and finally a set of attributes were selected as follows:

S.N.	VARIABLE	TYPE OF VARIABLE	SYMBO	FORMULA
01	Length of stirrup wire	Independent	Ls	L
02	Diameter of stirrup wire	Independent	Ds	L
03	Strength of stirrup wire	Independent	F	MLT^{-2}
04	Hardness of stirrup	Independent	Hs	$ML^{-1}T^{-2}$
05	Torque	Independent	Tq	$ML^{2}T^{-2}$
06	Length of bending rod	Independent	Lb	L
07	Noise	Independent	Db	--

08	Anthropometric data	Independent	Ad	--
09	Humidity	Independent	Ø	--
10	Air velocity	Independent	Va	LT^{-1}
11	Height of work station	Independent	Hw	L
12	Angular velocity	Independent	ω	T^{-1}
13	Modulus of elasticity	Independent	K	$ML^{-1}T^{-2}$
14	Production	Dependent	P	T^{-1}
15	Accuracy	Dependent	A	L
16	Human energy	Dependent	HE	$ML^{2}T^{-2}$
17	Age/skill	Independent	AS	--
18	Surrounding Temperatu	Independent	T	--
19	Weight	Independent	W	M

Table 1

PLANNING OF EXPERIMENTATION

The steps in planning of experimentation in manual stirrup making process [2][8][9] are as below –

i) Identification of variables

1) Dependent variables : The dependent variables in the process are
   a) Production rate Y1
   b) Accuracy Y2
   c) Human Energy Y3

2) Independent variables: The independent variables are

I) Operator related variables
   a. Anthropometric data
   b. Age/skill
   c. Weight

II) Environmental variables
   a. Noise
   b. Humidity
   c. Air velocity
   d. Surrounding Temperature

III) Material related variables
   a. Length of stirrup wire
   b. Diameter of stirrup wire
   c. Strength of stirrup wire
   d. Hardness of stirrup
   e. Torque
   f. Length of bending rod
   g. Height of work station
   h. Angular velocity
   i. Modulus of elasticity

ii) Measurement of variables

I) Dependent variables:

a. Production rate (Y1): The number of stirrups produced in a shift of three hours duration is measured and productivity is evaluated as under :

Productivity (rods/hour) = Number of stirrups/3

b. Accuracy (Y2): The accuracy is calculated by dividing the standard size by maximum deviation of side of stirrup.

c. Human energy (Y3): The human energy is calculated by using the pedometer.

II) Independent Variables:

a. Operator related variables: These are calculated by using measuring tape, weighing machine.

b. Environmental variables: These are calculated by using android applications.

c. Material related variables: For calculating these variables measuring tape, stop watch poldi hardness tester and Universal testing Machine (UTM) are used.

FORMULATION OF DIMENSIONAL EQUATION FOR MANUAL STIRRUP MAKING ACTIVITY

Rayleigh Method and Buckingham's π Method are the methods of dimensional analysis. In Rayleigh method there are certain limitations that are if any physical phenomenon involves more than three independent variable then this method becomes more complex and cumbersome. Hence, Buckingham's π method is used and following π terms were obtained [6][12].

Sr.No	Description of Pi terms	Equation Pi terms
Independent terms		
01	Pi term relating dimension of stirrup	$\pi_1=Ds/Ls$
02	Pi term relating hardness of stirrup	$\pi_2=Hs*Ls^{*}\omega$
03	Pi term relating torque	$\pi_3= Tq/k*Ls$
04	Pi term relating length of bending rod	$\pi_4=Lb/Ls$
05	Noise	$\pi_5=Db$
06	Pi term relating air velocity	$\pi_6 =Va/Ls*\omega$
07	Pi term relating height of work station	$\pi_7 =Hw/Ls$
08	Pi term relating strength of stirrup	$\pi_8=F/Ls^2*k$
09	Pi term relating anthropometric data operator	$\pi_9=Ad$
10	Pi terms relating relative humidity	$\pi_{10}=Ø$
11	Surrounding Temperature	$\pi_{11} = t$
12	Age/skill	$\pi_{12} = AS$
13	Pi term relating weight	π_{13} $\omega^2*W/k*Ls$
Dependent terms		
14	Pi term relating Production rate	$\pi_{14}= P/\omega$
15	Pi term relating Accuracy	$\pi_{15}= A/Ls$
16	Pi term relating Human Energy	$\pi_{16}= HE/Ls*\omega*k$

Table 2

CLUBBING OF Pi-TERMS

Out of our 16 Pi-terms π14, π15 and π16 are the dependent variables (i.e. output) while π1- π13 are independent variables (details available in Table 1). So we have clubbed together the Pi-terms to reduce the variables in a model. The first seven independent terms π1- π7 are clubbed together to give input variable X1, and π8- π13 are clubbed together to give X2 and the dependent variables are Y1,Y2 and Y3.

X1 = input independent variable (clubbing of π1- π7)

X1 = input independent variable (clubbing of π8- π13)

Y1 = production rate of stirrups (π14)

Y2 = inaccuracy of stirrups (π15)

Y3 = human energy consumption (π16)

FORMULATION OF MODEL

The model is formulated by

1) Taking the readings of the activity according to the sample size (for infinite population) calculated.
2) Forming pi terms and clubbing it.
3) Forming the test envelop.
4) Generating the reading using the random numbers [8][9]

The tests envelop for independent and dependent variables is shown in table 3.

Sr.no	Dimensionless variables	Test envelop	Test sequence
1	X1	9.999-4.324	Random
2	X2	9.634-4.813	Random
3	Y1	0.053-0.011	Random
4	Y2	0.00290-0.00048	Random
5	Y3	0.0089-0.0002	Random

Table 3

Test envelop of data have been generated by random numbers and used for formulation of model is shown in table 4.

X1	X2	Y1	Y2	Y3	Ran #
9.999	9.634	0.053	0.0029	0.0089	
5.09949	4.91334	0.02703	0.001479	0.004539	0.51
7.409259	7.138794	0.039273	0.002149	0.006595	0.741
5.439456	5.240896	0.028832	0.001578	0.004842	0.544
5.209479	5.019314	0.027613	0.001511	0.004637	0.521
9.689031	9.335346	0.051357	0.00281	0.008624	0.969
7.919208	7.630128	0.041976	0.002297	0.007049	0.792
7.39926	7.12916	0.03922	0.002146	0.006586	0.74
6.339366	6.107956	0.033602	0.001839	0.005643	0.634
4.324	4.813	0.011	0.00048	0.0002	

Table 4

Various mathematical models are as follows [9].

SAMPLE SIZE FOR ACTIVITY

Author have determined sample size for manual stirrup making activity i.e. 165 by using formula

$$n=(z^*\sigma)^2/E^2$$ [10][11].

Where,

n= sample size

z= tail value

σ_p = standard deviation of Population

e = error of estimation or margin of error

7.1 LINEAR MODEL

In linear model the relationship between a scalar dependent variable y and one or more independent variables denoted X is plotted. The case of one independent variable is called simple linear regression. For more than one independent variable, it is called multiple linear regression.

So plotting the graph of X1 and X2 with Y1 on a line fit (simple linear graph), we get equations

Y1 = 0.0062X1 – 0.0073

Y1 = 0.0065X2 – 0.0083

So, linear model becomes

Y1 = 0.0062X1 + 0.0065X2 (R^2 = 0.8982)

Similarly model for Y2 and Y3 are formulated in a similar way as(Annexure A)

Y2 = 0.0003X1 + 0.0004X2 (R^2 = 0.8734)

Y3 = 0.0012X1 + 0.0012X2 (R^2 = 0.7893)

7.2 LOG-LOG LINEAR MODEL

It is seen that the points are not lying properly in a straight line due to which the coefficient of determination of model is quite lower so taking the log on both sides' decreases the scale of graph and points come closer. So plotting the log-log graph makes model more efficient.

Y1 or Y2 = $K\ X1^a\ X2^b$ [8]

Where a and b are the slopes of graph of Y with X1 or X2 respectively.

So, from plotted log-log graphs (Annexure B) we get

a = 1.4376

b = 1.4274

$Y1 = K1\ (X1)^{1.4376}\ (X2)^{1.4274}$ (R^2 = 0.7466)

Similarly model for Y2 and Y3 are formulated in a similar way as

$Y2 = K2\ (X1)^{1.5724}\ (X2)^{1.5375}$ (R^2 = 0.6808)

$Y3 = K3\ (X1)^{2.7627}\ (X2)^{2.5092}$ (R^2 = 0.4207)

By putting the values in all readings and taking average we get

K1 = 1.63E-04 K2 = 5.63E-06 K3 = 3.14E-07

7.3 EXPONENTIAL MODEL

This model fits the points on a semi-log pattern (log of Y1 vs X1 or X2) as shown on Annexure C. the exponential model is in a form of

$Y1/Y2 = K\, e^{X1a} e^{X2b}$ [8]

Where a and b are the slopes of graph of Y with X1 or X2 respectively.

So, from plotted exponential graphs (Annexure C) we get

a = 0.1993

b = 0.2026

$Y1 = K\, e^{0.1993\, X1} e^{0.2026\, X2}$ ($R^2 = 0.6205$)

Similarly model for Y2 and Y3 are formulated in a similar way as

$Y2 = K\, e^{0.2163\, X1} e^{0.2174\, X2}$ ($R^2 = 0.6233$)

$Y3 = K\, e^{0.3477\, X1} e^{0.3661\, X2}$ ($R^2 = 0.3622$)

By putting the values in all readings and taking average we get

K1 = 2.09E-03 K2 = 1.03E-04 K3 = 2.98E-04

7.4 POLYNOMIAL MODEL

This model fits the points on a polynomial pattern (SIMPLE GRAPH) as shown on Annexure C. the exponential model is in a form of

$Y1 \text{ or } Y2 = K + aX1^2 + bX1 + cX2^2 + dX2$ [8]

Where a b c d are the slopes of graph of Y with X1 or X2 respectively.

So, from plotted exponential graphs (Annexure D) we get

a = -0.0006   c = -0.0006   b = 0.0155   d = 0.0155

$Y1 = K - 0.0006X1^2 + 0.0155X1 - 0.0006X2^2 + 0.0155X2$ ($R^2 = 0.9195$)

Similarly model for Y2 and Y3 are formulated in a similar way as

$Y2 = K - 4E\text{-}05X1^2 + 0.001X1 - 4E\text{-}05X2^2 + 0.0009X2$ ($R^2 = 0.9004$)

$Y3 = K - 0.0002X1^2 + 0.0037X1 - 0.0002X2^2 + 0.0004X2$ ($R^2 = 0.8360$)

By putting the values in all readings and taking average we get

K1 = -1.16E-01 K2 = -7.05E-03   K3 = -2.68E-03

VALIDATION OF MODEL

To establish the accuracy of the model the error i.e the difference between actual value of dependent variable and predicted value of dependent variable by substituting the values of independent variables. This experimentation is done for 25 readings and error is evaluated. On the basis of error value the coefficient of determination (R^2) is evaluated. Coefficient of determination provides a measure of how well future outcomes likely to be predicted by this model the value of R^2 is evaluated by using the formula as given below[9]:

$$R^2 = 1 - \frac{\Sigma(y_i - f_i)^2}{\Sigma(y_i - y)^2}$$

Where,

Y_i – observed value of dependent variable for i^{th} experimental set up

f_i – Predicted value of dependent variable for i^{th} experimental set up

and y=mean of y_i

R^2 = coefficient of determination

yi	fi	yi-fi	sq.(yi-fi)	yi-y	sq.(yi-y)
0.053	0.0726	-0.0196	0.0004	0.0124	0.0002
0.0514	0.0703	-0.0189	0.0004	0.0514	0.0026
0.042	0.0525	-0.0105	0.0001	0.042	0.0018
0.0288	0.0153	0.0135	0.0002	0.0288	0.0008
0.0276	0.0111	0.0165	0.0003	0.0276	0.0008
0.0514	0.0703	-0.0189	0.0004	0.0514	0.0026
0.042	0.0525	-0.0105	0.0001	0.042	0.0018
0.0392	0.0458	-0.0066	0	0.0392	0.0015
0.0336	0.0304	0.0032	0	0.0336	0.0011
0.0514	0.0703	-0.0189	0.0004	0.0514	0.0026
0.042	0.0525	-0.0105	0.0001	0.042	0.0018
0.0392	0.0458	-0.0066	0	0.0392	0.0015
0.0336	0.0304	0.0032	0	0.0336	0.0011
0.0393	0.046	-0.0067	0	0.0393	0.0015
0.0288	0.0153	0.0135	0.0002	0.0288	0.0008
0.0276	0.0111	0.0165	0.0003	0.0276	0.0008
0.0514	0.0703	-0.0189	0.0004	0.0514	0.0026
0.0392	0.0458	-0.0066	0	0.0392	0.0015
0.0336	0.0304	0.0032	0	0.0336	0.0011
0.0514	0.0703	-0.0189	0.0004	0.0514	0.0026
0.042	0.0525	-0.0105	0.0001	0.042	0.0018
0.0392	0.0458	-0.0066	0	0.0392	0.0015
0.0336	0.0304	0.0032	0	0.0336	0.0011
0.0514	0.0703	-0.0189	0.0004	0.0514	0.0026
0.042	0.0525	-0.0105	0.0001	0.042	0.0018
0.0406		SUM	0.0042	SUM	0.0402

Thus this shows production rate model is valid with $R^{2} = 89.43$

Similarly, Validation of accuracy and human energy is done.

CONCLUSION

The model must be selected which gives highest efficiency and validity. For this statistical and mathematical techniques are used. The models are compared on the basis of coefficient of determination (R^2) which indicates the degree of validity to which the output can be calculated by a particular model. The model and their respective coefficient of determination (R^2) are as follows:

Sr No.	Model		R^2
1	Linear model	Y1 = 0.0062X1 + 0.0065X2	0.8982
		Y2 = 0.0003X1 + 0.0004X2	0.8734
		Y3 = 0.0012X1 + 0.0012X2	0.7893
2	Log-Log Mod	$Y1 = K1\,(X1)^{1.4376}\,(X2)^{1.4274}$	0.7466
		$Y2 = K2\,(X1)^{1.5724}\,(X2)^{1.5375}$	0.6808
		$Y3 = K3\,(X1)^{2.7627}\,(X2)^{2.5092}$	0.4207
3	Expo. Model	$Y1 = K\,e^{0.1993\,X1}\,e^{0.2026\,X2}$	0.6205
		$Y2 = K\,e^{0.2163\,X1}\,e^{0.2174\,X2}$	0.6233
		$Y3 = K\,e^{0.3477\,X1}\,e^{0.3661\,X2}$	0.3622
4	Poly Nomial Model	$Y1 = K – 0.0006X1^2 + 0.0155X$ $0.0006X2^2 + 0.0155X2$	0.9195
		$Y2 = K – 4E\text{-}05X1^2 + 0.001X1 -$ $4E\text{-}05X2^2 + 0.0009X2$	0.9004
		$Y3 = K – 0.0002X1^2 + 0.0037X$ $0.0002X2^2 + 0.0004X2$	0.836

So, we can conclude that the polynomial model is giving the highest efficiency as the coefficient of determination (R^2) is highest for all the three models. So we prefer polynomial model. Also the R^2 obtained by validation for polynomial model is same as obtained by graph hence polynomial model is best suited for stirrup making activity.

ANNEXURES

1. Annexure A – Graphs of linear Model
2. Annexure B – Graphs of exponential Model
3. Annexure C – Graphs of polynomial Model

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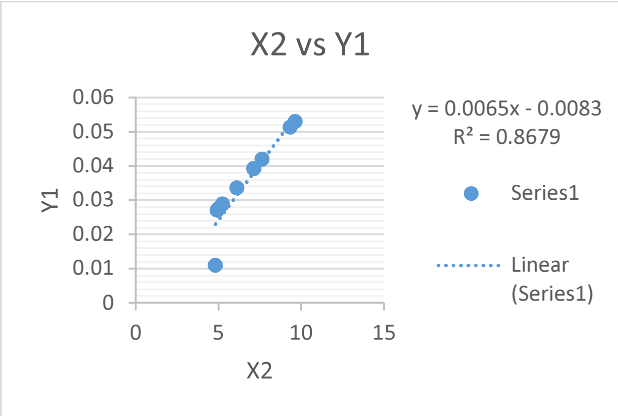
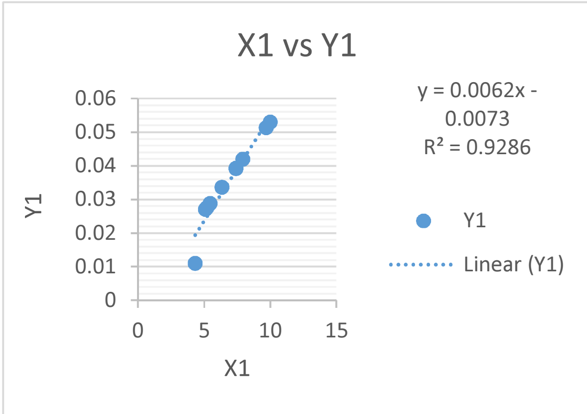
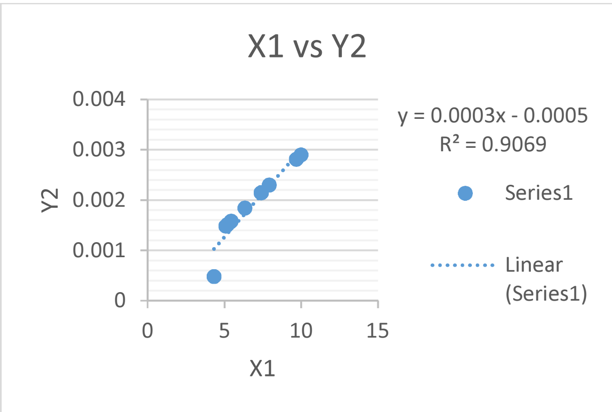
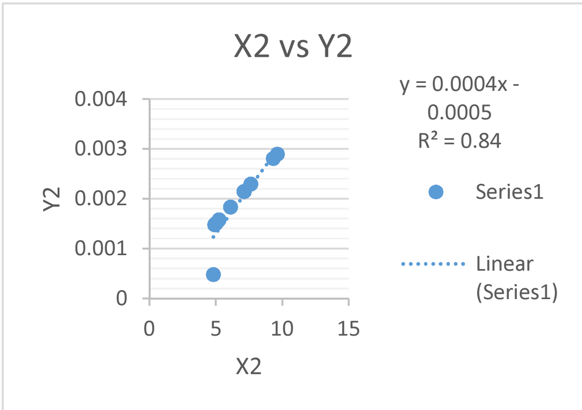
ANNEXURE A

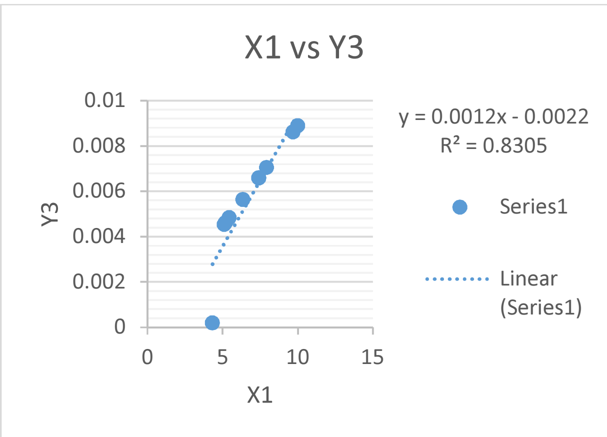
LINEAR GRAPHS

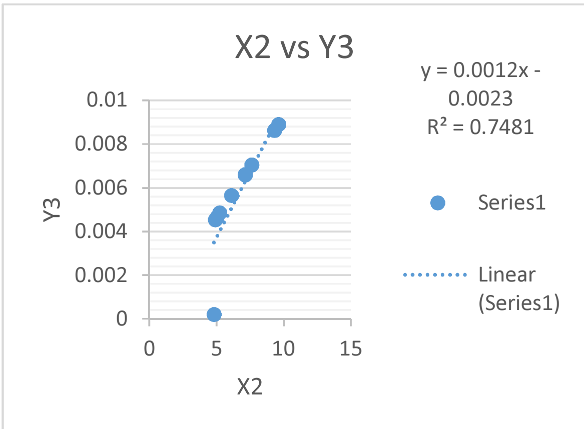






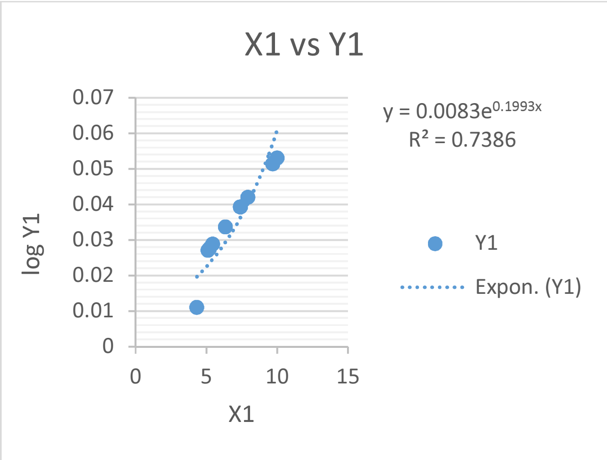


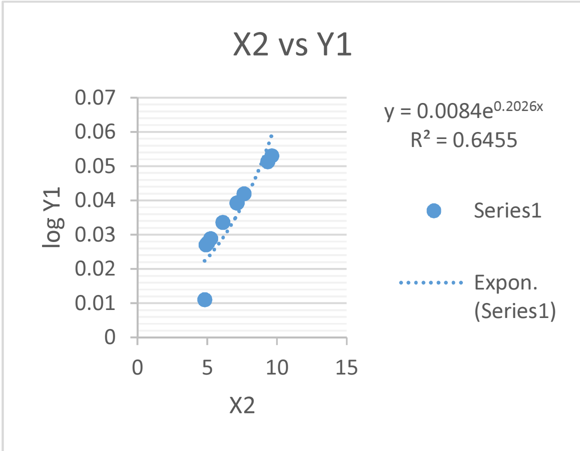


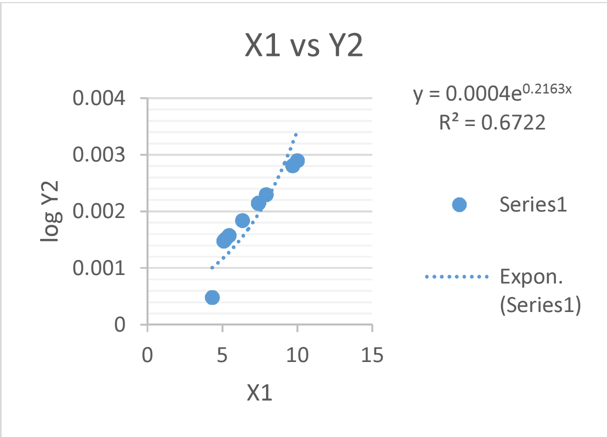


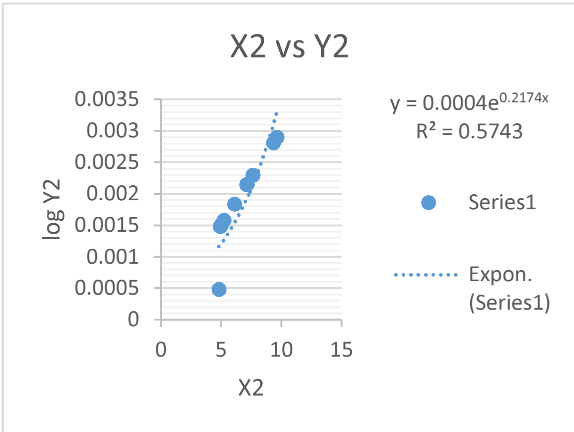
ANNEXURE B

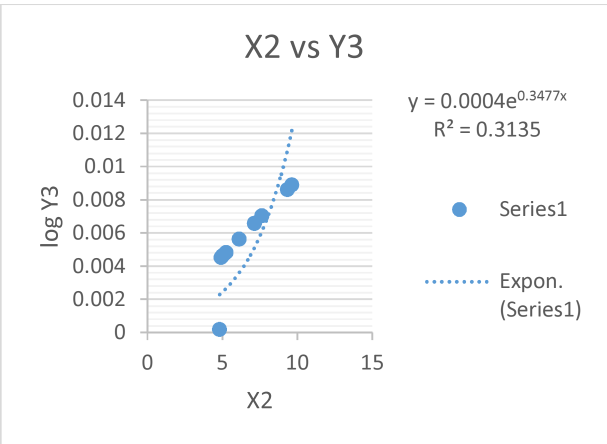
EXPONENTIAL GRAPHS

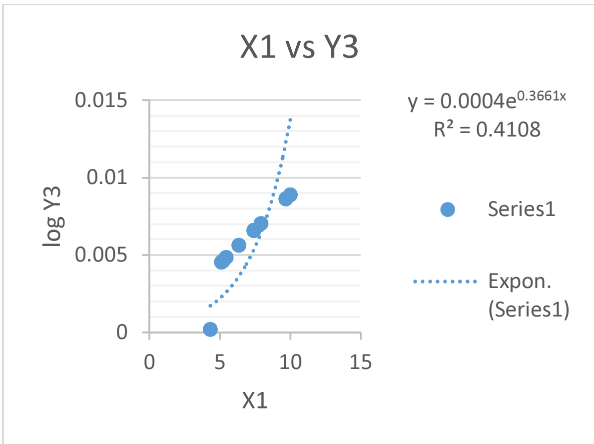












ANNEXURE C

POLYNOMIAL GRAPHS