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Development of specification writing procedure for mixture proportions for laterite cement bricks using the Central Composite Design Approach

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Abstract

A specification writing procedure was developed to obtain component mixes to produce laterite-cement bricks meeting user-defined requirements. The procedure was developed using the Central Composite Design (CCD) of the Response Surface Methodology (RSM) of experimental design. It essentially focused on selecting component proportions to obtain response prediction for a three-component mixture for building bricks production using water, cement and laterite with percentage sand replacement. Compaction was carried out using the commercially available Hydrafrom Twin-M7 machine exerting a compactive effort of 10MN/m^2. Five blends of bricks were investigated with cement content ranging between 8-20 percent by weight of laterite and 0-20 percent silica sand replacements. At the specified ages of 7 and 28 days, the compressive strength was measured using Testometric FS300CT Universal Testing Machine and responses were modeled as second order quadratic equations. An inverse relationship for response prediction for strength was obtained and compressive strength achievable ranges between 7.00 -19.00 N/mm^2. A specification writing form is proposed which will enable the selection of constituent materials and acceptance criteria to be met to enable both cement and plastic bonds achievable.

Keywords: Specification writing, Form, laterite-cement bricks, Central Composite Design, Response Surface Methodology, Compressive strength

1.0 INTRODUCTION

The need to select a mixture to produce laterite-cement bricks satisfying user-defined requirements of strength and durability demands a higher complexity of the mixture design. To achieve this higher performance laterite bricks, the traditional method of using trial mixes would be incapable. These performance criteria could include mechanical properties such as strength, young modulus of elasticity, creep and shrinkage. It is desired, for site production, to obtain a standard which would form a basis for performance and acceptance criteria to be achieved. This can nonetheless be achieved except through specifications writing procedure.

Laterite, according to Gidigasu (1976) is described as a light to dark homogeneous, vesicular, unstratified and clinker-like soil material consisting mainly of oxides and hydroxides of aluminium, iron, manganese and silica which hardens on extraction and exposure. It is described as a class of pedogenics where the cementing materials are the sesquioxides content and should normally constitute not less than 50 percent of the mineralogical composition according to this definition. This definition describes the material in its natural form. However, for building construction purposes, cement is usually added to improve the properties of the bricks.

Laterite bricks have a very good thermal property, shock and earthquake resistance (Hydraform, 2014) and particularly impact resistance. Some research outputs (Osunade and Fajobi, 2000; Madu, 1984; Gidigasu, 1976; Awoyera and Akinwumi, 2014; Hydraform, 2014) have tried to confirm the acceptability of its properties for a series of acceptance criteria. Among these properties include strength, absorption characteristics, resistance to abrasion and reduction in the number of structural frames required in a building up to two-storey high.

Various attempts have also been made to improve laterite-cement material as a building material for sustainable housing construction. These include development and manufacturing of compression moulding machines for mechanical stabilization of bricks (Hydraform, 2014; NBRRI, 2013; Cinva Ram, 1999; Adeyemi, 1987). Stabilization of laterite soil with cement otherwise called soil-cement mixture was also investigated (Hydraform, 2014; Madu, 1984; Aguwa, 2009; Osunade and Fajobi, 2000) as well as stabilization with Locust Waste Bean Ash (Osinubi and Oyelakin, 2012), stabilization with Bentonite treatment (Amadi et al, 2011), stabilization with lime (Singh, 2006), among others. Other pozzolana treatments included Corn Cob Ash, Rice Husk Ash, Pumice Slag Ash, Burnt Clay Brick Ash, Sugarcane bagasse Ash, etc.

Statistical experimental design procedure for mixture experiments was used to fix variable inputs to established design points. It generally employs the fitting of a second order quadratic model for each of the measured responses after removing insignificant terms in the model. The resulting response equations where insignificant terms are eliminated now become the response prediction equations. An advantage of this type of statistical experimental design procedure is that the responses can be characterized by an uncertainty (variability) which has an important implication for specification writing especially in site production (Simons et al, 1999; Montgomery, 2001). These responses are always targeted at yielding a target or mean strength which implies that at least 95 percent of the results are expected to fall within the normal distribution curve or more precisely, probability $p \leq 0.05$.

The Central Composite Design (CCD) is essentially a factorial experimental design employed for modeling a response as a second order quadratic model, (Simon et al, 1999). Each response property can be optimized using the response surface method to obtain a second order quadratic model of the form (Montgomery, 2001):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum\sum_{i<j} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \qquad (1)$$

where "y" the response is the property of the mixture. The values $x_i s$ are the components and the parameters β_i and β_{ij} are the linear and quadratic coefficients fitting the experimental data for the linear and interactive terms respectively. The Central Composite Design is run in 2-level factorial design. In this method, the influence of all the variables, factors and the interaction effects are investigated at two levels consisting 2^n experiments

A characteristic rotatability designs in CCD used here implies that predicted values should have equal variance at locations equidistant from the origin (Simon et al, 1999; Montgomery, 2001). The construction of the design matrix is also implementable using the Design Expert statistical software (Design Expert, 2000).

2.0 MATERIALS AND METHODOLOGY

The laterite sample used was obtained from an existing burrow pit within Ilorin environs, Kwara State (KW-31, Elevation 317, and Coordinates 663093, 935109) using a method of disturbed sampling at depths 0.5m – 1.5m depth. Two grading zones of silica sand, namely zones 2 and 3 sand otherwise called coarse (C) and fine (F) sands were used. The sand samples for Coarse and Fine sands were collected from the Stream beds within the tributaries of Asa River in Ilorin. Ordinary Portland cement complying with BS 3148, 1980 and NIS 444, 2003 respectively was used. The physical and geotechnical properties of the laterite sample used were: Liquid limit: 49%; plastic limit: 30.6%; plasticity index: 18.4%; specific gravity: 2.64; linear shrinkage: 10.1mm; maximum dry density: 1821kg/m^3; optimum moisture content: 14.1%; colour: reddish brown; condition of sample: air dry; soil classification: A-2-7. Mineralogical properties include: iron oxide content: 18.01% and sesquioxide content: 42.21%.

Batching, mixing and casting of specimens using 100% laterite-cement mixture as a control, two percentage sand replacement with proportions of 10% and 20% silica sand was carried out. Brick samples (96mm x 93.6mm x 145mm) were cured and tested at 7 and 28 days to obtain the compressive strength properties using a Testometric Universal Testing Machine Model FS300CT. ASTM C 170-90 test plan.

3.1 Methodology for estimation of constituent proportions within the design domain

The expression of the absolute volume of the mixture is expressed (Aguwa, 2009) as:

$$\frac{water}{Gs_{water} \times 1000} + \frac{cement}{Gs_{cement} \times 1000} + \frac{laterite}{Gs_{laterite} \times 1000} = 1 \qquad (2)$$

$where\ Gs = specific\ gravity$

An augmented Simplex [3,2] lattice design was initially used to obtain a design matrix whose vertices were 8%, 14% and 20% cement contents representing ratios 1:12.5; 1:7.14 and 1:5 fitted in a manner as to yield an optimum within the design domain selected. This is shown in Appendix A.1. The pseudo component variables of all other binary, interior and centre points were transformed into their actual factor variables by the method described by Mama and Osadebe, (2014).

3.2 Determination of Dry Density/Optimum Moisture Content relationship and estimation of revised mixing water

The optimum moisture content corresponding to the maximum dry density was used to determine the quantity of mixing water to produce the maximum dry compacted soil per cubic meter of the soil-cement mixture. The 4.5kg rammer method was used in accordance with the procedure described in BS 1377 (1990).

3.3 Revised mixing water estimation

The moisture required which corresponds to the maximum dry density was used to replace the starting mixing water. The calculated limits/domains for the five blends are as summarized in equations 3(a) – 3(e).

$$0.262 \leq x_1 \leq 0.267$$

$$\left.\begin{array}{l} 0.259 \leq x_1 \leq 0.262 \\ 0.046 \leq x_2 \leq 0.106 \\ 0.633 \leq x_3 \leq 0.694 \end{array}\right\} CCD - F1; \quad (3c)$$

$$\left.\begin{array}{l} 0.263 \leq x_1 \leq 0.266 \\ 0.046 \leq x_2 \leq 0.106 \end{array}\right\} CCD - C2; \quad (3d)$$

$$\left.\begin{array}{l} 0.256 \leq x_1 \leq 0.268 \\ 0.046 \leq x_2 \leq 0.107 \\ 0.637 \leq x_3 \leq 0.687 \end{array}\right\} CCD - F2; \quad (3e)$$

The Letters C1, F1 and C2, F2 immediately after the hyphen represents Coarse (C) and Fine (F) sand. The figures 0, 1 and 2 represents zero (0), ten (10) and twenty (20) percent silica sand replacement respectively.

3.4 Mathematical relationship between mixture proportions

Using the augmented [3,2] Simplex lattice design, the expression relating the new water requirement (Y) was obtained as shown in equation (4). Detailed procedure for mixing water estimation was given by Alao and Jimoh (2017). Once the ratio of cement to laterite has been selected, the mixing water requirement can be estimated.

$$CCD - 0; \qquad Y = 269.5 - 36.93 * \left(\frac{Cement}{Laterite}\right) \qquad (4a)$$

$$CCD - C1; \qquad Y = 259.8 - 39.40 * \left(\frac{Cement}{Laterite}\right) \qquad (4b)$$

$$CCD - F1; \qquad Y = 258.5 - 18.42 * \left(\frac{Cement}{Laterite}\right) \qquad (4c)$$

$$CCD - C2; \qquad Y = 269.4 - 29.77 * \left(\frac{Cement}{Laterite}\right) \qquad (4d)$$

$$CCD - F2; \qquad Y = 276.6 - 99.04 * \left(\frac{Cement}{Laterite}\right) \qquad (4e)$$

Similarly, using the same Scheffe' augmented [3,2] lattice design, laterite quantity can be calculated once the cement quantity has been select. The equations relating laterite quantity based on cement quantity selected is shown in equation (5).

$$CCD - 0; \qquad L = 1927 - 0.7767 * Cement \qquad (5a)$$
$$CCD - C1; \qquad L = 1956 - 0.9058 * Cement \qquad (5b)$$
$$CCD - F1; \qquad L = 1959 - 0.8697 * Cement \qquad (5c)$$
$$CCD - C2; \qquad L = 1928 - 0.7886 * Cement \qquad (5d)$$
$$CCD - F2; \qquad L = 1907 - 0.6749 * Cement \qquad (5e)$$

3.5 Example of Construction of the CCD design matrix

The bounds represent the proportions of the constituent mixtures for low and high cement content of 8 and 20 percent respectively as shown in rows (1) and (3) of Appendix A.2. Sample summary mixture proportions estimation is shown in Table 1.

Table 1: Sample Summary Mixture proportions in coded and actual variables

CCD-0										
The design matrix		x_1=water; x_2=cement x_3=100% laterite						Y1=f_{c7}	Y2=f_{c28}	Y3=cost
		Variables						Response		
		coded			actual (kg)			N/mm²	N/mm²	Naira
Experiment no.	Point	x_1	x_2	x_3	x1	x2	x3	y1	y2	y3
1	Factorial	-1	-1	-1	261.26	145.33	1670.30	6.46	10.47	25.52
2	Factorial	1	-1	-1	265.75	145.33	1670.30	6.51	9.11	25.40
3	Factorial	-1	1	-1	261.26	334.05	1670.30	12.51	16.65	38.00
4	Factorial	1	1	-1	265.75	334.05	1670.30	11.20	17.37	37.83
5	Factorial	-1	-1	1	261.26	145.33	1816.63	6.60	10.53	25.26
6	Factorial	1	-1	1	265.75	145.33	1816.63	7.63	8.40	25.15
7	Factorial	-1	1	1	261.26	334.05	1816.63	12.17	16.15	37.10
8	Factorial	1	1	1	265.75	334.05	1816.63	12.40	17.28	36.94
9	Axial	-1.682	0	0	259.73	239.69	1743.45	9.54	12.02	31.69
10	Axial	1.682	0	0	267.28	239.69	1743.46	8.03	11.71	31.45
11	Axial	0	-1.682	0	263.50	80.97	1743.46	4.37	5.89	20.84
12	Axial	0	1.682	0	263.50	398.41	1743.46	14.71	19.90	41.27
13	Axial	0	0	-1.682	263.50	239.69	1620.40	7.79	12.84	32.10
14	Axial	0	0	1.682	263.50	239.69	1866.52	8.61	13.93	31.10
15	Centre	0	0	0	263.50	239.69	1743.46	9.08	13.12	31.57
16	Centre	0	0	0	263.50	239.69	1743.46	9.05	13.59	31.57
17	Centre	0	0	0	263.50	239.69	1743.46	9.23	13.10	31.57
18	Centre	0	0	0	263.50	239.69	1743.46	9.07	12.88	31.57
19	Centre	0	0	0	263.50	239.69	1743.46	8.99	12.76	31.57
20	Centre	0	0	0	263.50	239.69	1743.46	9.71	13.78	31.57

4.0 RESULTS AND DISCUSSION

The modeling of response predictions for brick strength at 7 and 28 days was carried out. The result of the study has shown that strength still remains the primary response prediction for describing all other properties. For example, the bricks with higher strength yield high Young's Modulus of elasticity and lower strain.

4.1 Description of the selected model using the Central Composite Design method

The statistical significance with low probability value of $p \leq 0.05$ calculated shows that a model, coefficient and intercept are significant and should be included in the model. Similarly, other inferences and residuals are calculated, to validate the fitted model prediction. Here, all the interaction terms have been eliminated; which shows that they are not significant in the model. The general second order quadratic model is of the form: $ax^2 - bx - c$ as shown in Table 2

CCD-0;	$1/(fc_{,28})$ = 0.21363-0.000856443 * Cement + 0.00000116686 * Cement^2
CCD-C1;	$1/(fc_{,28})$ = 0.2996-0.00147587 * Cement + 0.00000234307 * Cement^2
CCD-F1;	$1/(fc_{,28})$ = 0.23053-0.00101814 * Cement + 0.00000149142 * Cement^2
CCD-C2;	$1/(fc_{,28})$ = 0.29822-0.00141862 * Cement + 0.00000209428 * Cement^2
CCD-F2;	$1/(fc_{,28})$ = 0.25648 -0.00117542 * Cement + 0.00000169111 * Cement^2

Table 2(b) Response prediction for 7-day strength: CCD method

CCD-0:	$1/(f_{c,,7}) = 0.27845-0.000995268 * \text{Cement} + 0.00000121943 * \text{Cement}^\wedge 2$
CCD-C1:	$1/(f_{c,,7}) = 0.44452-0.00217823 * \text{Cement} + 0.00000339415 * \text{Cement}^\wedge 2$
CCD-F1:	$1/(f_{c,,7}) = 0.2871-0.0011235 * \text{Cement} + 0.00000147466 * \text{Cement}^\wedge 2$
CCD-C2:	$1/(f_{c,,7}) = 0.39451-0.00176367 * \text{Cement} + 0.00000239979 * \text{Cement}^\wedge 2$
CCD-F2:	$1/(f_{c,,7}) = 0.35948 -0.00146593 * \text{Cement} + 0.00000190695 * \text{Cement}^\wedge 2$

4.2 Comparative compressive strength results using Central Composite Design

It can also be validated that the measured properties of bricks produced are largely dependent on the quantity of cement and compactive effort and this is shown in Table 3. Similarly, production of bricks within 8 - 20 percent cement content design domain has shown reasonable results that would guide against bricks that would be durable. The results of bricks also satisfy minimum code requirements for compressive strength of load bearing walls: IS 3620 (1979) *Indian Standards*: 2.8MPa; *Australian Standard* 2733 (1984): 2.0N/mm^2; NIS 87 (2004) 'SON': 2.8N/mm^2; *SANS* 1215 (2008). *South African National Standards*: 3.5MPa.

Table 3: Comparative compressive strength results using Central Composite Design

			Hydraform (2014)	Aguwa (2009)	Guettala et al (2006)	Awoyera & Akinwurni (2014)	CCD - 0	CCD - C1	CCD - F1	CCD - C2	CCD - F2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
S/No.	Cement Content (%)	Compactive effort MN/m^2	10	4	15	2	10	10	10	10	10
1	4	COMPRESSIVE STRENGTH N/mm^2	-	1.9	-	-	-	-	-	-	-
2	5		3	-	15.4	-	-	-	-	-	-
3	6		-	3.5	-	-	-	-	-	-	-
4	7		5	-	-	-	-	-	-	-	-
5	8		-	5.1	-	2.3	8.78	7.46	8.84	8.76	8.22
6	10		8	6.1	18.4	3.49	10.35	9.23	10.63	10.54	10.09
7	12		-	6.5	-	3.96	12.14	11.27	12.69	12.58	12.37
8	14		-	7.1	-	-	14.03	13.25	14.82	14.69	14.89
9	15		10	-	-	-	-	-	-	-	
10	16		-	8.3	-	-	15.8	14.61	16.6	16.5	17.27
11	18		-	9.2	-	-	17.13	14.88	17.55	17.51	18.85
12	20		12	9.6	-	-	-	-	-	-	-
13	25		14	-	-	-	-	-	-	-	-

* The highlighted header row represents the compactive effort in MN/m^2

* The serial numbers 5 through 11; columns (8) through (12) are estimated using the example in Section 4.16

**CCD represents Central Composite method

* The Letters C1, F1 and C2, F2 immediately after the hyphen represents Coarse and Fine sand, 10 percent and 20 percent blends respectively

4.3 Example on optimization of component mixes to meet user-defined requirement using approximate CCD design

This method starts as an iterative process by initially selecting a cement quantity and thus obtaining the desired strength. The procedure is stated thus:

a) Start by calculating the quantity of cement from within the limits suggested. The quantity of cement may be estimated by substitution of the reciprocal (inverse) of the compressive strength and finding the positive root of the quadratic expression representing the response prediction for strength

ii) Substitute the cement quantity in the equation expressing the compressive strength
iii) Calculate the inverse or reciprocal of the value obtained in (ii)
iv) Calculate the corresponding quantity of laterite from the equation relating the calculated cement quantity
v) Calculate the corresponding quantity of water from the equation relating the calculated cement/ laterite ratio
vi) Calculate cement:laterite ratio

Using the same problem statement:

i) Starting with the lowest limit of cement (absolute volume = 0.046) represents 145kg of cement, that is (0.046 x 3150 = 145kg), where unit weight of cement is 3150kg/m^3
ii) Substituting the cement quantity in the equation

$$^{1}/_{fc_{28}} = 0.21363 - 0.000856443 \cdot 145 - 0.00000116686 \cdot 145^2 = 0.113979$$

i) The inverse is 8.77N/mm^2
ii) The corresponding quantity of laterite from equation (8) relating the calculated cement quantity =1927-0.7767 * *cement*; gives (1927-(0.7767*145)) = 1814.3785kg/m^3.
iii) The corresponding quantity of water from the equation relating the calculated cement/ laterite ratio is:water = 269.5-36.93*cement/laterite. This substitution gives = [269.5-{36.93*(145/1814.3785)}] = 266.55kg/m^3
iv) The cement:laterite ratio is 145/1814.3785 = 1:12.5 (8% cement content)

5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the CCD method, it has been shown that a specification writing for composite bricks satisfying user-specified requirements is practicable. Similarly, in using this method, responses capable of achieving target mean strengths can be developed. This procedure is implementable computationally. Either fine or coarse sand within grading zones 2 and 3 can be used, the blends are suitable and yielding nearly same results within the domain of cement:laterite considered.

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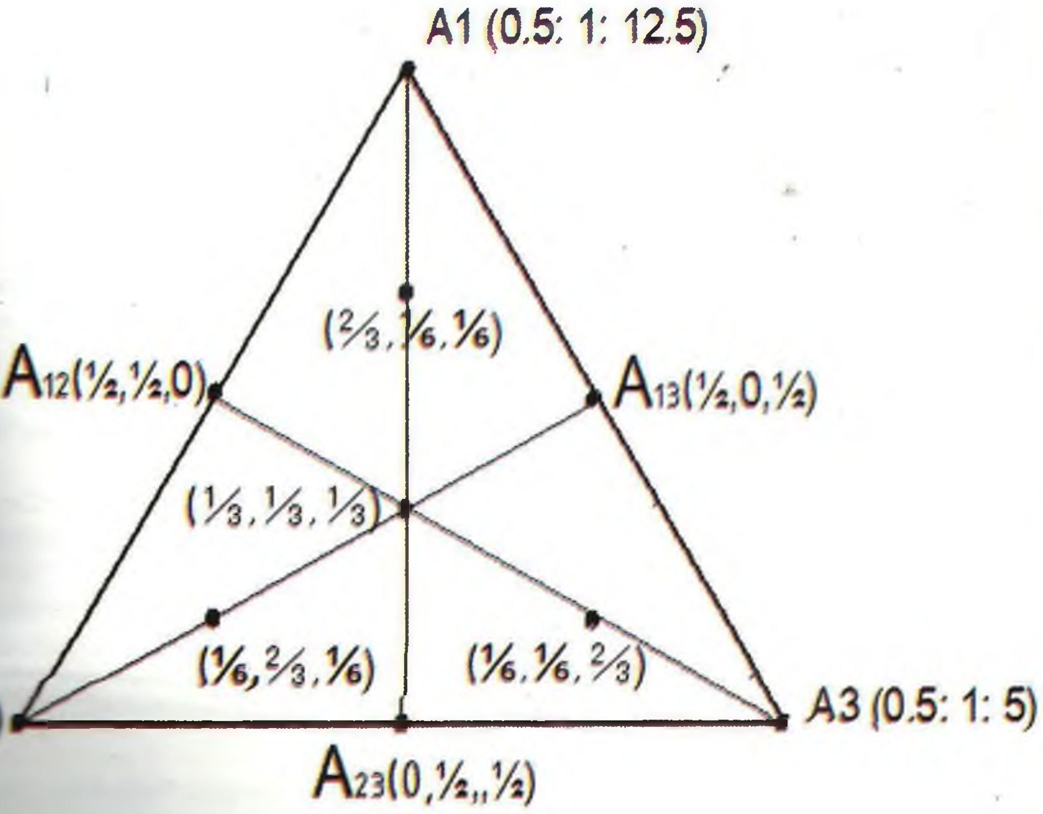
APPENDIX



Appendix A.1: An augmented [3, 2] Simplex lattice points

Appendix A.2:
Design matrix at Optimum Moisture Content using an augmented [3, 2] Simplex lattice

[illegible]	Pseudo component ratios x1=water, x2=cement, x3=laterite			Actual components ratios			Actual component mixes, kg/m^3 (0% sand replacement)		
[illegible]	X1	X2	X3	X_1 water	X_2 Cement	X_3 Laterite	water	cement	laterite
(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
[illegible]	1	0	0	1.83	1.00	12.50	265.75	145.33	1816.63
[illegible]	0	1	0	1.09	1.00	7.14	264.69	243.32	1737.29
[illegible]	0	0	1	0.78	1.00	5.00	261.26	334.06	1670.30
[illegible]	½	½	0	1.46	1.00	9.82	265.66	181.90	1786.22
[illegible]	½	0	½	1.31	1.00	8.75	265.45	202.25	1769.70
[illegible]	[illegible]	½	½	0.94	1.00	6.07	263.55	281.44	1708.35
[illegible]	[illegible]	[illegible]	[illegible]	1.16	1.00	7.68	265.03	227.79	1749.40
[illegible]	[illegible]	[illegible]	[illegible]	1.53	1.00	10.36	265.71	173.11	1793.44
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.00	6.61	264.22	260.80	1723.88
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.00	8.21	265.28	214.37	1760.00

(b)

S/no.	Coordinate Points		Pseudo component ratios x_1=water, x_2=cement, x_3=laterite			Actual components ratios			Actual component mixes, m^3		
			X1	X2	X3	x_1 water	x_2 Cement	x_3 Laterite	x_1 water	x_2 cement	x_3 laterite
(1)	(2)		(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	PURE	A1	1	0	0	1.83	1.00	12.50	0.266	0.046	0.688
2		A2	0	1	0	1.09	1.00	7.14	0.265	0.077	0.658
3		A3	0	0	1	0.78	1.00	5.00	0.261	0.106	0.633
4	BINARY	A12	½	½	0	1.46	1.00	9.82	0.266	0.058	0.677
5		A13	½	0	½	1.31	1.00	8.75	0.265	0.064	0.670
6		A23	0	½	½	0.94	1.00	6.07	0.264	0.089	0.647
7	CONTROL	C1	⅙	⅔	⅙	1.16	1.00	7.68	0.265	0.072	0.663
8		C2	⅔	⅙	⅙	1.53	1.00	10.36	0.266	0.055	0.679
9		C3	⅙	⅙	⅔	1.01	1.00	6.61	0.264	0.083	0.653
10	CENTRE	O	⅓	⅓	⅓	1.24	1.00	8.21	0.265	0.068	0.667

**The highlighted are the upper and the lower limits on the domains of constituent proportions by weight and volume*

**The quantities in columns 9, 10, 11 are the respective unit weights per m^3 of the mixture proportions for water, cement and laterites respectively*

**A1, A2, A3 represent pure blends, A12, A13, A23 represent binary blends, C1, C2, C3 represent control points and O represents centre point fitted in the factor space*

Appendix A.3: Laterite-cement Mix Design form

Laterite-cement mix design form

Job Title:...

Project Manager:.......................................

Physical and Geotechnical Parameters

Liquid Limit (%) ______

Plastic Limit (%) ______

Plasticity Index (%) 10 ≤ ______ ≤ 20%

Specific Gravity ______

Linear Shrinkage (mm) ______

Maximum Dry Density kg/m^3 ______

Colour ______

Soil Classification A-2-7

Iron Oxide Content Fe_2O_3 % ______

Sesquioxide Content %

ent Type: Ordinary Portland Cement

culations:

Quantity of Cement ______ kg

Target Mean Strength ______

The inverse is: ______ N/mm^2

Quantity of Laterite (eqn 5) ______ kg

Quantity of Water (eqn 4) ______ kg

Cement:Laterite Ratio ______

Cement Content ______ %

Adjustment for Water ______