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Design of statistical experiments to optimise the composition of clay-bonded moulding sand mixtures containing organic additives

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Abstract

Regression equations relating the response of green compression strength, shatter index and bulk density of moulding sand with variations in amounts of active clay, dead clay, moisture and a chosen organic additive have been developed and reported by the authors in an earlier paper. The usefulness of regression equations in optimizing the composition of the moulding sand to achieve the requisite properties is shown in this paper. Illustrative nomograms have been constructed which give optimal combination of the amounts of active clay and organic additives for known amounts of dead clay and moisture.

Key words: Design of experiments, composition variables, moulding sand, active clay, dead clay, moisture, organic additives, response variables, green compression strength, shatter index, bulk density, regression analysis, optimisation, nomogram.

1. Introduction

Statistical design of experiments has been employed extensively in many fields of research. In foundry, this technique has proved useful for optimisation of sand mixtures[1]. Clay-bonded sands account for the bulk of castings and it is not uncommon to find considerable amount of inactive (dead) clay in the moulding sand after repeated use. Though it has been known that organic additives minimise the detrimental effects of dead clay, no systematic work seems to have been done earlier to make a comparative evaluation of their effects. As statistical design of experiments provides an elegant path for this purpose and has the advantage of requiring minimum number of trials[2–8], this technique was used in this work for a comparative study. Properties of bentonite-bonded sands (bonded with calcium-based bentonite) containing known amount of dead clay, and starch or dextrin or molasses were determined and the relative effects evaluated. These have been reported in detail in a previous paper[2]. The regression equations developed earlier have been subsequently utilized to arrive at optimal combination of organic additives and active clay to get desired properties despite the presence of dead clay.

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2. Experimental

Silica sand from Mangalore sea coast having a fairly uniform grain size distribution with AFS, GFN 56, AFS clay of 0.4% and uniformity coefficient of about 2 was used as the base sand in the design of experiments. Foundry-grade calcium-based bentonite formed the binder. Three commercially available organic additives, *viz.*, starch,dextrin and molasses were used as organic additives and were added individually in the experiments. Moulding sand mixtures were prepared in a laboratory-type sand muller having a batch capacity of about 5 kg. Sand with known amount of dead clay and the chosen organic additive was dry mixed for 1 min, and subsequently mulling was carried out for about six minutes after the addition of water. The mulled mixtures were stored in polyethylene bags nearly half-an-hour before testing for green-sand properties. Detailed description of the experimental procedure, criteria for establishing optimum levels of clay and moisture contents and preparation of base sand with a known amount of dead clay to simulate the conditions of reused moulding sands on foundry floor are provided elsewhere[2,3].

The standard DIN procedure (52401) was adopted for preparing the 50 mm dia × 50 mm height AFS standard sand specimens. Green compression strength, shatter index and bulk density were determined using a GF Universal sand testing machine, a Ridsdale shatter test equipment and a sensitive laboratory balance respectively. The moisture content in the sand was determined precisely by the standard oven drying method.

The regression equations developed earlier[2] have been used here for the optimization of composition of a given moulding mix (through nomograms) to realise the required properties of the sand mixtures on the foundry floor.

3. Results and discussion

The technique of statistical design of experiments has been applied by the authors in a previous paper[2] to relate the four composition variables, *viz.*, active clay, dead clay, moisture and organic additive with the properties of sand mixture. The purpose then was

Table I
The range and intervals of variations involved in the design of factorial experiments

Sl· no·	Factor	Codes	Upper level (+1)	Base level (0)	Lower level (−1)	Interval of variations
1·	Dead clay (%)	X_1	24	16	8	8
2·	Active clay (%)	X_2	10	8	6	2
3·	Moisture (%)	X_3	11	9	7	2
4·	Additives (%)	X_4				
	i· Starch		2·63	1·73	0·83	0·90
	ii. Dextrin		1·50	1·00	0·50	0·50
	iii. Molasses		3·38	2·26	1·13	1·13

to understand the role of dead clay on moulding sand behaviour and to assess the relative effectiveness of the three organic additives in minimising the detrimental effect of dead clay. The organic additive used was either starch or dextrin or molasses in the range of variations shown in Table I. Using the test results for the three additives shown in Table II, non-linear regression equations were developed relating the response properties *viz.*,

Table II

Results as per 2^4 factorial experiments in the case of starch, dextrin and molasses addition

Sl. no.	Experiments	Bulk density (Specimen wt. in g)			Green compression strength (g/cm^2)			Shatter index(%)		
		Trial (I)	Trial (II)	Mean Y	Trial (I)	Trial (II)	Mean Y	Trial (I)	Trial (II)	Mean Y
Starch										
1	(+ + + +)	156.27	156.30	156.285	655	655	655.0	85	86	85.5
2	(+ + + −)	161.52	161.10	161.310	630	625	627.5	77	79	78.0
3	(+ + − +)	147.66	147.49	147.575	1010	1005	1007.5	62	68	65.0
4	(+ + − −)	148.53	148.40	148.465	940	910	925.0	58	59	58.5
5	(+ − + +)	162.68	162.40	162.540	760	740	750.0	65	64	64.5
6	(+ − + −)	160.85	160.53	160.690	520	525	522.5	47	48	47.5
7	(+ − − +)	150.13	150.23	150.180	570	575	572.5	51	52	51.5
8	(+ − − −)	152.30	151.88	152.090	480	510	495.0	44	40	42.0
9	(− − − −)	155.75	155.38	155.565	570	580	575.0	65	66	65.0
10	(− − − +)	156.08	155.65	155.865	710	720	715.0	73	69	71.0
11	(− − + −)	162.29	162.82	162.555	380	375	377.5	59	61	60.0
12	(− − + +)	163.98	163.66	163.820	540	530	535.0	75	76	75.5
13	(− + − −)	151.61	151.95	151.780	1000	1005	1002.5	64	68	66.0
14	(− + − +)	153.57	153.90	153.735	1000	1000	1000.0	48	50	49.0
15	(− + + −)	164.01	163.65	163.830	920	900	910.0	92	94	93.0
16	(− + + +)	162.07	161.93	162.000	1060	1070	1065.0	95	95	95.0
Dextrin										
1	(+ + + +)	162.54	162.65	162.595	720	735	727.5	86	86	86.0
2	(+ + + −)	158.45	158.55	158.500	805	835	820.0	87	89	88.0
3	(+ + − +)	147.41	147.50	147.455	965	975	970.0	64	64	64.0
4	(+ + − −)	149.45	149.73	149.590	1030	1010	1020.0	72	73	72.5
5	(+ − + +)	157.50	157.31	157.405	345	350	347.5	41	45	43.0
6	(+ − + −)	157.43	157.29	157.360	350	360	355.0	41	39	40.0
7	(+ − − +)	150.21	149.87	150.040	425	430	427.5	40	44	42.0
8	(+ − − −)	153.71	153.35	153.530	460	470	465.0	42	39	40.5
9	(− − − −)	156.57	156.75	156.660	570	580	575.0	69	71	70.0
10	(− − − +)	156.30	156.60	156.450	535	540	537.5	66	71	68.5
11	(− − + −)	163.47	163.52	163.495	390	395	392.5	63	63	63.0
12	(− − + +)	165.20	165.07	165.135	385	380	382.5	61	61	61.0
13	(− + − −)	153.17	153.62	153.395	1025	1030	1027.5	74	79	76.5
14	(− + + −)	152.10	152.37	152.235	950	940	945.0	78	83	80.5
15	(− + + −)	163.92	163.86	163.890	815	820	817.5	90	92	91.0
16	(− + + +)	165.34	165.12	165.230	770	765	767.5	96	94	95.0

Table II (contd.)

Sl. no.	Experiments	Bulk density (Specimen wt. in g)			Green compression strength (g/cm^2)			Shatter index(%)		
		Trial (I)	Trial (II)	Mean Y	Trial (I)	Trial (II)	Mean Y	Trial (I)	Trial (II)	Mean Y
Molasses										
1	(+ + + +)	166.49	166.68	166.585	675	680	677.5	84	90	87.0
2	(+ + + −)	164.07	163.63	163.850	840	860	850.0	84	85	84.5
3	(+ + − +)	148.56	148.95	148.755	800	820	810.0	78	82	80.0
4	(+ + − −)	148.79	148.53	148.660	890	875	882.5	49	55	52.0
5	(+ − + +)	170.10	170.06	170.080	290	295	292.5	42	40	41.0
6	(+ − + −)	157.22	157.72	157.470	290	280	285.0	40	40	40.0
7	(+ − − +)	156.50	156.72	156.610	385	395	390.0	45	46	45.5
8	(+ − − −)	153.76	153.14	153.450	460	465	462.5	33	35	34.0
9	(− − − −)	159.20	159.75	159.475	375	380	377.5	65	68	66.5
10	(− − − +)	163.06	163.46	163.260	310	290	300.0	63	65	64.0
11	(− − + −)	168.53	168.37	168.450	275	280	277.5	49	50	49.5
12	(− − + +)	170.38	170.68	170.530	225	200	212.5	44	44	44.0
13	(− + − −)	154.15	153.96	154.055	950	980	965.0	92	93	92.5
14	(− + − +)	156.09	156.42	156.255	875	885	880.0	95	97	96.0
15	(− + + −)	167.83	168.06	167.945	780	765	772.5	94	95	94.5
16	(− + + +)	173.06	172.83	172.945	650	660	655.0	96	96	96.0

green compression strength, shatter index and bulk density to variations in dead clay, active clay, moisture and additives. These non-linear regression equations, developed using a computer programme, are given below:

3.1 *Regression equations for starch addition*

Green compression strength,(g/cm^2),

$$Y_{1g} = 733.44 - 39.06X_1 + 165.63X_2 - 53.13X_3 + 54.06X_4 - 56.25X_1X_2 - (2.5X_1X_3) - (2.18X_1X_4) - 31.56X_2X_3 - 21.25X_2X_4 - 16.88X_3X_4 - 75.3X_1X_2X_3 - (5.0X_1X_3X_4) - (4.06X_2X_3X_4) - (3.13X_1X_2X_4) - 21.56X_1X_2X_3X_4. \quad (1)$$

Shatter index, in %,

$$Y_{1s} = 66.72 - 5.16X_1 + 7.03X_2 + 8.16X_3 + 2.91X_4 + 3.16X_1X_2 - (0.84X_1X_3) + 2.15X_1X_4 + 5.96X_2X_3 - 3.03X_2X_4 + 2.34X_3X_4 - 3.28X_1X_2X_3 - (1.28X_1X_3X_4) + (0.15X_2X_3X_4) + 1.46X_1X_2X_4 + (0.96X_1X_2X_3X_4). \quad (2)$$

Bulk density, (specimen weight in g.),

$$Y_{1b} = 156.76 - 1.88X_1 - 1.15X_2 + 4.86X_3 - 0.27X_4 - 0.34X_1X_2 + 0.45X_1X_3 - 0.48X_1X_4 + 0.37X_2X_3 - 0.46X_2X_4 - 0.19X_3X_4 - 0.29X_1X_2X_3 - 0.79X_2X_3X_4 - 0.28X_1X_2X_4 - 0.19X_1X_2X_3X_4. \quad (3)$$

3.2 *Regression equations for dextrin addition*

Green compression strength,

$$Y_{2g} = 661.09 - 19.53X_1 + 225.78X_2 - 84.84X_3 - 22.97X_4 + 17.03X_1X_2 + (5.78X_1X_3) - (0.46X_1X_4) - 18.91X_2X_3 - 11.41X_2X_4 + (2.97X_3X_4) - (12.65X_1X_2X_3) - (4.53X_1X_3X_4) - (4.20X_2X_3X_4) - (0.78X_1X_2X_4) - (4.84X_1X_2X_3X_4). \quad (4)$$

Shatter index,

$$Y_{2s} = 67.59 - 8.09X_1 + 14.09X_2 + 3.28X_3 - (0.09X_4) + (4.03X_1X_2) + (1.46X_1X_3) - (0.65X_1X_4) + 5.03X_2X_3 - (0.22X_2X_4) + (0.46X_3X_4) - (0.41X_1X_2X_3) + (0.53X_1X_3X_4) + (0.34X_2X_3X_4) - 1.65X_1X_2X_1 + (0.28X_1X_2X_3X_4). \quad (5)$$

Bulk density,

$$Y_{2b} = 157.06 - 2.50X_1 - 0.45X_2 + 4.64X_3 + (0.007X_4) + 0.42X_1X_2 - 0.23X_1X_3 - 0.19X_1X_4 + 1.30X_2X_3 + 0.26X_2X_4 + 0.88X_3X_4 + 0.31X_1X_2X_3 + 0.34X_1X_3X_4 + 0.21X_2X_3X_4 + 0.42X_1X_2X_4 + (0.13X_1X_2X_3X_4). \quad (6)$$

3.3 *Regression equations for molasses addition*

Green compression strength,

$$Y_{3g} = 568.13 + 13.13X_1 + 243.44X_2 - 65.31X_3 - 40.94X_4 - 19.69X_1X_2 + 10.30X_1X_3 + (2.19X_1X_4) - (7.50X_2X_3) + 15.0X_2X_4 - (2.5X_3X_4) + (21.25X_1X_2X_3) - 14.06X_2X_3X_4 - (7.5X_1X_2X_4) - 8.40X_1X_2X_3X_4. \quad (7)$$

Shatter index,

$$Y_{3s} = 66.69 - 8.69X_1 + 18.63X_2 + (0.38X_3) + 2.5X_4 - (0.75X_1X_2) + 4.75X_1X_3 + 2.80X_1X_4 + 4.81X_2X_3 + 1.94X_2X_4 - 2.56X_3X_4 - (0.06X_1X_2X_3) - 1.94X_1X_3X_4 - (0.88X_2X_3X_4) + (0.31X_1X_2X_4) - (1.0X_1X_2X_3X_4). \quad (8)$$

Bulk density,

$$Y_{3b} = 161.15 - 2.97X_1 - 1.27X_2 + 6.08X_3 + 1.98X_4 + (0.05X_1X_2) + 0.23X_1X_3 + 0.35X_1X_4 + 1.87X_2X_3 - 0.73X_2X_4 + 0.82X_3X_4 + (0.08X_1X_2X_3) + 0.69X_1X_3X_4 - (0.14X_2X_3X_4) - (0.89X_1X_2X_4) - (0.71X_1X_2X_3X_4) \quad (9)$$

where Y_{ig}, Y_{is} and Y_{ib} respectively represent green compression strength, shatter index and bulk density of three additives, ω = 1, 2 and 3 stand for the three additives, starch, dextrin and molasses respectively. Those of the terms which are bracketed in the above equations were found to be relatively insignificant after assessment by Student's 't' test criteria at 1% as well as at 5% significance levels. Hence these terms could be ignored while optimising. The coded factors, X_1, X_2, X_3, & X_4 (see Table I), in the above equations are as enumerated below:

X_1 = (dead clay per cent − 16)/8
X_2 = (active clay per cent − 8)/2
X_3 = (moisture per cent − 9)/2
X_4 = (starch per cent − 1.73)/0.9
X_4 = (dextrin per cent − 1)/0.5
X_4 = (Molasses per cent − 2.26)/1.13

These equations are valid within the range of variations of the factors studied and are applicable under the experimental conditions mentioned in the present work.

4. Optimization of the composition of sand mixtures

As there are four independent variables, two need to be fixed so that the relationship between the other two may be represented in two dimensional nomograms similar to those constructed by earlier investigators[1,8]. For the purpose of this paper the moisture content and the dead clay content were treated as fixed, being held at their base levels and the relationship between the active clay and the chosen organic additive (starch, dextrin or molasses) for these conditions was established in the form of nomograms (fig. 1). The optimal combination of active clay and organic additive was then determined as that combination which satisfied the following criteria:

a) Green compression strength < 700 g/cm^2(10 psi)
b) Shatter index > 70%
c) Bulk density < 1.55 g/cm^3.

These criteria were chosen corresponding to the norms applicable to synthetic moulding sand used in foundries[9,10]. These procedure has been elaborated in what follows:

4.1 *Optimization of starch-active clay combination*

Figure 1(a) shows a nomogram constructed in the case of starch as an additive. The X and Y axes in the monogram are active clay (X_2) and starch (X_4) contents respectively. The dead clay content and moisture content were kept constant at zero levels (*i.e.*, $X_1 = X_3 = 0$). Since the factors X_1 and X_3 are fixed the regression equations derived earlier for starch *viz.*, (1), (2) and (3) reduce to the following simple form:

(i) Green compression strength (g/cm^2)

$$Y_{1g} = 733.44 + 165.63X_2 + 54.06X_4 - 21.25X_2X_4 \qquad (10)$$

(ii) Shatter index (%)

$$Y_{1s} = 66.72 + 7.03X_2 + 2.91X_4 - 3.03X_2X_4. \qquad (11)$$

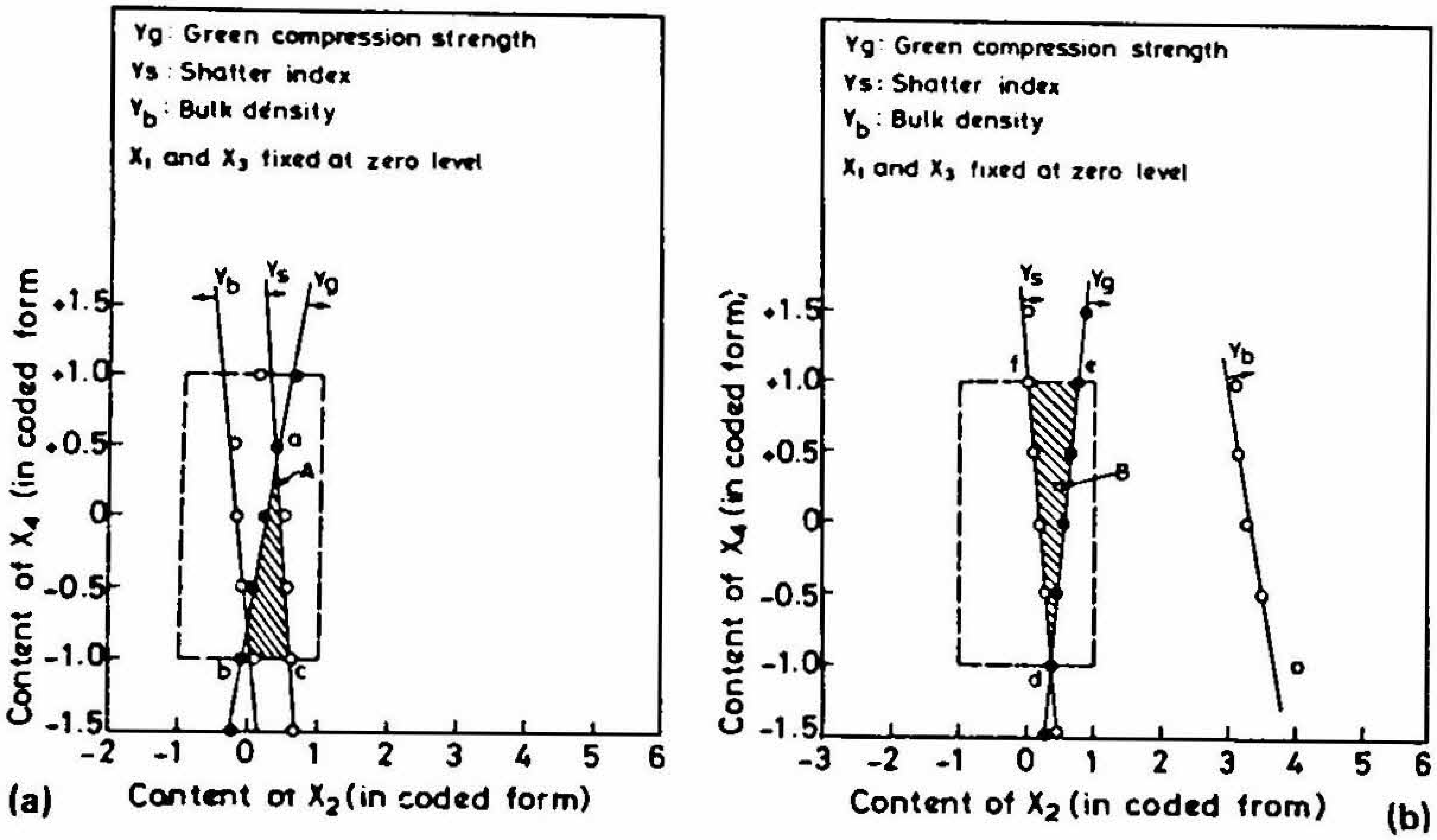

Fig. 1 Nomogram for optimising sand composition; (a) additive: starch. (b) additive: molasses.

(iii) Bulk density (g)

$$Y_{1b} = 156.76 - 1.15X_2 - 0.27X_4 - 0.46X_2X_4. \tag{12}$$

In the nomogram shown in fig.1, the plots of the above equations are given with arrows indicating the direction of movements of the plots for the value of Y lower than the maximum required (except for Y_{1s} more than the minimum required). Thus the area "abc" is obtained from which for a selected composition of the moulding sand, the optimum properties of the sand mixture can be determined and *vice versa*. The dotted rectangle gives the area which has been actually covered by the test during this investigation.

As an illustration of the validity of the optimization obtained through the nomogram, sand composition corresponding to a point 'A' inside the optimal region will now be considered. The composition in the coded form for this point is as follows:

$$X_1 = 0,\ X_2 = +0.15,\ X_3 = 0 \text{ and } X_4 = +0.4.$$

This composition also corresponds to the values required to obtain the green compression strength, bulk density and shatter index specified earlier. The derived value of the properties from the nomogram are also listed in Table III, where the excellent correspondence with the experimental values may be noted. A similar nomogram can be constructed for moulding sand with dextrin.

Table III
Experimental and calculated values of sand properties
Additives: (a) Starch and (b) Molasses

Property	Green compression strength, (g/cm^2)		Shatter index (%)		Bulk density (g/cm^3)	
	a	b	a	b	a	b
(i) Experimental	700	687	70.00	78	1.524	1.570
(ii) Calculated	770	677	69.00	77	1.520	1.562

4.2 *Optimization of molasses-active clay combination*

In the case of molasses also nomogram was constructed in the same way. The regression equations of molasses, (7), (8) and (9), reduce to the following form:

i. Green compression strength:
$$Y_{3g} = 568.13 + 243.44X_2 - 40.94X_4 - 15.0X_2X_4. \quad (13)$$

ii. Shatter index (%):
$$Y_{3s} = 66.69 + 18.63X_2 + 2.5X_4 + 1.94X_2X_4. \quad (14)$$

iii. Bulk density (g):
$$Y_{3b} = 161.15 - 1.27X_2 + 1.98X_4 - 0.73X_2X_4. \quad (15)$$

In fig. 1(b), the above equations have been plotted for the values of Y at a minimum with arrows indicating the direction of movement of the plots for the values of Y lesser than the maximum required as discussed earlier. Thus an area, 'def' is obtained here, from which for a selected composition of the sand, optimum properties of the sand mixture can be determined. The dotted rectangle shows the area which has been actually covered by the tests during this part of the investigation.

For verification of the validity of the optimization through the use of nomogram, the sand composition corresponding to point B inside the optimal region was selected. The properties of this composition as obtained experimentally and through nomogram are compared in Table III, where again the excellent correspondence may be noted.

5. Conclusion

Nomograms have been constructed which give optimum combination of active clay and chosen organic additive in order to get desired properties in the clay-bonded moulding sands containing given amounts of dead clay and moisture. Similar procedure may be adopted to relate any two of the variables at a time.

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