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Optimization of rheological properties of granular sub-base using cement stabilization

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Pavement performance is associated with the characteristics of soil sub-grade and underlying layers. The poor soil subgrade and sub-base can deteriorate the overlying upper pavement layers. The weak layers can be improved by stabilization to get the optimum performance of the pavement. The study is abort stabilized base and sub-base soils using ordinary Portland cement 43 (OPC 43). With the variation of cement from 1.5% to 7%, stabilized samples have been treated to have the highest moisture content and dry density possible. An optimization model has been developed for compressive strength using response surface methodology (RSM). The results have been obtained from the model satisfy the real-life field conditions. The outcomes suggest that the cement-stabilized gravels meet the compressive strength criteria specified by the Ministry of Rural Development (MoRD) specifications for rural roads in India.

Keywords: Cement stabilization, Compressive strength, Optimization, Response surface methodology

1 Introduction

Granular material is placed at the upper level of the sub-grade in the sub-base layer. The sub-base is often the primary load-bearing pavement layer. Its function is to allocate the load uniformly throughout the sub-grade. It allows traffic stresses to be lowered to appropriate levels in the road cross-section, preventing excessive deformation. It also serves as a working plate shape for building the higher pavement layers and acts as a drainage layer by avoiding soaking the sub-grade. Therefore, it is a barrier between the sub-grade and the road foundation. Thus, sub base is required to strengthen the pavement's structure beneath the roadway's surface. Soil stabilization or modification refers to improving the soil properties by blending and mixing other materials using mechanical compaction or chemicals. The choice of an appropriate stabilization method varies on the type of soil and its state. To strengthen its road surface and geotechnical applications, soil improvement includes increasing its bearing capacities, dry unit weight, volume changes, and other waste material.

Soil cement stabilization is the process in which cement is used as an admixture to cause bonding with soil particles that grow into the crystal, which interlocks with each other by giving high compressive strength. This improves the quality and bearing capacity of soil by making it more resistant to softening by water and makes it more desirable and efficient to use at a reasonable cost in comparison to other modes of stabilization[1].

Stabilization can be classified based on the additive types and the efforts used. The type of stabilization depends on various factors and underlying soil properties, which can be mechanical, physical, chemical, and physio- chemical technique, or a combination of any. Various additives have been used for the stabilization of soil based on specific requirements[1-19]. As a chemical admixture, sodium hydroxide effectively stabilizes clayey soils and sandy soil[1]. Cement kiln dust improved the shear strength properties of desert sands[2]. In one study, mechanical compaction and chemical stabilization combination improved the clay sandy soil and gave its optimum rheological properties like water resistance, shrinkage, splitting tensile strength, and compressive strength[3]. Waste materials have also been utilized for soil stabilization and enhanced soil stabilization properties[4,5,9]. In a few studies, cement has been used as an additive with waste materials for soil stabilization and improved the associated soil properties[5-7,12].

Cement treated base (CTB) is a compacted cement, aggregate, and water mixture based on specific

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strength constraints. Cement raises the shear strength of the soil, resulting in the overall gaining of strength, leading to load-bearing capacity & increases the life span of the road. The low stiffness causes unstabilized bases to deflect more than stabilized bases, which causes higher surface stresses and fatigue cracking. CTB offers greater stiffness, leading to lower deflection and causing less distresses. Several studies have used cement for stabilization purposes[2-8,11-17,20-31]. CTB can be used as slope protection on dams and embankments, highways, pavements, and terminals for roads and railways. CTB has improved the rheological properties of modified soil[2,3,9,11,14-17,21,24,29,31]. However, the dosages vary on the specific soil. Compressibility, compressive strength, Optimum Moisture Content (OMC) and shear strength properties of desert sands have been improved by cement stabilization of various soils[2,9,11,21].

However few additives have also enhanced the mechanical properties of modified soil[6,7,12-14,20,22,25,26]. Zeolite has improved cement-treated soils' unconfined compressive strength (UCS)25. Few waste materials like cement kiln dust (CKD), waste cooking oil (WCO), rice husk ash (RHA), and fly ash (F.A.) have improved the associated properties of cement-treated soil[5,6,12,13,15,17,20,22]. Nanosilica has also improved cement-treated sandy soil's mechanical and microstructure properties[25,26]. However, overall performance depends on the optimum dosage of additives and underlying soil properties. The optimum dosage of additives is crucial for cost-saving and project management. Various studies have used RSM to determine the optimum dosage of additives based on specific requirements. RSM-developed models have efficiently predicted the desired response to soil stabilization problems[32-34].

2 Materials and Methods

Sandy soil and gravel used in this study were brought from Akhewala Dahar and Sobhasar. The gravel was categorized as well-graded (G.W.) per Indian Standard Soil Classification System (ISSCS). In the ISSCS classification system, the soil is classified based on plasticity. It is known as high plasticity if the liquid limit is more than 50%, intermediate plastic if the liquid limit is between 35% to 50%, or low plastic if the liquid limit is less than 35%.Gravel is classified as well-graded gravel if the percentage passing from 75- the micron sieve is less than 5%. These classifications are established on the particle size evaluation and its consistency limit.

The uniformity coefficient (Cu) should not be less than five obtained from the particle size distribution curve. If material passing from a 425-micron sieve is plastic, its liquid limit should not exceed 45%, and its plasticity index not greater than 20%. Therefore, grain size analysis was carried out as per Indian procedure. Grain size analysis results indicate that soil contains 74.84% sand and 23.62% gravel. The Maximum Dry Density (MDD) and OMC observed are 1.96 and 10.10%, and values of Cu and Cc are 6.67 and 0.323, within the range after getting all the required values unconfined compressive strength test was done to determine compressive strength values for each cement content.

Cement stabilization is very effective for granular and sandy soils. Specifications in conformity with the guidelines of Rural Roads have been selected for reference. Therefore, varying percentages of cement with gravel and sand have been used to check its enhancement in compressive strength. Locally available soil and gravel in the proportion of (40% sand and +60% gravel) based on trial were used to get the desired compressive strength needed to meet the requirements of "MoRD specifications "Cement-varying content was added to check its required Unconfined Compressive Strength (UCS).

As per the specifications of MoRD for the base and Sub-base course, the ingredients were blended. Combined Gradation & proportioning of all aggregates for cement stabilization have been given in Table 1. Particle size distribution of gravel and sand and the specifications requirements of the Sub-base are shown in Fig. 1.

3 Results and Discussion

A minimum laboratory 7-day compressive strength for sub-base/base course as per MoRD specifications is 1.70 Mpa and 2.76 Mpa. These values should be achieved to enhance the strength and properties of the sub-base to make it desirable for use.

Compressive strength was measured from cement content varying from 1.5% to 7.5% with an increment of 1.5%. Dry density and bulk density increased to 10% water content, and after that decrease was found as per Fig. 2. Compressive strength variation with cement, w/c ratio, gravel, and sand content has been shown in Fig. 3. Compressive strength increased as per increasing gravel content as per Fig. 3 (c). However, a decrease was found with increasing sand content as per Fig. 3(d).

Table 1 — Combined gradation & proportioning for cement stabilization

IS Sieve Size	All in Aggregate		% by weight Passing		
% Blend	Sand (40%)	Gravel (60%)	Sub Base finer than	Base within the range	
				Lower	Upper
53.00	100	100	100	100	100
37.50	100	97.99	95	95	100
19.00	100	89.53	45	45	100
9.50	100	73.22	35	35	100
4.75	100	60.63	25	25	100
0.600	97.350	28.82	8	8	65
0.300	89.790	19.97	5	5	40
0.075	2.000	1.24	0	0	10

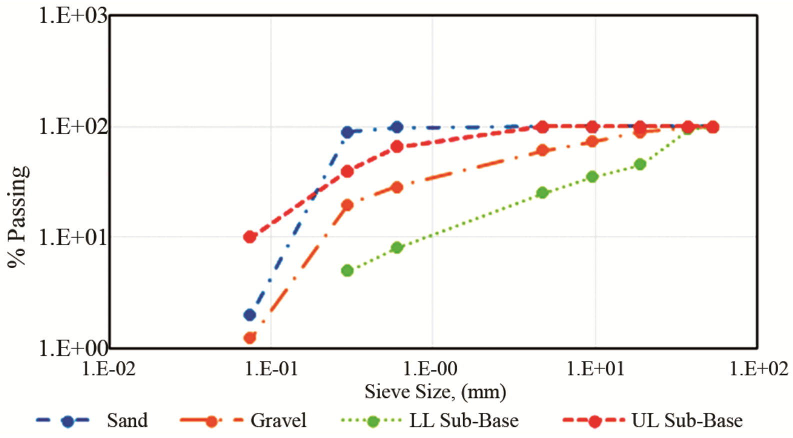

Fig. 1 — Particle size distribution and specifications requirements.

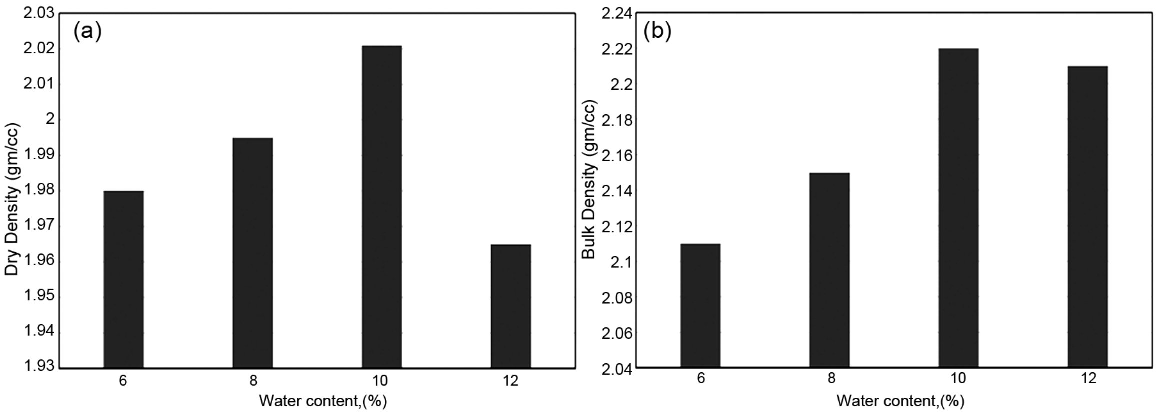

Fig. 2 — (a) Dry density and (b) bulk density versus water content.

Sand and gravel were used at 40% and 60%, respectively, based on trails to achieve the percentage passing within the range as per base course specifications. However, based on optimization results, gravel content was increased to assess the effect of gravel increase on compressive strength from 80% to 100% as per Fig 3 (c & d).The compressive strength was increased as per increasing cement. The compressive strength achieved from the various trial tests did not satisfy the desired strength per the specifications. Therefore, the trial of the design mix, by replacing sand with 100% gravel, was used with different cement content.

3.1 Optimization model

Experimental outcomes of all the trials for compressive strength have been shown in Table 2 with blend identification. The response surface model

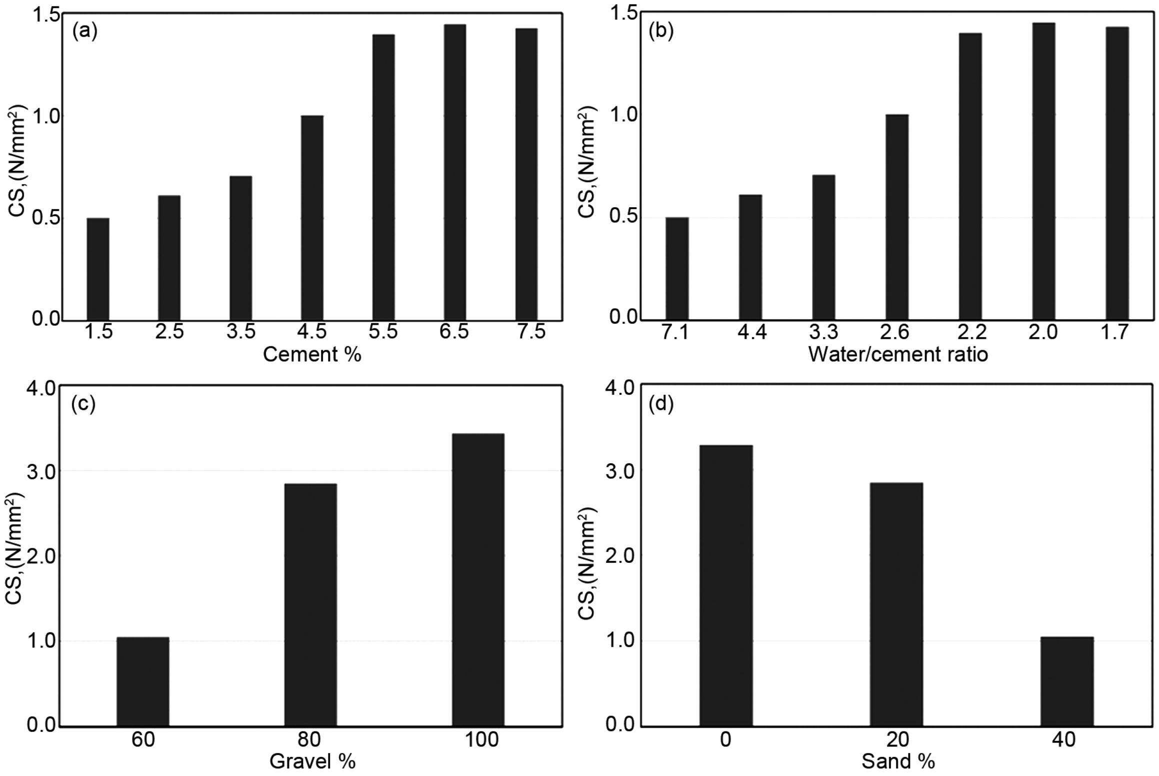

Fig. 3 — Compressive strength variation with (a) cement, (b)w/c ratio, (c) gravel, and (d) sand content

Table 2 — Effect of ingredients on compressive strength

Blend ID	W/C ratio	Gravel as (%)	Sand as B (%)	Cement as C (%)	Average compressive strength, (N/mm$^{2)}$
A1	2.42	100	0	5.0	3.44
A2	2.42	80	20	5.0	2.9
A3	2.42	60	40	5.0	1.1
A4	7.13	60	40	1.5	0.5
A5	4.44	60	40	2.5	0.6
A6	3.29	60	40	3.5	0.7
A7	2.65	60	40	4.5	1.0
A8	2.24	60	40	5.5	1.4
A9	1.95	60	40	6.5	1.4
A10	1.75	60	40	7.5	1.4

has generated an approximate relationship between input variables and output as a polynomial. Linear equation for Input factors and Output, *i.e.*, Compressive strength in the form of coded factors, is given below-

Compressive Strength =

$$2.95966*A + 0.209827*B + 10.7615*C \quad \ldots(1)$$

The factors' high and low levels have been encrypted as +1 and -1, respectively. The encrypted equation facilitates identifying the factors' relative impact by comparing the factor coefficients. The encrypted factors equation helps with response prediction for particular levels of each factor.

Figure 4 shows the performance prediction of the model for compressive strength values. Actual and predicted values have shown good agreement. Thus, it can be predicted that the proposed model serves prediction purposes well and generates a response surface showing very close parameter interaction.

Table 3 and Table 4 show the Fit Summary and Analysis of Variance (ANOVA) table for input parameters, interaction terms, and other parameters.

Model F-value 62.82 and p-value less than 0.0001 provides strong evidence against the null hypothesis and depict that model is highly significant and valuable. Lack of fit also shows a p-value less than 0.0001 and signifies that model correctly specifies the relationship between response and predictors. The f-value of terms A and B implies that these terms are significant in the model.

Table 5 and Table 6 show the fit statistics. Adequate precision determines the signal-to-noise ratio. A ratio more than 4 is suitable. Our model ratio of 23.078 signifies a sufficient signal.

Figure 5 shows the plot for the two-component mix. The x-axis shows the variation of gravel (X1) and sand (X2) on a single axis at a proportionate rate. Moving right to the X-axis increases the gravel and reduces the sand. From the output plot, It can be seen that increasing gravel and reducing sand, i.e., moving to the right on the X-axis improves the compressive strength (C) linearly.

3.2 Response surface plots

Figure 6 (a & b) shows the response surface for a combination of different input factor and compressive

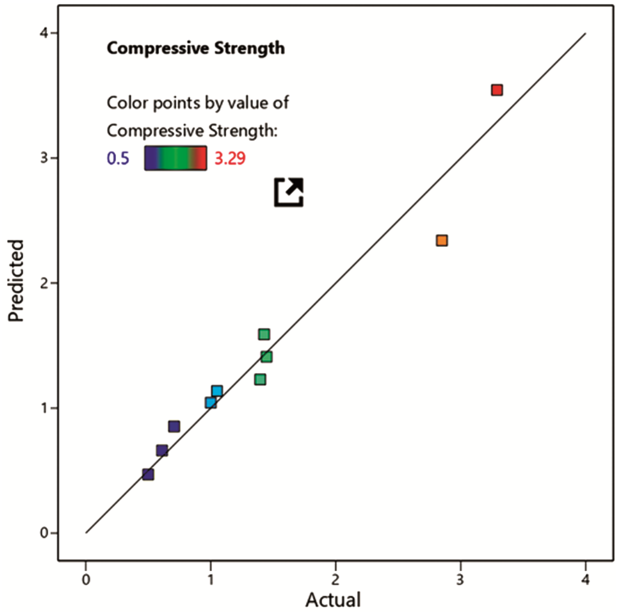

Fig. 4 — Performance prediction of the model.

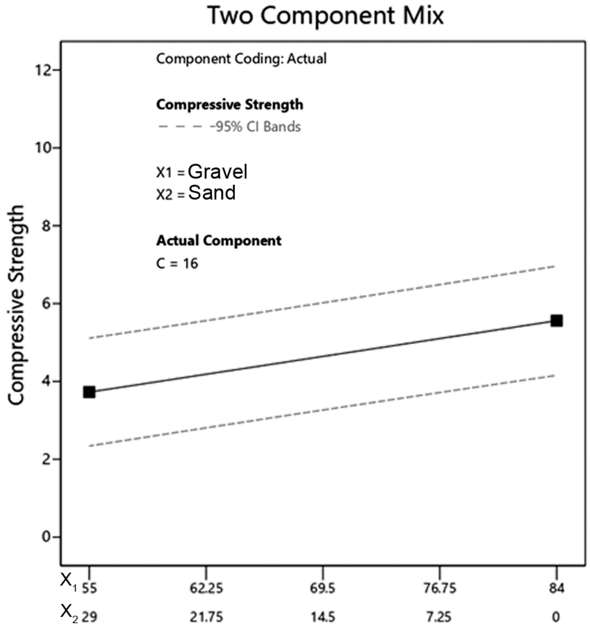

Fig. 5 — Effect of simultaneous variation in gravel and sand.

Table 3 — Fit Summary

Source	Sequential p-value	Adjusted R²	Predicted R²	
Linear	< 0.0001	0.9322	0.7067	Suggested
Quadratic	0.0168	0.9815		Aliased

Table 4 — Analysis of variance for model

Source	Sum of Squares	df	Mean square	F-value	p-value	
Model	7.45	2	3.72	62.86	< 0.0001	significant
$^{(1)}$Linear Mixture	7.45	2	3.72	62.86	< 0.0001	
Residual	0.4147	7	0.0592			
Cor Total	7.86	9				

Table 5 —Fit statistics

Std. Dev.	0.2435	R²	0.9472
Mean	1.43	Adjusted R²	0.9321
C.V. %	17.05	Predicted R²	0.7068
		Adeq Precision	23.0784

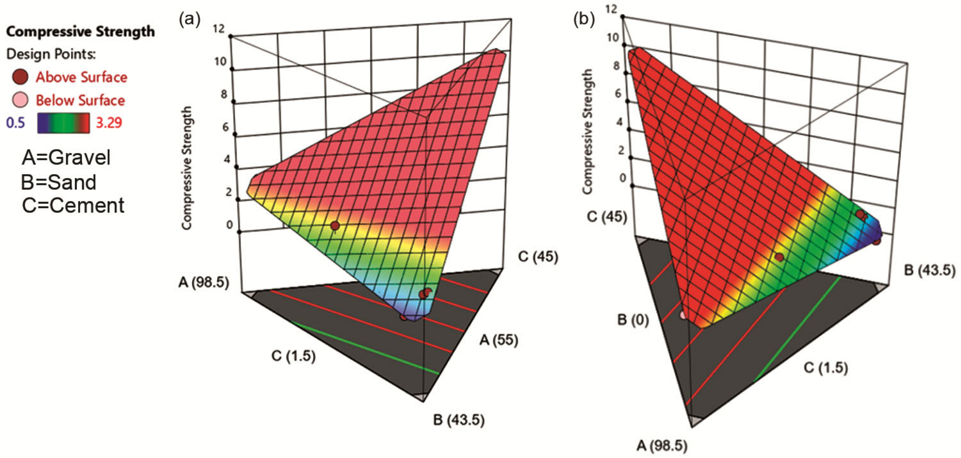

Fig. 6 — Response surface showing variation (a) Gravel & Cement proportion and (b) Sand & Cement proportion on front aris.

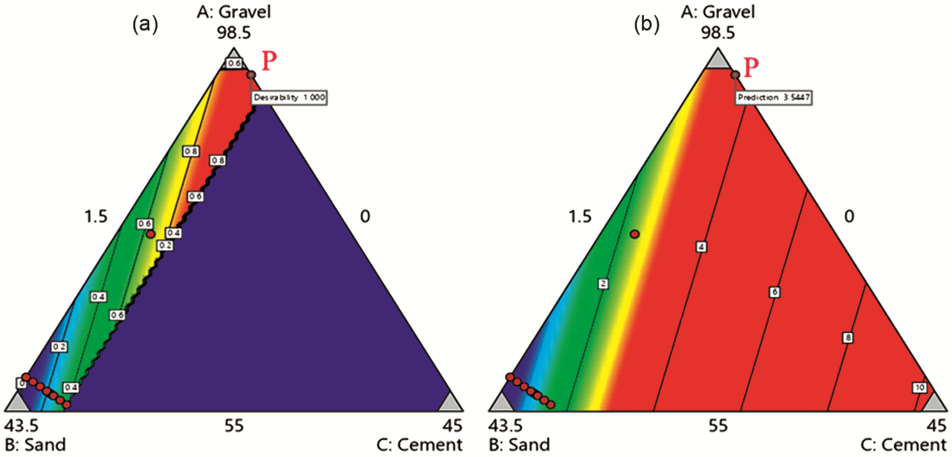

Fig. 7 — Contour plots for (a) desirability and (b) compressive strength.

strength. A, B and C denotes gravel proportion (X1), sand proportion (X2) and cement proportion (X3) respectively. Both figures represent the same plot but from different view. The plot shows the simultaneous interaction of compressive strength with all mixture components. It can be observed that reducing the sand contents increases the compressive strength. It is also observed that increasing the gravel and cement, respectively, and in combination, increases the compressive strength.

Optimization results are shown by contour plots in Fig. 7 The contour plot is a technique to represent a 3-dimensional response surface into a 2-dimensional plot with contour lines of all the points having the same response. These plots help obtain desired response values and input conditions. This can be termed an inverse approach to getting the expected output with the help of an equation. To get maximum compressive strength, a numerical optimization approach is used. Results of this optimization are shown in the form of contour plots in Fig. 7, Table 6 & Figure 7. Observing these tables and plots simultaneously provides the optimum contents for maximum compressive strength. From contour plots, it can be seen that desired optimum output can be found by maximum desirability point and maximum output point. It can be observed at the point P shown on the desirability and compressive strength plot. For the maximum desirability i.e. 1 (point P), at the optimum contents (Gravel A-95.238, Sand B -0.00, Cement C - 4.762), maximum output i.e. compressive strength 3.545 N/mm^2 is achieved.

This can also be seen from the Table 7 where, a total of 22 optimal solutions were found, and optimal condition for maximum strength has been seen as gravel- 95.238, sand- 0.00, and cement - 4.762, and Compressive strength at these contents will be 3.545, which is as per the specifications provided by the

Table 6 — Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Gravel	is in range	55	96	1	1	3
B:Sand	is in range	0	41	1	1	3
C:Cement	is in range	1.5	7	1	1	3
Compressive Strength	maximize	0.5	3.29	1	1	3

Table 7— Optimum solutions

Number	Gravel(%)	Sand(%)	Cement(%)	Compressive Strength (N/mm^2)	Desirability	
1	95.238	0.000	4.762	3.545	1.000	Selected
2	96.000	0.000	4.000	3.408	1.000	
3	92.434	2.908	4.659	3.342	1.000	
4	89.241	4.512	6.247	3.526	1.000	
5	93.375	0.186	6.439	3.834	1.000	
6	94.323	0.000	5.677	3.709	1.000	
7	85.562	8.047	6.391	3.328	1.000	
8	90.847	3.690	5.463	3.437	1.000	
9	87.660	6.186	6.153	3.403	1.000	
10	84.881	8.657	6.462	3.302	1.000	
11	91.425	2.579	5.996	3.603	1.000	
12	88.526	5.171	6.302	3.494	1.000	
13	92.373	1.165	6.463	3.776	1.000	
14	84.177	8.992	6.831	3.347	1.000	
15	88.534	5.959	5.507	3.302	1.000	
16	78.596	14.404	7.000	3.036	0.909	
17	74.092	18.908	7.000	2.751	0.807	
18	71.515	21.485	7.000	2.588	0.748	
19	63.274	29.726	7.000	2.067	0.562	
20	60.908	32.092	7.000	1.917	0.508	
21	56.991	36.009	7.000	1.670	0.419	
22	55.000	38.000	7.000	1.544	0.374	

MoRD specifications. Constraints for the optimum condition are shown in Table 6. Thus the point of the same optimization results can be seen in the contour plot and in the numerical optimization table.

4 Conclusion

CTB provides a more robust and stiffer base by reducing the deflections of traffic loads which leads to delaying the distresses, such as fatigue cracking, and extends the life of the pavement. For CTB construction, the material should be thoroughly mixed with a precise quantity of ingredients. The well-built uniform support offered by CTB leads to decreased stresses to the sub-grade. Cement stabilized thin layer can reduce more stress than an untreated base. The utmost advantage of the cement-treated base is its gaining strength property with age. The compressive strength achieved from the compressive testing machine for seven days holds good for complete gravel. Cement is a binder material that will thoroughly blend with the gravel, gaining the strength needed, as mentioned in the specifications. MDD and OMC value increases with an increase in cement content. Thus appropriate mix was developed according to the guidelines of IRC SP89-2010 & by adding 5% OPC. The unconfined compressive strength of this sample was found to be 3.44 (N/mm^2). Hence the sub-grade soil selected is suitable for the construction of roads. Compressive strength has been increased with an increase in cement and gravel content. However, a decrease in compressive strength with increased sand and water/cement ratio has been observed. The optimum dosage of cement and gravel for maximization of compressive strength is 4.76 % and 95.24 %, respectively.

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