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Optimizing Fiber Parameters Coupled with Chemical Treatment: PROMETHEE Approach

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Abstract

In order to combat issues related to expansive soils, chemical stabilization augmented with use of synthetic fibers is gaining focus in recent times. However, in most of these applications, the practicing field engineers face difficulty in selecting the right mix of fiber size, fiber dosage and stabilizer content. The decision becomes more typical, as the target is to achieve or enhance multiple geotechnical properties which differ with fiber dosage and stabilizer content based on governing mechanisms. Addressing these issues, in this study an attempt is made to present an approach for selecting fibre dosage and lime mix for a typical expansive semi-arid soil. In this article, the effect of randomly oriented polypropylene fiber inclusion in enhancing various geotechnical properties of a typical expansive semi-arid soil is studied. The addition of lime is considered in order to ensure proper bonding between clay particles and discrete fiber elements. PROMETHEE is adopted in order to assist in multi-criteria decision-making process. The approach evaluates multiple geotechnical properties for possible alternatives viz., untreated soil; lime treated soil and other including combinations of fiber dosage and fiber size in the presence of lime. The response measures being the targeted geotechnical properties which include, linear shrinkage tests, unconfined compression strength test, California Bearing Ratio behavior, compressibility characteristics and hydraulic conductivity. The study revealed the best possible alternative considering all the selected response measures.

Introduction

Civil engineering projects mostly include ‘unconfined compression shear strength’, in understanding the performance of soil as a backfill material (Moghal et al. 2014);‘hydraulic conductivity’, in estimating seepage quantities for water retention structures such as dams and reservoirs and in landfill liner applications (Puppala et al. 2004); ‘consolidation behaviour’, in estimating recoverable and irrecoverable settlements occurring in soils upon application of load (Moghal et al. 2015);‘California bearing ratio behaviour’, in estimating the suitability of soil and recycled resources as a potential subgrade materials for roads and ‘linear shrinkage behaviour’, to estimate the shrink/swell potential of cohesive soils (Puppala et al. 2004). In most cases the naturally available soils may not meet the requirements of a constructional material; under such scenarios suitable alternatives must be found.

Earth reinforcement is an efficient and unswerving technique employed to increase the strength and stability of soils, with applications ranging from retaining structures and embankments to sub-grade stabilisation beneath footings and pavements (Gray, Ohashi 1983). In general, expansive soils that create heave- and shrinkage-related stresses are considered to be extremely problematic in semi-arid regions worldwide, with such soils exhibiting large amounts of swell and shrinkage movements due to environmental and seasonal moisture changes (Nelson, Miller 1992). These soils are thus often chemically stabilised (with lime or cement) or reinforced with suitable materials (natural and synthetic fiber materials) in order to increase their potential for use in various civil engineering applications in general and geotechnical applications in particular. It is evident that such projects involve several multi-criteria problems based on various human perceptions and judgments that may have a long-term impact.

In the past, many researchers have used various multi-criteria decision making (MCDM) approaches in similar situations with multiple objectives. Typical application areas include energy planning (Afgan 2010), solid waste management (Vego et al. 2008), and transportation planning. In all such applications the decision-maker is required to choose among quantifiable or non-quantifiable multiple criteria. As the objectives are usually conflicting, the solution is thus dependent on the preferences of the decision-maker and in most cases calls for compromise. In order to circumvent these issues, researchers have employed various MCDM approaches aimed at the selection of one alternative from a given set of options. In the paper an attempt is made to make use of Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) (Behzadian et al. 2010). PROMETHEE has the ability to incorporate decision-making using positive and negative preference flow. Concepts such as preference flow, weights, geometrical analysis for interactive aid (GAIA) plane, as well as the sensitivity analyses, make this approach attractive in the assessment of alternatives. Partial and complete ranking also helps identify the most preferred alternative. However, decision makers are often interested not only in ranking alternatives but also in establishing the superiority of an alternative over another (if it exists). PROMETHEE extends considerable support in this regard.

In the present article, the effect of randomly oriented polypropylene fiber inclusion in terms of enhancing various geotechnical properties (unconfined compression strength, swell and compressibility, hydraulic conductivity, linear shrinkage, California bearing ratio) of a typical expansive semi-arid soil is studied. The addition of lime is also considered in order to ensure proper bonding between clay particles and discrete fiber elements, with its dosage fixed at 6% based on the Eades & Grim method (1966). Further, the effect of fiber dosage (0.2, 0.4 and 0.6% by weight of soil) and fiber length (6mm and 12mm) on the targeted soil properties is also studied. However, the degree and extent of improvement for each of the selected properties differs with fiber dosage and lime content based on governing mechanisms. As a result, the practising engineer typically has difficulty in selecting the right mix of fiber dosage and lime content to meet the optimum requirements of the targeted group of geotechnical properties. Details regarding the testing program and results, the PROMETHEE approach and the relative performance of every alternative are evaluated and presented in the following sections.

Testing Program

The entire testing program was based on variation in three factors: lime content, fiber dosage and fiber length. The corresponding levels of each factor and the respective notation adopted are presented in Table 1. The combined influence of each factor at their different levels of interaction was investigated in terms of the response of targeted soil geotechnical properties. Locally available soil from the township of Al-Ghat, with distinct mineralogy and plasticity characteristics, was selected. The physical properties of the soil are reported in Table 2. Quick lime was used as a chemical blender for both soils, with the amount of lime added, standardised at 6% by dry weight of soil (Eades and Grim, 1966). One types of fiber (Fibermesh) obtained from Propex Operating Company LLC, United Kingdom, is used (Fig. 1), the physico-chemical properties of which is shown in Table 3. Details regarding the experimental testing methodology & procedures adopted are presented in the following sub-sections.

Table 1. The Corresponding Levels of Each Factor and the Respective Notation Adopted In the Study

Factor	Levels (Code)	Alternatives Due to factor combination
Fiber type	Fibermesh (F)	FL1D1C1#; FL1D1C2; FL1D2C1; FL1D2C2; FL1D3C1; FL1D3C2; FL2D1C1; FL2D1C2; FL2D2C1; FL2D2C2; FL2D3C1; FL2D3C2; S; and SC2 #
Fiber length	6mm (L1$) & 12mm (L2)	
Fiber dosage	0.2% (D1), 0.4% (D2) & 0.6% (D3)	
Lime	0% (C1) & 6% (C2%)	
Response Measures		
LS* (%); Cs (%); Cc (%); HC (cm/s); CBR (%) and UCS (kPa)		

Note: $L1: Fiber length of 6mm; L2: Fiber length of 12mm; D1: Fiber dosage of 0.2%; D2: Fiber dosage of 0.4%; D3: Fiber dosage of 0.6%; C1: 0% lime; C2: 6% lime; 1 to 14: Alternatives due to factor combination;
#'FL1D1C1' represents soil treated with Fibermesh (length 6mm & dosage 0.2%) at 0% lime content. # S:Untreated Soil; SC2:Soil treated with 6% lime
*LS: Linear Shrinkage; Cc: Coefficient of Compressibility; Cs: Coefficient of Swell Index; HC: Hydraulic Conductivity; CBR: California Bearing Ratio; UCS: Unconfined Compression Strength;

Experimental Testing Methodology and Procedure

In order to carry out geotechnical testing (UCS, CBR, Consolidation, Hydraulic conductivity), all samples were compacted at their maximum dry density (MDD) values. MDD and corresponding optimum moisture content (OMC) values were determined in accordance with ASTM D698. Density was maintained at a constant level for all soil-lime-fiber mixes (Table 2). Following proper mixing, the tests were carried out in accordance with the standard relevant codes mentioned in Table 4. The unconfined compression strength values reported in Table 5 refer to 28 days cured, whereas the CBR values correspond to 14 days (unsoaked conditions). Hydraulic conductivity values were obtained after a curing period of 28 days. Samples were compacted in standard hydraulic conductivity moulds (ASTM D5856) and cured for 28 days in a desiccator under constant relative humidity (RH~95%). Water was then allowed to flow through the moulds, with samples saturated from bottom to top to ensure a uniform degree of saturation. Consolidation testing and linear shrinkage tests were carried out immediately after sample preparation as per the relevant standards mentioned in Table 4.

Table 2. Soil Physical Properties

Property	Value	Property	Value
Liquid limit (%)	66	USCS classification*	CH
Plastic limit (%)	32	Specific gravity	2.85
Plasticity index (%)	34	Natural moisture content (%)	3.2
Shrinkage limit (%)	15	Maximum dry density (MDD) (g/cm3)	1.64
Linear shrinkage (%)	31	Optimum moisture content (OMC) (%)	25
% Finer than 200 μm	87.3	Specific surface area (SSA) (BET Method) (m2/g)	27.08

*USCS refers to the unified soil classification system; CH refers to clay with high plasticity.

Table 3. Physico-Chemical Properties of Fibers

Property	Fibermesh	Property	Fibermesh
Tensile strength	330 N/mm^2	Melting point	324°F (162°C)
Specific gravity	0.91	Ignition point	1100°F (593°C)
Electrical conductivity	Low	Thermal conductivity	Low
Acid and salt resistance	High	Water absorption	Nil

FIG. 1. Fibers Used in the Study

Table 4 Details of Testing Procedures

Type of test	Relevant code
Liquid limit, plastic limit and plasticity index	ASTM D4318
Specific gravity	ASTM D854
Bar linear shrinkage test	Tex-107-E
Unconfined compression strength test	ASTM D2166
One-dimensional consolidation test	ASTM D2435
Hydraulic conductivity	ASTM D5856
California bearing ratio test	ASTM D1883

Experimental Results

In this study, 14 possible alternative combinations were studied, with six response measures computed for each alternative, producing a total of 84 (14 x 6) experimental results. Number of samples were used in each single experiment and all six response measures calculated for each sample. The average sample outcome is as presented in Table 5.

Table 5. Multi-Criteria Response Measures for Each Alternative

Alternative	'j' response measures, their units and objective					
	LS (%)	Cc (%)	Cs (%)	HC (cm/s)	CBR (%)	UCS (kPa)
	Min	Min	Min	Min	Max	Max
S	12.63	0.109	0.061	6.77E-7	5.96	598.11
SC2	8.64	0.025	0.020	7.26E-7	23.71	1493.85
FL1D1C1	9.70	0.114	0.066	6.14E-6	9.77	455.91
FL1D2C1	8.60	0.108	0.063	8.15E-6	13.81	384.37
FL1D3C1	7.50	0.103	0.061	7.22E-5	17.46	317.04
FL2D1C1	10.46	0.112	0.065	8.44E-6	10.22	327.99
FL2D2C1	10.43	0.102	0.064	4.66E-5	16.37	339.12
FL2D3C1	10.39	0.092	0.062	6.17E-4	19.44	365.77
FL1D1C2	4.39	0.017	0.025	1.44E-8	29.98	1668.12
FL1D2C2	3.57	0.022	0.022	9.27E-8	30.81	1730.24
FL1D3C2	2.75	0.027	0.020	3.21E-7	31.64	1810.48
FL2D1C2	3.03	0.025	0.017	1.86E-7	32.17	1051.08
FL2D2C2	2.42	0.029	0.018	5.66E-7	35.83	1169.20
FL2D3C2	1.82	0.034	0.019	2.44E-6	39.50	1299.33

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From Table 5, it is evident that the practising engineer will encounter difficulty in selecting the right mix of fiber type/dosage & lime content in meeting the requirements of the targeted geotechnical properties. In order to assist him/her in identifying the best possible combination, a multi-criteria approach based on PROMETHEE was adopted. The details of the approach and sequential steps involved are presented in the following section.

Adopted Multi-Criteria Approach: PROMOTHEE

This approach consists of four steps (Brans and Mareschal, 2005).

Step 1: *Construction of a generalised preference function* (P(a, b)): The approach assigns P(a, b) to each criterion, with each P(a, b) value varying from 0 to 1. The outcome implies as: (1) if generalised preference function equals to zero, then preference for alternative a is given over b, (2) if generalised preference function approximately equal to zero, then weak preference for alternative a is given over b, (3) if generalised preference function equals to one, then strict preference for alternative a is given over b and (4) if generalised preference function approximately equal to one, then strong preference for alternative a is given over b

Step 2: *Calculation of preference index* (Π (a, b)): Preference index ∏ (a, b), which also has the value interval [0, 1], is computed for each pair of alternatives using Equation 1

$$\prod (a, b) = [\textstyle\sum_{j=1}^{k} W_j P_j(a, b)] \div [\sum_j W_j] \qquad \text{Eq (1)}$$

Where, W_j is the weight associated with each criterion. This index expresses the preference for alternative 'a' over alternative 'b', considering over all criteria. The outcome implies as (1) if preference index equals to zero, then preference for alternative a is given over b, (2) if preference index approximately equal to zero, then weak preference for alternative a is given over b, (3) if preference index equals to one, then strict preference for alternative a is given over b and (4) if preference index approximately equal to one, then strong preference for alternative a is given over b.

Step 3: *Determination of outranking Relation*: The outranking relationship represents the dominance of each alternative over the others. To obtain the dominance value, two outranking flows are calculated for each alternative. 'Φ^+(a)' quantifies to what extent alternative 'a' dominates over the other alternatives, while 'Φ^-(a)' quantifies to what extent alternative 'a' is dominated by the other alternatives. Outranking relations are deduced by knowing the outranking flow for any two alternatives using the following logic:

- if $\Phi^+ (a) > \Phi^+ (b)$ :: a S+ b
- if $\Phi^- (a) < \Phi^- (b)$ :: a S- b
- if $\Phi+ (a) = \Phi+ (b)$ :: a I+ b
- if $\Phi- (a) = \Phi- (b)$ :: a I- b

Step 4: *Evaluation of complete ranking:* Based on the outranking relations between any two alternatives (Step 3), a partial ranking is computed as follows: (1) if (a S+b & aS-b) or (aS+b & aI+b) or (aS-b & aI-b), then a PI b : alternative a has preference over b, (2) if (a I+ b & a I- b), then a PI b: alternative a has preference over b, (3) if otherwise the information is inconsistent, then a RI b: alternative a is incompatible with b

Net outranking flow Φ for alternatives 'a' and 'b' is obtained using following equations:

$$\Phi (a) = \Phi^+ (a) - \Phi^- (a)\ldots \quad (2a)$$
$$\Phi (b) = \Phi^+ (b) - \Phi^- (b)\ldots \quad (2b)$$

A complete ranking is subsequently obtained using the logic as: (1) if Φ (a) > Φ (b), then a PII b : alternative a has complete preference over alternative b, (2) if Φ (a) = Φ (b), then a III b : alternative a has complete indifference over alternative b

The objective of the present study was to evaluate the comparative overall performance of 14 alternatives (Table 5), with the application of the above approach described in the following section.

Application of PROMETHEE

From Table 5 it is evident that no mix was found to be best at satisfying all six response measures. Using PROMETHEE, the outranking flows were obtained for each alternative, as presented in Table 6. Using these outranking flows, partial ranking, complete ranking, network and GAIA plane values were then obtained and are presented in Figs. 2 to 5.

Table 6. Ranking of Alternatives Based on Outranking Flows

Alternative	Outranking flow			Alternative	Outranking flow		
	Φ	Φ+	Φ-		Φ	Φ+	Φ-
FL1D3C2	0.2620	0.2738	0.0118	FL2D3C1	-0.1422	0.0601	0.2023
FL2D3C2	0.2480	0.2844	0.0364	FL1D3C1	-0.1830	0.0412	0.2243
FL1D2C2	0.2355	0.2620	0.0264	FL1D2C1	-0.1850	0.0486	0.2336
FL2D2C2	0.2243	0.2638	0.0396	FL2D2C1	-0.1893	0.0395	0.2288
FL1D1C2	0.2063	0.2432	0.0369	FL1D1C1	-0.2222	0.0482	0.2704
FL2D1C2	0.1899	0.2386	0.0487	S	-0.2790	0.0416	0.3206
SC2	0.1191	0.1906	0.0715	FL2D1C1	-0.2843	0.0148	0.2991

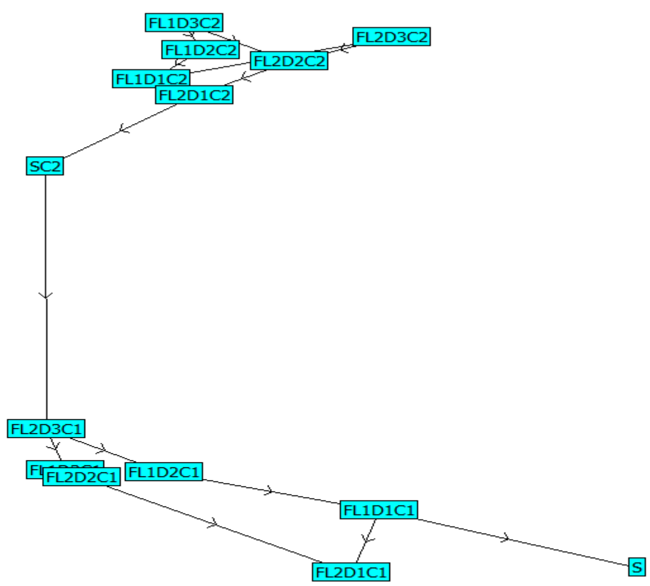

FIG. 2. Preference Network Diagram Based on PROMETHEE Approach

In Table 6, Φ+, Φ- and Φ scores are oriented such that the best are projected upwards. For a given set of alternatives, alternative "FL1D3C2" dominates all other alternatives. From Table 5, "FL1D3C2" corresponds to soil treated with Fibermesh of 6mm length at 0.6% dosage with lime (at 6%). Table 6 also reveals that alternative "FL2D1C1" highly underperforms compared to all other possible alternatives, including "S" (untreated soil). Simultaneously, the PROMETHEE approach a network was drawn (Figure 4) in which each alternative is represented by a 'node' and its preference over other alternatives by an 'arrow'. Fig. 4 also shows alternative "FL1D3C2" to be highly preferred over all other alternatives, with "FL2D1C1" again the least preferred. Importantly, alternative "SC2" is preferred over "S, FL2D3C1, FL1D2C1, FL1D1C1, FL2D2C1 and FL1D3C1".

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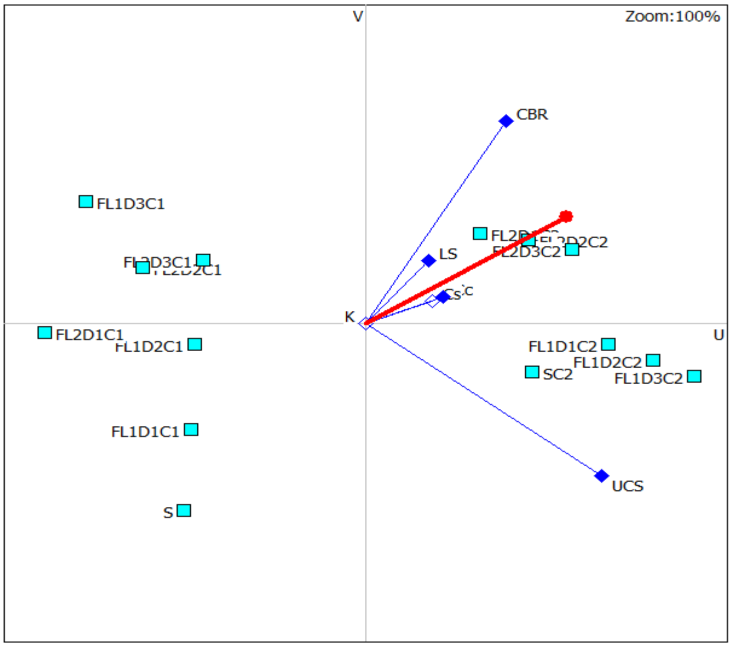

FIG. 3. Geometrical Analysis Based on Interactive Aid (GAIA) Plane

In the GAIA plane (Fig. 5), which is widely considered the best two-dimensional representation of any multi-criteria problem, alternatives are represented by points “ ”; alternatives similar to each other in performance appear close, while those that differ are placed away from each other. Response criteria expressing similar preferences are represented by axes oriented in the same directions (Fig. 5), with dissimilar (conflicting type) preferences represented by axes oriented in opposite directions. The length of a criterion axis is representative of its relative discriminating power. Fig. 5 illustrates that both UCS and CBR are discriminating criteria. The above analysis was carried out by assigning equal weights to each response measure. As decision-makers may not typically have any predetermined weights in mind, sensitivity analysis may thus be necessary. In the present study a special feature of the Visual PROMETHEE software, known as walking weights, was adopted for this purpose.

Sensitivity Analysis

Sensitivity analysis was carried out by assigning the response criteria weights as shown in Table 7. Criterion weights are decided base on the type of objective function of response measure i.e. either maximization or minimization. For response measures with maximization objectives, the field engineer might set higher and equal weight. While for the response measures with minimization objectives he/she might set lower and equal weight (refer Set2) and otherwise (refer Set 3). Set1 represents an equal weight allocation for all response measures. Sets 2 and 3 represent an unequal weight allocation for all response measures. Fig. 4 represents analysis corresponding to network, for the application of Set2 weighting. For this set, based on the objectives of the response measures shown in Table 5, relatively higher weights (33%) are assigned to the response measures CBR and UCS. On similar lines, Fig. 5 represents analysis corresponding to network, for the application of Set3 weighting. Again based on the response measure objectives shown in Table 5, in this set relatively higher weights (21%) are assigned to the response measures LS, Cc, Cs and HC. Although it is evident from the above sets that the model is sensitive to changes in response measure weights, it is interesting to note that alternative “FL1D3C2” again dominates all other alternatives while “FL2D1C1” is again the least preferred. Accordingly, the study reveals that untreated soil (alternative “S”) is the worst alternative and should be treated with the right amounts of admixture (in the form of lime) and reinforced with an optimum fiber dosage in order to address problems associated with soil geotechnical properties.

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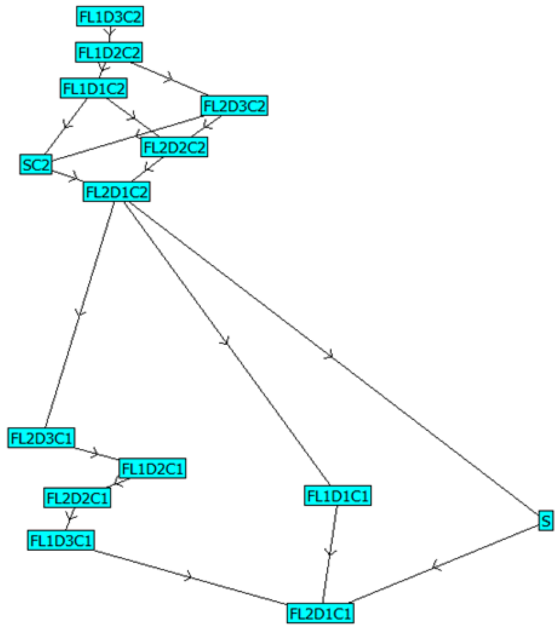

FIG. 4. Response Measure Weight Allocation: Preference Network Diagram Based on PROMETHEE Approach (For Set 2)

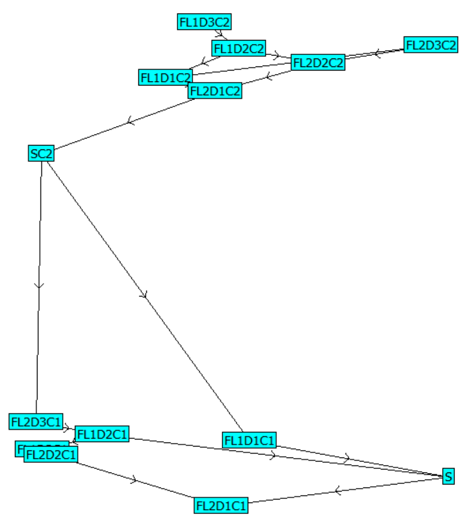

FIG. 5. Response Measure Weight Allocation: Preference Network Diagram Based on PROMETHEE Approach (For Set 3)

Table 7. Response Measure Weight Allocation for Sensitivity Analysis

Criterion		LS	Cc	Cs	HC	CBR	UCS
Weight	Set 1*	17	17	17	17	17	17
(%)	Set 2	8	8	8	8	33	33
	Set 3	21	21	21	21	8	8

* Figs. 2 and 3 represent analysis carried out based on Set1 weight allocation

Conclusion

In this study, the effect of randomly oriented polypropylene fiber inclusion in the presence/absence of lime in terms of enhancing various geotechnical properties (unconfined compression strength, swell and compressibility, hydraulic conductivity, linear shrinkage and California bearing ratio) of a typical semi-arid soil was investigated. As the practising engineer typically has difficulty in selecting the right mix of fiber size, dosage and lime content in meeting the optimum requirements for these geotechnical properties, the PROMETHEE method was adopted in order to assist in the decision-making process. A total of 14 possible alternative combinations were analysed based on variation in fibermesh size, dosage and lime content, with six geotechnical properties (response measures) computed for each alternative. The obtained results enabled the identification of groups of criteria expressing similar preferences. Sensitivity analysis was then carried out to better understand the conflicts to be solved in order to make a decision. In the current study, soil treated with fiber (6mm length and at 0.6% dosage) with lime (6%) was found to be preferred over all other possible alternatives, while soil treated with fiber (12mm length and 0.2% dosage) without any lime addition was the least preferred option for the practising engineer. The proposed method is flexible and considers both qualitative and quantitative attributes in selecting the right mix of reinforcement in the form of fiber in the presence of an additive.

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References

Afgan, N.H. (2010). “Sustainability Paradigm: Intelligent Energy System.” *Sustainability.*, Vol. 2(12): 3812-3830.

ASTM D1883: 2007/E2. Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils. *ASTM West Conshohocken, PA*.

ASTM D2166: 2006. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. *ASTM West Conshohocken, PA*.

ASTM D2435: 2004. Standard Test Methods for One-Dimensional Consolidation of Soils Using Incremental Loading. *ASTM International, West Conshohocken, PA*.

ASTM D4318: 2010/E1. Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils. *ASTM West Conshohocken, PA*.

ASTM D5856:2007. Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter. *ASTM West Conshohocken, PA*.

ASTM D698: 2012/E2. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m^3)). *ASTM West Conshohocken, PA*.

ASTM D854: 2006. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. *ASTM West Conshohocken, PA*.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A. and Aghdasi, M. (2010). “PROMETHEE: A comprehensive literature review on methodologies and applications.” *Eur. J. of Operat. Res.*, Vol. 200(1): 198-215.

Brans, J.P. and Mareschal, B.F. (2005). “Promethee Methods.” *Multiple Criteria Decision Analysis: State of the Art Surveys*, pp. 163-186. Springer New York.

Eades, J.L. and Grim, R.E. (1966). “A Quick test to determine lime requirements for lime stabilization.” *Transp. Res. Rec.*, Vol. 139: 61-72.

Gray, D.H. and Ohashi, H. (1983). “Mechanics of Fiber Reinforcement in Sand.” *J. of Geotech. Engrg.*, Vol. 109(3): 335-353.

Moghal, A.A.B., Al-Obaid, A.K. and Refeai, T.O. (2014). "Effect of Accelerated Loading on the Compressibility Characteristics of Lime Treated Semi Arid Soils." *J. of Mat. Civ. Engrg.,* Vol. 26(5): 1009-1016.

Moghal, A.A.B., Al-Obaid, A.K., Refeai, T.O. and Al-Shamrani, M.A. (2015). "Compressibility and Durability Characteristics of Lime Treated Expansive Semiarid Soils." *J. Testing and Eval.*, Vol. 43(2): 255-263.

Nelson, D.J. and Miller, J.D. (1992). "Expansive soils: problems and practice in foundation and pavement engineering." *John Wiley & Sons*, New York.

Puppala, A., Griffin, J., Hoyos, L. and Chomtid, S. (2004). "Studies on Sulfate-Resistant Cement Stabilization Methods to Address Sulfate-Induced Soil Heave." *J. Geotechnical & Geoenv. Engrg.*, Vol. 130(4): 391-402.

Tex-107-E: 1999. Test Procedure for Determining the Bar Linear Shrinkage of Soils. Texas Department of Transportation Document, Construction Division, Austin, Texas.

Vego, G., Kučar-Dragičević, S. and Koprivanac, N. (2008). "Application of multi-criteria decision-making on strategic municipal solid waste management in Dalmatia, Croatia." *Waste Man.,* Vol. 28(11): 2192-2201.