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Selection of Most Suitable Stabilized/Solidified Dredged Soil to Use in Highway Subgrade Layer Construction

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ABSTRACT

The dredging of lakes, rivers, drains or water bodies, etc. is a regular practice all over the world and disposal of these dredged soils is a major problem due to the scarcity of open land in the urban areas. At present for handling this problem, engineers and soil experts are trying to find out alternative solutions such as the use of the dredged soil as constructional material in different development projects. This study deals with the contaminated dredged soil of Najafgarh drain, a major connecting drain of Yamuna river (Delhi) and aims at its use as alternative highway subgrade material after stabilization/solidification with cement, bottom ash and steel slag in different ratios. As the dredged soil contains a certain amount of organic matter that the influence the chemical process of stabilization/solidification, thus thermal treatment of raw dredged soil has also been carried out to ascertain its effects on stabilization/solidification. Furthermore, samples out of all those have satisfied the acceptance criteria of highway subgrade material have been selected, and finally, the most suitable sample out of them has been decided along with the assessment of its degree of suitability to use as highway subgrade materials. For both cases, the concept of the fuzzy logic of Prof. Latfi Zadeh has been introduced.

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1. Introduction

In general, the geotechnical and chemical properties of dredged soils are found to be of very poor quality, and thus without improvement of its properties, it does not permit to use it directly to the construction site [1,2]. At present, the world is not facing only the disposal of contaminated dredged soil but like out of many: disposal of fly ash and steel slag are also common major problems as far as environmental safety concerns. In this study attempt has been made to deal with three major wastes of Delhi i.e. (i) contaminated dredged soil of Najafgarh drain, (ii) bottom ash (BA) of National Thermal Power Plant, and (iii) ground granulated steel slag (GGSS) of Bhushan Steel Pvt. Ltd. and to reuse them as constructional fill material in different development projects after stabilization/solidification [3–8].

Fig.1 (a) and Fig.1 (b) shows Najafgarh drain site where dredging work was in progress during the study and banks of the drain where materials were dumped after dredging.

Fig. 1 (a). Dredging work at Najafgarh Drain.

Fig. 1 (b). Dumped dredged soil along the banks of the Najafgarh Drain.

From the series of the literature review [9–13] it has been revealed that bottom ash and steel slag both can be used as partial replacement of cement due to their pozzolanic characteristics. Thus to improve the properties of contaminated dredged soils of Najafgarh Drain, the waste 'bottom ash' and 'steel slag' were mixed with cement in the different ratio for stabilization/ solidification and replace the cement quantity to make it economical.

In this study, a series of laboratory tests on 'Compaction', 'Unconfined Compressive Strength (UCS)', 'California Bearing Ratio (CBR)', 'Durability' and 'Heavy Metal' has been performed for thirty-five different samples that were prepared with thermal treatment and without thermal treatment. From the results of all tests, the samples those have fulfilled the acceptance criteria of subgrade materials were selected first and then using 'fuzzy decision model', the best suitable sample out of them has been decided. Finally, the degree of suitability to use this optimal sample as highway subgrade material has been assessed using the concept of fuzzy logic of Prof. Latfi Zadeh [14].

1.1. The concept of fuzzy logic

'Fuzzy logic' was first introduced by Prof. Latfi Zadeh in his first research paper **'**Fuzzy sets, Information and Control 8 (1965)' and is now accepted worldwide as the best tool to tackle the weakness of 'Boolean logic' that was introduced by a German mathematician, Prof. George

Cantor. He defined the crisp set as a collection of elements in a given domain in which elements either belong to the set or does not belong to the set. To specify an element within a set or not, a clear boundary always exists in between the universal set and its subset. The belongingness of element can express only by one way: yes or no, true or false, white or black, day or night, accepted or not accepted, etc and naturally the membership value of any element should either be 0 or 1 and neither in between 0 and 1. Thus, it cannot give a precise solution in our many real-life problems because of the involvement of uncertainty in between the region of 0 and 1.

The fuzzy logic of Prof. Latfi Zadeh has solved the uncertainty of this region very successfully and used the degree of membership values of each element within [0, 1] according to their degree of belongingness into the set in question. Here each membership value represents a certain degree of belongingness of the element in the set. In fuzzy logic, a statement is to be neither 'completely true' nor 'completely false' rather it deals with the degree of truthness in between two post specified area like true and false, black and white, yes and no, good and bad, etc. few out of infinity. Naturally, the membership value will be 1 when the statement is absolutely true and membership value will be 0 when it is absolutely false. Whereas membership value in between 0 & 1 will represent partially false or partially true conditions of the statement.

Thus a fuzzy set is defined as, $A = \{(x_1, \mu_A(x_1)), (x_2, \mu_A(x_2)), \ldots, (x_n, \mu_A(x_n))\}$, where $\mu_A(x)$ is the degree of membership value of element x in set A and can assign any value within 0 and 1. The higher value of $\mu_A(x)$ represents a greater degree of belongingness of element *x* to the sub set A [14–16].

1.2. Membership value

The membership value of a fuzzy set is the key tool of its logic, which can use to minimize the uncertainty involved in a linguistic variable. Membership value of any object of a fuzzy set represents the value of gradual transition from region completely outside periphery boundary of the set to region completely inside the boundary of the set. There are numerous types of membership functions to evaluate the membership value of a fuzzy set, but triangles and trapezoid membership functions are most commonly used in practice. The membership value of any event can be evaluated in three processes that are (i) by interviewing method among, (ii) by using available local data or information, and (iii) by using existing record or performances. However, the first process has more capability to give a better result and thus it is used worldwide in large scale [16]. The example as given below will help to understand how to assess the membership values of a real-life problem.

Suppose X is the domain of additives = {cement, bottom ash, GGSS} and Y is the domain of the capability of working as stabilizing agent = {excellent, best, good} be two universes, then a possible membership value of each member of X to be {(cement, 0.9), (bottom ash, 0.4), (GGSS, 0.6)} like this.

1.3. Linguistic variables

The fuzzy logic has given a new direction to solve the quantum of truthness of linguistic variables/ dialogs of our daily life issues and jobs that involved uncertainty, vagueness, and ambiguity. Thus all kinds of linguistic variables are considered as a fuzzy variable. As for example to collect the data from a soil expert about 'Stabilization quality mixed with an additive', then obviously his views and expression will be as low, high, excellent, good, very good, very poor, poor, etc. All these terms are expressed as linguistic variables of the fuzzy set theory [14].

2. Materials

The materials used in this study were 'dredged soils' and three additives: 'Ordinary Portland Cement (OPC)'; 'Bottom Ash (BA)' and 'Ground Granulated Steel Slag (GGSS)'.

The geotechnical properties and heavy metal concentration of raw dredged soil have been studied and given in Table 1 and Table 2.

Table 1
Geotechnical properties of raw dredged soil.

Property	Value	Code used
Water content (In-situ) (%)	28	IS 2720 Part 2, 1973
Grain Size Distribution		IS 2720 Part 4, 1985
Gravel (%)	4	
Sand (%)	34	
Silt (%)	60	
Clay (%)	2	
Coefficient of uniformity (Cu)	10.76	
Coefficient of curvature (Cc)	4.45	
Specific Gravity	2.52	IS 2720 Part 3, 2002
Atterberg's Limit		IS 2720 Part 5, 1985
Liquid limit (%)	20.99	
Plastic limit (%)	Non plastic	
Differential Free Swell Index	Nil	IS 2720 Part 40, 1977
Compaction Characteristics		IS 2720 Part 7, 1980
Max Dry Density (MDD) (g/cm^3)	1.64	
Optimum Moisture Content (OMC) (%)	13.5	
CBR (%)		IS 2720 Part 16, 1987
Unsoaked	1.45	
Soaked	1.03	
Unconfined Compressive strength (kPa)	197.11	IS 2720 Part 10, 2006
Organic matter (%)	2.15	IS 2720 Part 22, 1987

Table 2
Heavy metal concentration in raw dredged soil.

Metals	Concentration (mg/l or ppm)
Nickel	383.0
Chromium	109.0
Zinc	2660.0
Lead	74.5
Cadmium	27.1

For the morphological properties of dredged soil, Scanning Electron Microscope test (SEM) was also conducted at two different magnifications: at x500 and at x5000 and from the both scans as shown in Fig. 2 (a) & Fig. 2 (b), and it has been observed that soil grains have rough surface texture with semi-angular shape & large voids.

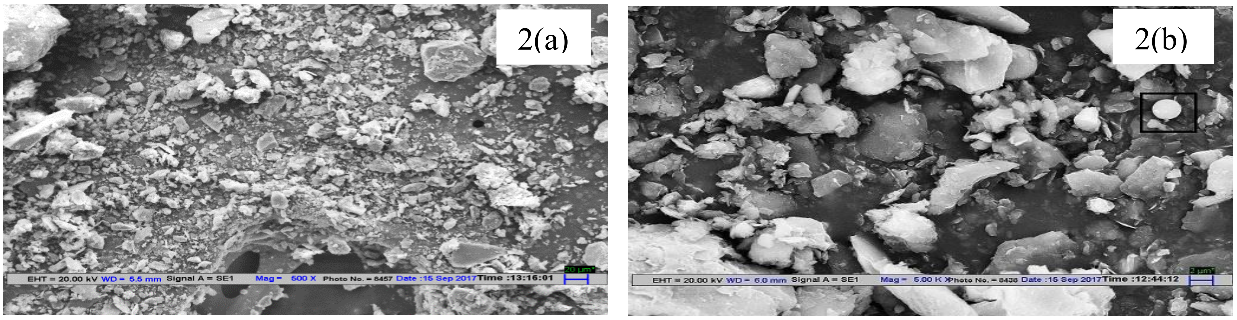

Fig. 1. SEM images of dredged soil.

In this case study, the ordinary Portland cement used was of Grade-43 (J.K. Lakshmi Cement) with the specific gravity of 3.15, the bottom ash was obtained from National Thermal Power Plant, Badarpur, New Delhi with the specific gravity of 2.1. Steel slag was collected from Bhushan Steel Pvt. Ltd., Ghaziabad (U.P.) which was then powdered by grinding it in Los Angles abrasion machine. The specific gravity of Ground granulated steel slag after grinding was found to be 2.79.

The chemical composition of raw contaminated dredged soil, bottom ash and GGSS was determined by performing EDXRF (Modal-Epsilon 5 analytical (Netherland) and for cement specimen, it was obtained from J.K. Lakshmi Cement. Results are presented in Table 3.

Table 3
Chemical composition of dredged soil and stabilizing agents.

Materials	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)
Raw contaminated dredged soil	70.40	4.15	14.23	2.10	1.89
Cement	20.00	3.00	5.50	61.1	2.50
Bottom ash	44.82	10.50	26.27	5.83	1.15
GGSS	8.46	0.42	10.16	78.08	1.41

3. Methodology

This study is done in three phases: (i) laboratory experimental study on each sample; (ii) using fuzzy decision model, to find out the most suitable stabilized/solidified dredged soil samples out of n-alternatives those have satisfied the acceptance criteria of highway subgrade materials and (iii) using fuzzy tool, to assess the degree of suitability of best suitable stabilized/solidified dredged soil samples to use as highway subgrade materials.

3.1. Laboratory experimental study

For laboratory experiment, total thirty five samples of dredged soil were prepared on seven categories of different specimens: (i) raw dredged soil (DS), (ii) dredged soil stabilized with cement (DS-C), (iii) dredged soil stabilized with cement-bottom ash (1:1) mix (DS-CBA), (iv) thermally treated dredged soil (TDS), (v) thermally treated dredged soil stabilized with cement (TDS-C), (vi) thermally treated dredged soil stabilized with cement-bottom ash (1:1) mix (TDS-CBA), and (vii) dredged soil stabilized with cement-GGSS (1:1) mix (DS-CS). From the research works done by earlier [17], the mixing percentage of all additives, i.e. (cement), (cement + bottom ash at 1:1 mix) and (cement + GGSS at 1:1 mix) with dredged soil were taken as 4-20% by weight of dry soil. Table 4 presents all thirty-five samples that were prepared at different mix proportions.

Table 4
Mix proportion of different samples (%age by weight).

Sample	Cement (%)	Bottom Ash (%)	Sample	Cement (%)	Bottom Ash (%)	Sample	Cement (%)	GGSS (%)
DS-4C	4	0	TDS-4C	4	0	DS-4CS	2	2
DS-6C	6	0	TDS-6C	6	0	DS-6CS	3	3
DS-8C	8	0	TDS-8C	8	0	DS-8CS	4	4
DS-10C	10	0	TDS-10C	10	0	DS-10CS	5	5
DS-12C	12	0	TDS-12C	12	0	DS-12CS	6	6
DS-16C	16	0	TDS-16C	16	0	DS-16CS	8	8
DS-20C	20	0	TDS-20C	20	0	DS-20CS	10	10
DS-4CBA	2	2	TDS-4CBA	2	2	--	--	--
DS-6CBA	3	3	TDS-6CBA	3	3	--	--	--
DS-8CBA	4	4	TDS-8CBA	4	4	--	--	--
DS-10CBA	5	5	TDS-10CBA	5	5	--	--	--
DS-12CBA	6	6	TDS-12CBA	6	6	--	--	--
DS-16CBA	8	8	TDS-16CBA	8	8	--	--	--
DS-20CBA	10	10	TDS-20CBA	10	10	--	--	--

3.1.1. Laboratory tests

The laboratory tests were carried out by performing ‘Maximum dry density (MDD)’, ‘Optimum moisture content (OMC)’, ‘Unconfined compressive strength (UCS), ‘California bearing ratio (CBR), ‘Durability’ and ‘Heavy metals’ on all thirty-five samples and their results are discussed in the next section.

The Standard Proctor compaction test was performed according to I.S.2720-7 (1980) on all samples to achieve MDD and OMC. In each test, 100 mm diameter and 127.3 mm height (1000 ml) mold was used, and samples were compacted in three equal layers by rammer of weight 2.6 kg and falling from a height of 310 mm. Extra care was given while preparation of dredged soil samples mixed with cement, cement-bottom ash and cement-GGSS. The compaction for these mixes was completed within 20 minutes after mixing of stabilizer as per IS 4332-3 (2010).

Unconfined compressive strength (UCS) of soil was used to determine the maximum compressive strength of specimens DS and TDS in accordance with IS 2720-10 (1991) and specimens DS-C, DS-CBA, TDS-C, and TDS-CBA, in accordance with IS 4332 -5 (1970). First, three identical samples of size 38 mm in diameter and 76 mm in height for all specimens were prepared. For each sample, the soil was compacted statically in UCS mold by applying pressure through compression testing machine at their respective MDD & OMC and then wrapped in thin plastic sheets. The specimens DS and TDS were tested on the day of casting and specimens DS-C, DS-CBA, TDS-C, TDS-CBA, and DS-CS were tested after curing of 7 days and 28 days in a curing tank maintained at 23^{0}C temperature and 100% humidity. During testing, the loading rate was maintained at 1.25 mm/min for all samples. Since no minimum UCS value to be achieved has been mentioned in IRC-SP: 89 [18] for improved subgrade, the UCS values are not considered mandatory for subgrade materials. However, in the fuzzy model for selection of best suitable sample out of n-alternative and to assess its degree of suitability, the UCS values are also taken under considerations.

For CBR tests samples were prepared in a cylindrical mold of diameter 150 mm and height 175 mm and then all samples were compacted at their respective MDD & OMC according to IS 2720-16 (1987). The DS and TDS specimens were tested in unsoaked conditions and four days soaking conditions in water, whereas specimens mixed with stabilizers were cured for three days followed by 96 hours soaking condition in water in accordance with IRC 50-1973 [19]. The minimum CBR value of a stabilized sample to be accepted for the use of subgrade materials was fixed as 15% [18].

The durability test (wetting & drying method) in accordance with IS 4332- 4 (1968) was carried out, and samples were prepared at their respective value of MDD & OMC. The compacted samples were then wrapped in thin plastic sheets to avoid any moisture loss and kept for 24 hours. After that the specimens were cured for seven days and thereafter were immersed in water for 5 hours, followed by drying in the oven at 70^{0}C for 42 hours which termed as one wet-dry cycle. After the end of each cycle, the samples were brushed along the height as well as diameter with a steel brush at approximately 1.4 kgf force and soil cement losses were recorded in percentage. For use in the subgrade, the loss of soil-cement limit after completion of 12 wet-dry cycles has considered as maximum of 10% in this study [20].

Finally, the heavy metal tests were conducted following ‘Toxicity Characteristic Leaching Procedure (TCLP)’ [21] and concentration of Lead (Pb), Cadmium (Cd), Chromium (Cr), Zinc (Zn), and Nickel (Ni) were found out by using AAS4129 Atomic Absorption Spectrophotometer. As per USEPA guidelines the maximum concentration of heavy metals for Pb, Cd, Cr, Zn, and Ni should not exceed 5.0, 1.0, 5.0, 5.0 and 3.0 mg/l respectively [22].

3.2. Fuzzy decision (FD)

The concept of fuzzy logic can arrive at a suitable decision by an expert by incorporating his individual’s perception about alternative options and their constraints and employed as simple fuzzy sets. In the fuzzy decision model, the goals and constraints are to be developed as fuzzy sets that lead sufficient to absorb vagueness connected with each choice and its constraints [16].

Thus the model of fuzzy decision (FD) can achieve the targeted goal of this study where multiple constraints are tackled with expert decisions minimizing the vagueness of fuzzy sets of each.

This study aimed at to use the stabilized/solidified dredged soil as subgrade materials where ‘UCS value’ and ‘CBR value’ are considered as two goals and ‘cement consumption’, ‘soil cement loss’ and ‘total heavy metal concentration’ are considered as three constraints. To understand the function of FD an algorithm is presented below.

The algorithm of FD:

The fuzzy decision is an area which logically studies about how the decision is actually made and how better they can be made successfully. In the fuzzy decision, the membership value (μ) for the maximum favorable condition of a given goal (G) or constraint(C) is treated as 1, and for the minimum, it is 0.

Let us consider a group of ‘Samples’ which have passed all the acceptance criteria of subgrade materials as

‘Samples’ = $\{s_1, s_2, s_3, s_L\} = \{si\}$, for i = 1, 2, 3, L

Suppose a fuzzy set G associated with each sample (s_i) such that

$G = \{ \mu(g_i/s_i) \} = \{ \mu(g_1/s_1), \mu (g_2/s_2), \mu (g_3/s_3), \ldots, \mu (g_L/s_L)\}$, for i = 1, 2, 3, …, L

And if the two fuzzy sets C_1 and C_2 describing two constraints associated with each sample (s_i) such that

$C_1 = \{ \mu_1(c_i/s_i)\} = \{ \mu_1(c_1/s_1), \mu_1(c_2/s_2), \mu_1(c_3/s_3), \ldots, \mu_1(c_L/s_L) \}$, for i = 1, 2, 3, …, L

And $C_2 = \{ \mu_2(c_i/s_i)\} = \{ \mu_2(c_1/s_1), \mu_2(c_2/s_2), \mu_2(c_3/s_3), \ldots, \mu_2(c_L/s_L) \}$, for i = 1, 2, 3, …, L

Then the Fuzzy Decision (FD) will be given by, FD = Max $\{D (sample_i)\}$,

where $D (sample_i)$ = [sub set-G ∩ sub set-C_1 ∩ subset-C_2]

$= Min \{\mu(g_i/s_i), \mu_1(c_i/s_i), \mu_2(c_i/s_i) \}$

3.3. Fuzzy assessment tool

This fuzzy assessment tool has applied on finally decided best sample selected from the above ‘Algorithm of FD’. For the better understanding of fuzzy tool, some useful components are discussed below.

3.3.1. Fuzzy attribute

Fuzzy attributes are linguistic descriptions or expression to be collected from different sources for evaluation of their degree of membership values independently [15,16]. For example, in a case study of soil quality, the linguistic expressions of a soil expert are often found like: high CBR, low UCS, low plastic limit, high organic content, etc. few out of infinity which to is called as fuzzy attributes for soil quality assessment.

3.3.2. Weighted average

Let $\mu(x_i)$ be a fuzzy set of a finite set X and for each element $x \in X$, there is an associated weight $Wx_i \in R+$ (Non-negative real numbers), then the 'weighted average' of the fuzzy set $\mu(x_i)$ is the non-negative number $a(\mu)$ and is given by

$$a(\mu) = (\sum \mu(xi).Wxi) / \sum Wx_i \quad \forall, \quad i = 1, 2, 3, \ldots \tag{1}$$

3.3.3. Degree of suitability of soil sample

When a sample satisfied all acceptance criteria to use for highway subgrade fill materials and ready to use in construction then naturally an overall degree of suitability to use it is very essential to a specialized soil engineer or expert. Now depending upon the value of a (μ), a grading of suitability with the degree of certainty has been proposed in below.

For 'Excellent', grade = A, if $0.8 < a(\mu) \leq 1$

For 'Best', grade = B, if $0.6 < a(\mu) \leq .8$

For 'Good', grade = C, if $0.4 < a(\mu) \leq .6$

For 'Bad', grade = D, if $0.2 < a(\mu) \leq .4$

For 'Worst', grade = E, if $0 \leq a(\mu) \leq .2$.

4. Results and discussion

In this section test results of 35 different samples of Table 4 has been presented to finalize which samples actually passed the acceptance criteria of highway sub grade material. And next using fuzzy decision model, the best suitable sample out of all those have passed the acceptance criteria of highway subgrade material have been selected. Thereafter, the study was carried out to assess the degree of suitability to use this best suitable sample as highway subgrade materials. In below Table 5, 6, 7, 8 and 9 respectively are presented the results of compaction tests, UCS tests, CBR tests, durability tests, and heavy metals tests.

Table 5
Compaction test results of different samples.

Sample	MDD (g/cm^3)	OMC (%)	Sample	MDD (g/cm^3)	OMC (%)	Sample	MDD (g/cm^3)	OMC (%)
DS-4C	1.64	16.70	TDS-4C	1.66	17.20	DS-4CS	1.65	16.80
DS-6C	1.63	18.63	TDS-6C	1.65	18.30	DS-6CS	1.655	18.72
DS-8C	1.61	20.00	TDS-8C	1.65	20.80	DS-8CS	1.66	20.50
DS-10C	1.61	20.30	TDS-10C	1.64	21.50	DS-10CS	1.67	21.40
DS-12C	1.61	20.94	TDS-12C	1.64	23.20	DS-12CS	1.69	21.80
DS-16C	1.61	21.10	TDS-16C	1.64	24.95	DS-16CS	1.70	22.30
DS-20C	1.61	21.23	TDS-20C	1.64	26.00	DS-20CS	1.70	22.90
DS-4CBA	1.60	17.60	TDS-4CBA	1.66	17.40	--	--	--
DS-6CBA	1.60	17.70	TDS-6CBA	1.65	18.35	--	--	--
DS-8CBA	1.59	18.00	TDS-8CBA	1.65	21.20	--	--	--
DS-10CBA	1.59	18.30	TDS-10CBA	1.64	22.40	--	--	--
DS-12CBA	1.58	18.80	TDS-12CBA	1.64	23.80	--	--	--
DS-16CBA	1.61	19.50	TDS-16CBA	1.63	26.40	--	--	--
DS-20CBA	1.61	19.80	TDS-20CBA	1.62	27.90	--	--	--

Table 6
UCS test results of different samples at 7 days curing.

Sample	UCS (kPa)	Sample	UCS (kPa)	Sample	UCS (kPa)
DS-4C	565.78	TDS-4C	627.62	DS-4CS	396.05
DS-6C	621.74	TDS-6C	706.07	DS-6CS	466.31
DS-8C	770.80	TDS-8C	872.79	DS-8CS	632.06
DS-10C	925.75	TDS-10C	1059.12	DS-10CS	740.60
DS-12C	1107.17	TDS-12C	1418.04	DS-12CS	841.45
DS-16C	1765.90	TDS-16C	1873.07	DS-16CS	1324.43
DS-20C	1993.69	TDS-20C	2275.14	DS-20CS	1475.33
DS-4CBA	402.07	TDS-4CBA	404.03	--	--
DS-6CBA	445.09	TDS-6CBA	549.17	--	--
DS-8CBA	600.17	TDS-8CBA	774.72	--	--
DS-10CBA	706.08	TDS-10CBA	913.97	--	--
DS-12CBA	798.26	TDS-12CBA	1029.70	--	--
DS-16CBA	921.83	TDS-16CBA	1210.14	--	--
DS-20CBA	1200.33	TDS-20CBA	1756.3	--	--

Table 7
CBR test results of different samples.

Sample	CBR (%)	Sample	CBR (%)	Sample	CBR (%)
DS-4C	12.76	TDS-4C	13.83	DS-4CS	2.90
DS-6C	14.90	TDS-6C	22.52	DS-6CS	7.20
DS-8C	19.21	TDS-8C	25.34	DS-8CS	15.20
DS-10C	21.00	TDS-10C	31.02	DS-10CS	17.30
DS-12C	26.26	TDS-12C	35.40	DS-12CS	21.88
DS-16C	33.36	TDS-16C	42.74	DS-16CS	27.40
DS-20C	46.87	TDS-20C	49.82	DS-20CS	33.50
DS-4CBA	3.01	TDS-4CBA	4.79	--	--
DS-6CBA	6.71	TDS-6CBA	8.66	--	--
DS-8CBA	14.77	TDS-8CBA	16.94	--	--
DS-10CBA	17.63	TDS-10CBA	20.19	--	--
DS-12CBA	20.77	TDS-12CBA	25.18	--	--
DS-16CBA	26.48	TDS-16CBA	28.48	--	--
DS-20CBA	31.73	TDS-20CBA	36.64	--	--

Table 8
Durability test results of different samples.

Sample	Soil losses (%)	Sample	Soil losses (%)	Sample	Soil losses (%)
DS-4C	Specimen failed	TDS-4C	Specimen failed	DS-4CS	Specimen failed
DS-6C	14.78	TDS-6C	10.5	DS-6CS	Specimen failed
DS-8C	13.86	TDS-8C	9.02	DS-8CS	Specimen failed
DS-10C	9.02	TDS-10C	8.56	DS-10CS	15.30
DS-12C	7.42	TDS-12C	6.54	DS-12CS	12.80
DS-16C	2.59	TDS-16C	1.19	DS-16CS	9.94
DS-20C	0.72	TDS-20C	0.57	DS-20CS	6.00
DS-4CBA	Specimen failed	TDS-4CBA	Specimen failed	--	--
DS-6CBA	Specimen failed	TDS-6CBA	Specimen failed	--	--
DS-8CBA	Specimen failed	TDS-8CBA	Specimen failed	--	--
DS-10CBA	15.04	TDS-10CBA	13.58	--	--
DS-12CBA	13.20	TDS-12CBA	9.82	--	--
DS-16CBA	10.42	TDS-16CBA	8.02	--	--
DS-20CBA	6.56	TDS-20CBA	4.22	--	--

Table 9
Concentration of heavy metal for different samples after 28 days curing.

Sample	28-days curing	Sample	28-days curing	Sample	28-days curing
DS-4C	Could not fulfill durability criteria	TDS-4C	Could not fulfill durability criteria	DS-4CS	Could not fulfill durability criteria
DS-6C	Could not fulfill durability criteria	TDS-6C	Could not fulfill durability criteria	DS-6CS	Could not fulfill durability criteria
DS-8C	Could not fulfill durability criteria	TDS-8C	Total = 3.942 mg/l Cd= 0.088 mg/l Ni=0.42 mg/l Cr= 0.054 mg/l Pb = 1.56 mg/l Zn = 1.82 mg/l	DS-8CS	Could not fulfill durability criteria
DS-10C	Total =1.82 mg/l Cd=0.018 mg/l Ni=0.166mg/l Cr=0.062 mg/l Pb =0.062 mg/l Zn =1.52 mg/l	TDS-10C	Total = 1.7 mg/l Cd= 0.016 mg/l Ni= 0.1520 mg/l Cr= 0.045 mg/l Pb = 0.057 mg/l Zn = 1.43 mg/l	DS-10CS	Total = 10.1944 mg/l Cd= 0.868 mg/l Ni= 2.88 mg/l Cr= 1.1224 mg/l Pb = 2.344 mg/l Zn = 2.98 mg/l
DS-12C	Total =1.24 mg/l Cd=0.0127 mg/l Ni=0.098 mg/l Cr=.0304 mg/l Pb =0.041 mg/l Zn =1.057 mg/l	TDS-12C	Total = 0.2652 mg/l Cd= 0.0122 mg/l Ni= 0.095 mg/l Cr=0.034 mg/l Pb =0.034 mg/l Zn =0.09 mg/l	DS-12CS	Total = 4.592 mg/l Cd= 0.03 mg/l Ni= 1.4 mg/l Cr= 0.81 mg/l Pb = 0.052 mg/l Zn =2.3 mg/l
DS-16C	Total =1.15 mg/l Cd=.0108 mg/l Ni=0.0844 mg/l Cr=0.026 mg/l Pb =0.032 mg/l Zn =1.002 mg/l	TDS-16C	Total = 0.221 mg/l Cd= 0.01mg/l Ni= 0.076mg/l Cr= 0.023mg/l Pb =0.024 mg/l Zn = 0.088mg/l	DS-16CS	Total =2.091 mg/l Cd= 0.022mg/l Ni= 0.388mg/l Cr= 0.047 mg/l Pb = 0.0337 mg/l Zn = 1.60 mg/l
DS-20C	Total =0.197 mg/l Cd=0.0084 mg/l Ni= 0.0334 mg/l Cr=0.0187 mg/l Pb = 0.0125 mg/l Zn =0.1246 mg/l	TDS-20C	Total =0.118 mg/l Cd= 0.0078 mg/l Ni= 0.032 mg/l Cr= 0.015 mg/l Pb = 0.011 mg/l Zn = 0.046 mg/l	DS-20CS	Total = 1.392 mg/l Cd=0.018 mg/l Ni= 0.124 mg/l Cr= 0.03 mg/l Pb = 0.02 mg/l Zn = 1.20 mg/l
DS-4CBA	Could not fulfill durability criteria	TDS-4CBA	Could not fulfill durability criteria	--	--
DS-6CBA	Could not fulfill durability criteria	TDS-6CBA	Could not fulfill durability criteria	--	--
DS-8CBA	Could not fulfill durability criteria	TDS-8CBA	Could not fulfill durability criteria	--	--
DS-10CBA	Could not fulfill durability criteria	TDS-10CBA	Could not fulfill durability criteria	--	--
DS-12CBA	Could not fulfill durability criteria	TDS-12CBA	Total = 1.29 mg/l Cd=0.0154 mg/l Ni=0.40 mg/l Cr= 0.0832 mg/l Pb = .0662 mg/l Zn =0.664 mg/l	--	--
DS-16CBA	Could not fulfill durability criteria	TDS-16CBA	Total = 1.18 mg/l Cd=0.0132 mg/l Ni=0.308 mg/l Cr= 0.0544 mg/l Pb = 0.052 mg/l Zn = 0.752 mg/l	--	--
DS-20CBA	Total =0.76 mg/l Cd=0.0084 mg/l Ni= 0.0334 mg/l Cr= 0.0187 mg/l Pb =0.0125 mg/l Zn = 0.1246 mg/l	TDS-20CBA	Total = 0.6441 mg/l Cd=0.0214 mg/l Ni=0.20 mg/l Cr= 0.0423 mg/l Pb = 0.0524 mg/l Zn = 0.328 mg/l	--	--

Now considering the acceptance criteria of highway subgrade materials, samples those have fulfilled all required criteria were selected and their sample matrix is presented below in Table 10. From the above laboratory test results of total thirty-five samples, only five samples, i.e. DS-10C, DS-20CBA, TDS-8C, TDS-12CBA, and DS-16CS were found finally to pass all the criteria of highway subgrade materials. Next using the algorithm of fuzzy decision model the most suitable sample out of them had been decided to assess its degree of suitability.

Table 10
Sample matrix.

Sample	Cement Consumption (% by weight of soil)	UCS value (kPa)	CBR value (%)	Soil cement losses (%)	Total heavy metal (mg/l)
DS-10C	10	925.75	21.00	9.02	1.8283
DS-20CBA	10	1200.33	31.73	6.56	0.7615
TDS-8C	8	872.79	25.34	9.02	2.197
TDS-12CBA	6	1029.69	25.18	9.82	1.2288
DS-16 CS	8	1324.43	27.4	9.94	2.091

For the construction of a highway, it is highly desirable that UCS value and CBR value should be high and others parameters like cement consumption, soil cement loss and total heavy metal concentration will be less. In fuzzy decision model, the ‘UCS value’ and ‘CBR value’ has considered as two goals G_1 & G_2 and ‘cement consumption’, ‘soil cement loss’ and ‘total heavy metal concentrations’ has considered as three constraints, i.e. C_1, C_2, and C_3. Now from normal perception of human being the fuzzy sets of all options of fuzzy decision technique could be modeled as:

$G_1 = \mu(g_1/Sample_i)$ = [0.75/(DS-10C),0.90/(DS-20CBA), 0.60/(TDS-8C), 0.80/(TDS-12CBA), 1.0/(DSS-16 C)]

$G_2 = \mu(g_2/Sample_i)$ = [0.70/(DS-10C), 1.0/(DS-20CBA), 0.85/(TDS-8C), 0.8/(TDS-12CBA), 0.95/(DSS-16 C)]

$C_1 = \mu(C_1/ Sample_i)$ = [1.0/(DS-10C), 1.0/(DS-20CBA), 0.80/(TDS-8C), 0.60/(TDS-12CBA), 0.80/(DSS-16 C)]

$C_2 = \mu(C_2/ Sample_i)$ = [0.85/(DS-10C), 0.50/(DS-20CBA),0.85/(TDS-8C),0.90/(TDS-12CBA), 1.0/(DSS-16 C)]

$C_3 = \mu(C_3/ Sample_i)$ = [0.65/(DS-10C), 0.30/(DS-20CBA), 1.0/(TDS-8C), 1.0/(TDS-12CBA), 0.90/(DSS-16 C)]

Therefore, D ($Sample_i$)

= [0.65/(DS-10C), 0.30/(DS-20CBA), 0.60/(TDS-8C), 0.60/(TDS-12CBA), 0.80/(DSS-16C)]

So the outcome result of fuzzy decision is given by

FD = Max {D ($Sample_i$)} = 0.80/ (DSS-16C)

Therefore, it is finally decided that sample DSS-16C is the best suitable sample out of five alternatives of Table 10. The next job is to assess the degree of suitability of sample DSS-16C to use as highway subgrade material.

To do this the different test results of sample DSS-16C are presented below in Table 11 for assessment of its degree of suitability using the fuzzy tool.

Table 11
Different test results of sample DSS-16C.

Sample	Cement Consumption (% by weight of soil)	UCS value (kPa)	CBR value (%)	Soil cement losses (%)	Total heavy metal (mg/l)
DSS-16C	8	1324.43	27.4	9.94	2.091

To assess the degree of suitability of sample DSS-16C, following fuzzy five attributes has been considered for direct interaction with soil engineering experts. For the simplicity of assessment, five experts were also selected to obtain their individual views and perceptions and assessed the membership value of each attribute out of 100. The attributes are:

x_1 = low consumption of cement

x_2 = high UCS value

x_3 = high CBR value

x_4 = low soil cement losses

x_5 = low heavy metals

Considering the importance of each attribute during construction of a highway, the weighted value of each attribute has been prefixed before taking the expert's views (for simplicity of calculation, the total weighted value was considered as 100). Here 'low consumption of cement' and 'high CBR value' are considered as two major important attributes, and their weighted values have prefixed 35 and 30 out of 100. Similarly, the weighted value of attribute 'high UCS value = 10', 'low soil cement losses = 15' and 'low heavy metals = 10' has been prefixed. Next, the membership values of all the attributes have obtained from individual views & perceptions of five experts independently, and are presented below in Table 12 for further assessment of the degree of suitability of sample DSS-16C.

Table 12
Average membership values of attributes.

Attribute	Expert-1	Expert-2	Expert-3	Expert-4	Expert-5	Average Membership value	Weighted value of attribute (W_x)
x_1	0.75	0.85	0.60	0.90	0.65	0.75	35
x_2	0.40	0.55	0.50	0.40	0.30	0.43	10
x_3	0.70	0.70	0.65	0.60	0.50	0.63	30
x_4	0.20	0.10	0.25	0.30	0.10	0.19	15
x_5	0.90	0.80	0.70	0.85	0.70	0.79	10

The weighted average of sample DSS-16C is calculated as 0.596, and consequently, the grade is awarded as ‘C’ means the sample in the question of degree of suitability to use as subgrade materials is ‘Good’.

5. Conclusion

The dredged soil of Najafgarh drain is contaminated and possesses very poor geotechnical properties to use it directly as subgrade materials in highway construction. Attempt to use this waste material in the construction of highway subgrade layer after stabilizing/solidifying with cement, cement- bottom ash mix (1:1) and cement-GGSS mix (1:1) has been made and found to be successful. Study on thermal treatment of dredged soil has also given a new direction to improve the chemical process of stabilizing/solidifying treatment on the addition of the above mentioned additives. Out of thirty-five samples, only five samples, i.e., DS-10C, DS-20CBA, TDS-8C, TDS-12CBA, and DS-16CS fulfilled the acceptance criteria of highway subgrade materials, and finally, DS-16CS has been selected as the most suitable sample to be used as subgrade material with the degree of suitability in the rank of ‘good’.

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