Journal of Engineering Science and Technology
Vol. 14, No. 4 (Year) 2034 - 2051

USE OF CONTAMINATED DREDGED SOIL IN DIFFERENT PAVEMENT LAYERS AFTER THERMAL TREATMENT AND STABILIZATION/SOLIDIFICATION

ANJALI GUPTA[1,*], VINOD K. ARORA[2], SRIJIT BISWAS[3]

[1]Department of Civil Engineering,
National Institute of Technology, Kurukshetra, 136118, Haryana, India and
Department of Civil Engineering, Manav Rachna International Institute of Research and Studies, Faridabad, 121004, Haryana, India
[2]National Institute of Technology, Kurukshetra, 136118, Haryana, India
[3]Manav Rachna International Institute of Research and Studies,
Faridabad, 121004, Haryana, India
*Corresponding Author: anjaligupta.eng@gmail.com

Abstract

In this study, an attempt has been made to reduce organic matter, heavy metal concentration and improve the strength and durability of contaminated dredged soil by thermal treatment at 310 ^{0}C followed by stabilization/solidification using cement and cement-bottom ash mix. The thermal treatment leads to a reduction of the organic matter content of the dredged soil. Furthermore, bottom ash has been used to partially replace the cement content. A comparison of different test results was done on contaminated dredged soil stabilized/solidified with and without thermal treatment. Results indicated that after thermal treatment followed by stabilization/solidification, the properties of contaminated dredged soil has improved and many specimens fulfilled the required acceptance criteria to use them as construction materials in different pavement layers.

Keywords: Contaminated dredged soil, Pavement layers, Stabilization/solidification, Thermal treatment.

1. Introduction

The periodic dredging of the sediments and debris from the bottom of lakes, riverbeds, harbours, reservoirs or major drains is required to increase flood carrying capacity of the watercourse [1-3]. Amar et al. [4] and Huang et al. [5] mentioned that about 50 million m^3 of dredged soil is generated annually in France, 300 million m^3 in Europe, 100 million m^3 in China and 300 million m^3 in the USA. These soils generally contain heavy metals and organic matter and have poor geotechnical properties; as a result, these soils cannot be used directly as construction material, hence, disposed-off. However, the disposal of such soils is a matter of concern all over the world due to its large volume and environmental impact. A similar problem is faced in Delhi Zone (India) due to dredged soil generated from connecting drains of River Yamuna.

River Yamuna in 22 Km stretch of Delhi zone is connected to 22 major drains. Based on studies by Misra [6] and Central Pollution Control Board [7], these drains are incessantly receiving sediments, sewage, and sludge from various point and nonpoint sources, which are polluting and reducing flood carrying capacity of these drains as well as river Yamuna. Hence, to clean and increase flood carrying capacity of these drains, desilting work using draglines and barge-mounted dredging machines is in progress and as per records, the total quantity of dredged soils removed was about 830,000 m^3 in the year 2010-2013, 338,132 m^3 in the year 2016 and 285,384 m^3 in the year 2017 [8, 9]. Since the amount of dredged soil is large and in cities like Delhi disposal is more difficult due to the scarcity of land, conversion of these sediments into useful resources is urgently needed to maintain these sediments as well as preserve the environment towards more sustainable circumstances.

From the previous studies, it was found that stabilization/solidification is a promising technique that could be used to convert such contaminated dredged soils into useful resources and in most of the studies cement has come out as the most effective stabilizer [10-12]. But the presence of organic matter in these soils interferes with the cementing process resulting in the negative effect on stabilization/solidification [13-16]. Literature review revealed that thermal treatment is one of the effective and irreversible methods to reduce organic matter [17-19]. Hence, in this study the treatment of contaminated dredged soil has been done by following two sequential steps; i) thermal treatment of the dredged soil to reduce organic matter, ii) stabilization/solidification of dredged soils using cement and cement-bottom ash mix.

The purpose of using bottom ash is to partially replace the cement and make the mix economical. According to Cheriaf et al. [20], from the literature review, it has been found that bottom ash possesses pozzolanic characteristics and can replace cement effectively [20]. Results of thermally treated soil were also compared with the results of dredged soil stabilized/solidified without thermal treatment. In both cases, cement and cement-bottom ash mix have been used as stabilizing/solidifying agent and a comparison has been made based on strength, durability and leaching characteristics of the dredged soil so that it can be used as construction material in different pavement layers. Furthermore, morphological changes for stabilized/solidified dredged soil with or without thermal treatment using Scanning Electron Microscopy (SEM) were also investigated.

2. Materials

The soil used in this study was collected from the banks of Najafgarh drain (South West of Delhi, India) where dredging work was in progress. The location map of the drain is shown in Fig. 1.

Fig. 1. Location map of Najafgarh drain [21].

The stabilizing/solidifying agents used in this study are cement (*C*) and Bottom Ash (BA) as both these have the binding capacity. Also, bottom ash when finely powdered has the capability to promote the pozzolanic reaction due to high percentages of silica (SiO_2) and alumina (Al_2O_3) contents, which are key ingredients of cement [20]. From the chemical composition results shown in Table 1, it can be seen that for finely powdered bottom ash the sum of SiO_2 +Al_2O_3 + Fe_2O_3 approximated to 81.59%, which is greater than the 70% as recommended by ASTM standard for pozzolana [22]. Thus, the addition of bottom ash as partial replacement of cement contributes to environmental pollution control as well as extends economic benefits by replacing the cement.

In this case study, the ordinary Portland cement used was of Grade-43 (J. K. Lakshmi Cement) with the specific gravity of 3.15 and the bottom ash was obtained from National Thermal Power Plant, Badarpur, New Delhi (India) with the specific gravity of 2.1. The chemical composition of raw contaminated dredged soil and bottom ash was determined by performing EDXRF (Modal-Epsilon 5 Panalytical (Netherland)) and for cement, specimen was obtained from J. K. Lakshmi Cement. The results are presented in Table 1.

Table 1. Chemical composition of raw contaminated dredged soil, bottom ash and cement.

Chemical composition	Raw contaminated dredged soil (%)	Bottom ash (%)	Cement (%)
SiO_2	70.40	44.82	20$\pm$1
Al_2O_3	14.24	26.27	5 $\pm$ 0.5
Fe_2O_3	4.16	10.50	3 $\pm$ 0.5
CaO	2.11	5.83	61 $\pm$ 1
MgO	1.89	1.15	2.5 $\pm$ 1

3. Experimental Work

The present study was done in two phases. In the first phase, a test study on dredged soil stabilized/solidified with cement and cement-bottom ash mix was performed and in the second phase, it was thermally treated to reduce organic matter followed by stabilization/solidification with same stabilizers as in the first phase. In both, the phases percentage of cement and cement-bottom ash mix (1:1) were kept constant. Figure 2 represents the flowchart of procedure followed in laboratory to determine the properties of raw contaminated dredged soil (DS), contaminated dredged soil mixed with cement (DS-C), contaminated dredged soil mixed with cement-bottom ash (1:1) (DS-CBA), contaminated dredged soil after thermal treatment (TDS), contaminated dredged soil after thermal treatment mixed with cement (TDS-C), contaminated dredged soil after thermal treatment mixed with cement-bottom ash (1:1) (TDS-CBA).

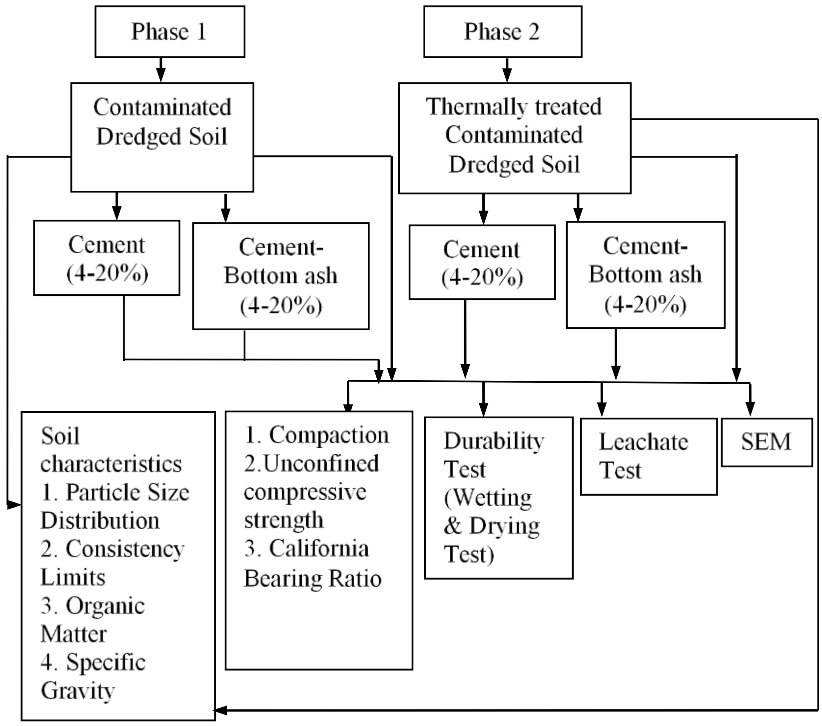


Fig. 2. Flow chart of procedure followed in this study.

Since this soil falls under the A-4 group, 7-12% of cement by weight is required for stabilization as recommended by soil cement laboratory handbook by Portland cement association [23], however, based upon literature review this preliminary estimate may change for contaminated soils. Kogbara [24] reviewed that cement requirement for stabilizing contaminated soil may range from 4% to 20% by weight of the dry mass of the soil. Hence, based upon findings mixing proportion of 4-20% of cement has been taken in the current study.

Hessling et al. [18] in their study reported that soil heated at 310 ^{0}C for 24 hours to remove organic carbon and then stabilized/solidified with cement showed better results in comparison to no heating done. Hence, in this study, the thermal treatment of dredged soil has been done by using a muffle furnace at 310 ^{0}C to remove the organic matter completely.

Testing procedure

The summary of mix proportion (% age by weight of dry soil) of all the specimens is given below in Table 2.

The particle-size distribution tests were carried out in accordance with IS 2720 (Part-4) using sieves and hydrometer. Consistency limits such as Liquid Limit (LL) and Plastic Limit (PL) were done as per IS 2720 (Part-5). Since the dredged soil was silty in nature and conducting the liquid limit test by using Cassagrande's apparatus was difficult, the liquid limit was performed using the cone penetrometer method. The specific gravity of ash samples was determined by Pycnometer bottle as per IS 2720 (Part-3). The total organic content of the dredged soil was determined using IS 2720 (Part- 22).

The standard Proctor compaction test was conducted as per I.S.2720 (Part-7) for various combinations as mentioned in Table 2 to find out the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). For conducting tests on the specimen DS and TDS selected amount of water was mixed with soil and then compacted in a mould of diameter 100 mm and height 127.3 mm (1000 ml) in 3 equal layers by rammer of weight 2.6 kg with a free fall of 310 mm. Each layer was compacted by giving 25 blows. Whereas for DS-C, DS-CBA, TDS-C, and TDS-CBA initially the soil was dry mixed with stabilizers and thereafter mixed with water thoroughly. The compaction of each specimen, in this case, was completed within 20 minutes as per IS 4332 (Part-3).

Unconfined Compressive Strength (UCS) of soil was used to determine the maximum compressive strength of specimens DS and TDS in accordance with IS 2720 (Part-10) and specimens DS-C, DS-CBA, TDS-C, and TDS-CBA in accordance with IS 4332 (Part-5). For testing, three identical specimens of size 38 mm in diameter and 76 mm in height were prepared.

For each specimen, the soil was compacted statically in UCS mould by applying pressure through compression testing machine at their respective MDD and OMC and 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, and TDS-CBA were tested after curing for a period of 7 days and 28 days in a curing tank maintained at 23 ^{0}C temperature and 100% humidity. All the specimens were tested using a loading rate of 1.25 mm/min.

CBR tests were performed using IS 2720 (Part-16) in unsoaked and soaked conditions. All the specimens were prepared in a cylindrical mould of 150 mm diameter and 175 mm height at their respective MDD and OMC. The DS and TDS specimens were tested in unsoaked conditions and 4 days soaking conditions in water, whereas specimens DS-C, DS-CBA, TDS-C, and TDS-CBA were cured for 3 days followed by 96 hours soaking condition in water in accordance with IRC 50-1973. Thereafter the CBR tests were performed on all the specimens.

Durability test on specimens was performed by wetting and drying method as per IS 4332 (Part-4). For conducting tests, the specimens were prepared by following the same procedure as for unconfined compressive strength test and cured for 7 days at 23 ^{0}C temperature and 100% humidity. Thereafter specimens were soaked in water for 5 hours, followed by drying in the oven at 70 ^{0}C for 42 hours, which forms one wet-dry cycle. This test procedure continued up to 12 cycles. After the end of each cycle, the specimens were brushed with a steel brush at about 1.4 kg force along the diameter and height and soil cement losses were recorded in percentage.

The leachate test studies were done to determine the heavy metals present in the dredged soil that would leach out and contaminate the environment. The preparation of specimens was done by following the same procedure as for UCS.

In this study, Toxicity Characteristic Leaching Procedure (TCLP) defined by the US EPA (Method 1311) was used and heavy metals Cd, Zn, Cr, Pb, and Ni were analysed using AAS4129 Atomic Absorption Spectrophotometer [25].

The morphological properties of the mixes were evaluated by using a Zeiss EVO 50 Scanning electron microscope on samples cured for 7 days and 28 days. The soil specimens were coated with gold in sputter coating to avoid charge accumulation of the specimen during the testing and SEM images of the specimens focused at 1000× magnification were analysed for microstructural bonding of the mixture.

Table 2. Mix proportion of cement and cement-bottom ash mix.

Specimen		**Stabilizer**		
Dredged soil	**Dredged soil after thermal treatment**	**Cement (%)**	**Bottom ash (%)**	**Total (%)**
DS	TDS	0	0	0
DS-4C	TDS-4C	4	0	4
DS-6C	TDS-6C	6	0	6
DS-8C	TDS-8C	8	0	8
DS-10C	TDS-10C	10	0	10
DS-12C	TDS-12C	12	0	12
DS-16C	TDS-16C	16	0	16
DS-20C	TDS-20C	20	0	20
DS-4CBA	TDS-4CBA	2	2	4
DS-6CBA	TDS-6CBA	3	3	6
DS-8CBA	TDS-8CBA	4	4	8
DS-10CBA	TDS-10CBA	5	5	10
DS-12CBA	TDS-12CBA	6	6	12
DS-16CBA	TDS-16CBA	8	8	16
DS-20CBA	TDS-20CBA	10	10	20

4. Results and Discussion

The experimental results of all the specimens for both phases were analysed and presented sequentially below to arrive at a conclusion regarding the use of dredged soil as a construction material in different pavement layers.

4.1. Soil characteristics

Particle size distribution curves of DS and TDS were shown in Fig. 3. From the results, it was found that DS majorly consists of 4% gravel, 34% sand, 60% silt, and 2% clay fraction. The soil was classified as silty soil with low compressibility (ML) as per IS standard classification or *A*-4 as per AASHTO classification with a Coefficient of Curvature (C_c) 4.45 and Coefficient of Uniformity (C_u) 10.76. Whereas after thermal treatment the grain size analysis curve of TDS showed 1% gravel, 46% sand, 52% silt, and 1% clay. The C_c value decreased to 2.86 and C_u to 9.71, which lead to changes in the percentage of the size of particles. This may be due to the coating of fine particles into sand-sized particles.

Liquid limit of DS was 20.99% and the plastic limit was nil. After thermal treatment of dredged soil, liquid limit reduced to 20.22% and plastic limit remained the same. The specific gravity of DS was 2.52, while after thermal treatment at elevated temperature the specific gravity of TDS increased to 2.54. This increase may be due to the reduction of organic matter on the thermal treatment of the soil. The amount of organic matter in DS was 2.15%, however, after thermal treatment at 310 ^{0}C, the value organic matter reduced to approximately zero.

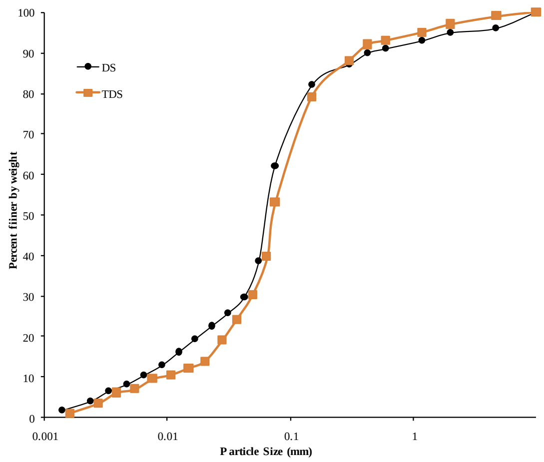


Fig. 3. Particle size distribution curve of DS and TDS.

4.2. Compaction

MDD value of the specimen DS was found to be 1642 kg/m^3 and OMC is 13.5%. After thermal treatment, the MDD value of the specimen TDS increased to 1680 kg/m^3, which was 2.31% higher than the MDD value of DS. The corresponding OMC value is 16.5%, which was 22.2% higher than the OMC of DS. The increase in the OM*C* after thermal treatment may be attributed to evaporation of water from the voids of the soil.

Figures 4 and 5 show the variation of MDD and OMC at different stabilizer content for contaminated dredged soil with or without thermal treatment.

Results revealed that on the addition of 4-8% cement to DS (represented by trend line DS-C), the MDD value decreased from 1640 kg/m^3 to 1610 kg/m^3 and thereafter on a further increase of cement content no decrease in MDD was observed. This might be related to the hydration reaction between the dredged soil and cement in the presence of moisture leading to base exchange, aggregation and flocculation, which cause the formation of voids and hence, decrease in MDD. The OMC value of DS on the addition of 4-20% cement increased from 16.7% to 21.23% as shown in Fig. 5. The increase of moisture content was attributed to the pozzolanic reaction of cemented soil.

For dredged soil stabilized/solidified with cement-bottom ash mix (represented by trend line DS-CBA), we can see decrease in MDD values from 1600 kg/m^3 to 1580 kg/m^3 with the increase of cement-bottom ash mix up to 12% and thereafter on further increase of cement-bottom ash mix content it increased to a constant value of 1610 kg/m^3. OMC value increased from 17.6% to 19.8% with the increase of cement-bottom ash mix to the dredged soil.

From Fig. 4, it can be observed that on the incorporation of 4-10% cement to TDS, the MDD of TDS-C decreased from 1660 kg/m^3 to 1640 kg/m^3 and thereafter it achieved a constant value of 1640 kg/m^3 on the further increase of cement up to 20%. Whereas OMC value increased from 17.2% to 26.0 % with the increase of cement content from 4% to 20%. The results also highlighted that MDD of TDS-CBA decreased from 1660 kg/m^3 to 1620 kg/m^3 with the increase of cement-bottom ash content from 4% to 20% and OMC increased from 17.4 % to 27.9%.

On comparison of the results of MDD and OMC of stabilized/solidified specimens with or without thermal treatment, it has been found that both MDD and OMC increased to the certain extent after thermal treatment of the dredged soil in comparison to the results of without thermal treatment specimens.

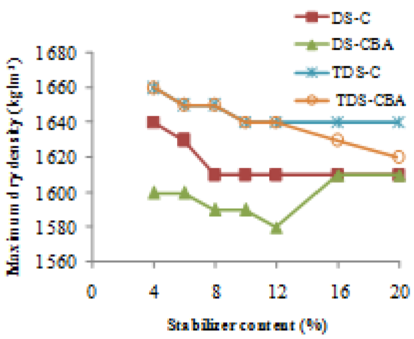


Fig. 4. Variation of MDD at different stabilizer content.

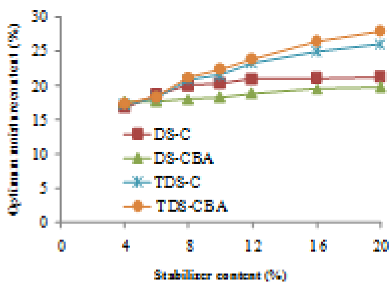


Fig. 5. Variation of OMC at different stabilizer content.

4.3. Unconfined compressive strength

The specimen DS has low UCS value of 197.11 kPa and on thermal treatment, specimen TDS obtained a UCS value of 230.45 kPa, which was 17% higher than the UCS value of DS.

The graphical test results of UCS of all the specimens at 7 days and 28 days curing are given below in Figs. 6(a) and (b).

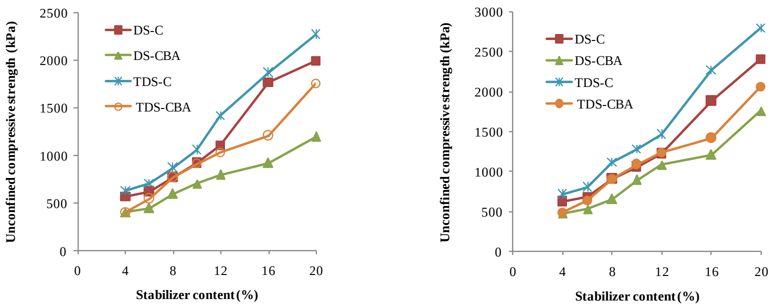
On addition of 4-20% cement, the UCS value of DS-C increased from 565.78 kPa to 1993.69 kPa after 7 days curing and from 629.58 kPa to 2408.51 kPa after 28 days curing as shown in Figs. 6(a) and (b) respectively. The increase in value may be attributed to the continuous formation of calcium silicate hydrate (C-S-H) and calcium aluminium silicate hydrate (C-A-S-H), which are pozzolanic products. Results also showed that UCS value increased as cement-bottom ash mix (DS-CBA) percentage increased.

In the second phase of study after thermal treatment, on the addition of 4-20% cement UCS values of TDS-C increased from 627.63 kPa to 2275.14 kPa and were higher in comparison to DS-C. Such improvement in the UCS values may be due to the reduction of organic matter on thermal treatment. For TDS-CBA also trends were the same.

From the comparison of results of UCS value of DS-CBA, TDS-CBA and DS-C, TDS-C, it has been found that the UCS value of DS-CBA and TDS-CBA were higher than DS-C and TDS-C when compared on the basis of percentage of cement present in both the mixes as mentioned in Table 3. For example, a UCS value of DS-4C (4% cement) is 565.78 kPa after 7 days curing whereas for DS-8CBA (4% cement + 4% bottom ash) is 600.17 kPa showing a 6% increase in UCS value. This shows that the replacement of cement by bottom ash was effective and improved UCS values.

Table 3. UCS and CBR values of dredged soil stabilized/ solidified with cement and cement-bottom ash mix.

Specimen	UCS-7 days, kPa	CBR, %	Specimen	UCS-7 days, kPa	CBR, %	Mix proportion in % age
DS-4C	565.78	12.76	TDS-4C	627.63	13.83	4% C
DS-6C	621.74	14.90	TDS-6C	706.08	22.52	6% C
DS-8C	770.80	19.21	TDS-8C	872.79	25.34	8% C
DS-10C	925.75	21.00	TDS-10C	1059.12	31.02	10% C
DS-12C	1107.17	26.26	TDS-12C	1418.04	35.40	12% C
DS-16C	1765.90	33.36	TDS-16C	1873.07	42.74	16% C
DS-20C	1993.69	46.87	TDS-20C	2275.14	49.82	20% C
DS-4CBA	402.07	3.01	TDS-4CBA	404.03	4.79	2% C + 2% BA
DS-6CBA	445.09	6.71	TDS-6CBA	549.17	8.66	3% C + 3% BA
DS-8CBA	600.17	14.77	TDS-8CBA	774.73	16.94	4% C + 4% BA
DS-10CBA	706.08	17.63	TDS-10CBA	913.98	20.19	5% C + 5% BA
DS-12CBA	798.26	20.77	TDS-12CBA	1029.70	25.18	6% C + 6% BA
DS-16CBA	921.83	26.48	TDS-16CBA	1210.14	28.48	8% C + 8% BA
DS-20CBA	1200.33	31.73	TDS-20CBA	1756.30	36.64	10% C+ 10% BA



(a) 7 days curing. **(b) 28 days curing**

Fig. 6. Graphical representation of test results of UCS.

4.4. California bearing ratio

The CBR value of DS was found to be 1.45% and 1.03% for unsoaked condition and soaked condition that shows soil possess lower strength. After thermal treatment, CBR values for unsoaked and soaked conditions of TDS were 13.25% and 3.01%, respectively, which were 89% (unsoaked) and 65.8% (soaked) higher than CBR values of DS. This increase in CBR value denotes strength development after thermal treatment of dredged soil.

Figure 7 shows the effect of the addition of the variable percentage of cement, cement-bottom ash mix on CBR values of contaminated dredged soil with or without thermal treatment. The CBR value of DS-C increased from 12.76% to 46.87%, while for DS-CBA from 3.01% to 31.73% with an increase of additive contents from 4% to 20%.

Similarly, the CBR value of TDS-C increased from 13.83% to 49.82% with the increase of cement from 4-20% and from 4.79% to 29.93% for TDS-CBA on the addition of 4-20% of the cement-bottom ash mix (1:1). The achieved CBR values reported in Table 3 indicated that after thermal treatment CBR values increased in comparison to results of without thermal treatment. The results also revealed that bottom ash effectively replaced the cement as CBR values of DS-CBA and TDS-CBA were higher than DS-C and TDS-C for the same percentage of cement content.

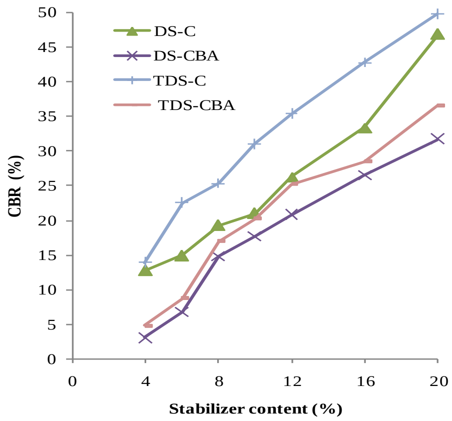


Fig. 7. Variation of CBR values at different stabilizer content.

4.5. Wetting and drying test

After testing of DS and TDS specimens, it has been observed both failed to complete 12 cycles of wetting and drying test. Figure 8 presents the variation of percentage soil cement losses on the addition of the stabilizer to dredged soil with or without thermal treatment.

Results revealed that on the addition of cement, all specimens except DS-4C passed 12 cycles. The soil-cement losses decreased from 14.78% to 0.72% with the increase in cement from 6% to 20%. Whereas for DS-CBA, the specimen DS-10CBA, DS-12CBA, DS-16CBA, DS-20CBA could survive 12 cycles and soil cement losses were 15.04%, 13.20%, 10.42% and 6.56% respectively.

The trend of wetting and drying test for the specimens of thermally treated dredged soil was similar to dredged soil after stabilization/solidification, i.e., the specimen TDS, TDS-4C, TDS-4CBA, TDS-6CBA, TDS-8CBA failed to complete 12 cycles. However, soil cement losses decreased from 10.5 % to 0.57% on increase of cement from 6% to 20% and from 13.58% to 4.22% on increase of cement-bottom ash content from 10% to 20%.

From the overall results of wetting and drying test, it was observed that the specimens DS-10C, DS-12C, DS-16C, DS-20C, DS-20CBA, TDS-8C, TDS-10C, TDS-12C, TDS-16C, TDS-20C, TDS-12CBA, TDS-16CBA, and TDS-20CBA have fulfilled the acceptance criteria of less than 10% soil-cement losses [23].

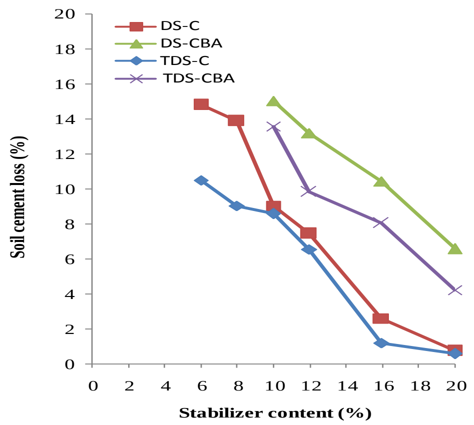


Fig. 8. Variation of percentage soil-cement losses.

4.6. Leachate test results

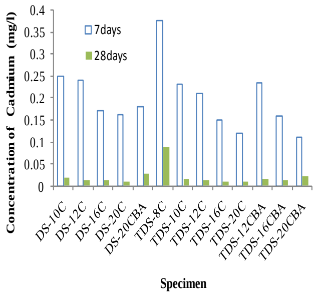
Leachate test was performed on specimen DS and TDS and on stabilized/solidified specimens, those fulfilled the acceptance criteria as mentioned above. Since there are guidelines in IRC 37 [26] regarding additional requirements of leachability and concentration of heavy metal, however, in the absence of any specified minimum or regulatory limit TCLP hazardous waste limit, mg/l was taken as the standard.

The results of the concentration of heavy metals in DS and TDS using TCLP leaching test were represented in Table 4, which indicated that the heavy metal concentration in DS is quite high from the USEPA regulatory limits for heavy metals and soil was in hazardous limits. After thermal treatment, heavy metals concentration decreased in comparison to DS but still remains within the hazardous limit.

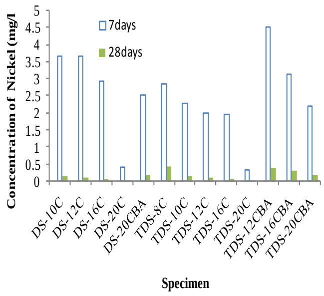
Figures 9(a) to (e) show concentration of heavy metals, namely Cd, Ni, Cr, Pb, and Zn obtained from leachate test. From the results, it has been found that after 7 days curing, the concentration of heavy metal for specimen DS-16C, DS-20C, TDS-16C, and TDS-20C was less than the maximum concentration criteria. Whereas for specimen DS-10C, DS-12C, DS-20CBA, TDS-6C, TDS-8C, TDS-10C, TDS-12C, TDS-20CBA concentration of zinc was high and for TDS-12CBA and TDS-16CBA concentration of zinc and nickel were high. After 28 days curing, the leaching levels of all the specimens were within acceptable limits with no environmental risk.

Table 4. Heavy metal concentration in DS and TDS.

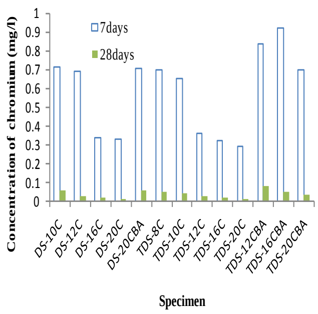
Heavy metal	USEPA regulatory limits for heavy metals concentrations, mg/l [27]	Concentration (DS), mg/l	Concentration (TDS), mg/l
Cd	<1	27.1	26.6
Ni	<3	383.0	277.0
Cr	<5	109.0	53.0
Pb	<5	74.5	69.3
Zn	<5	2660.0	1440.0



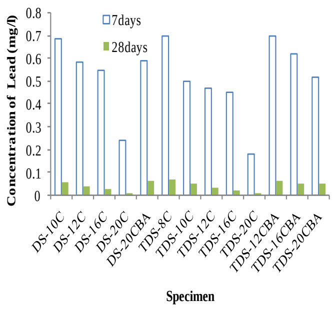
(a) Cadmium.



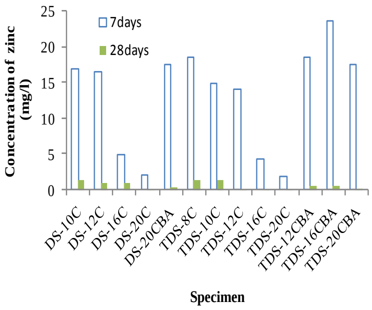
(b) Nickel.



c) Chromium.



(d) Lead.

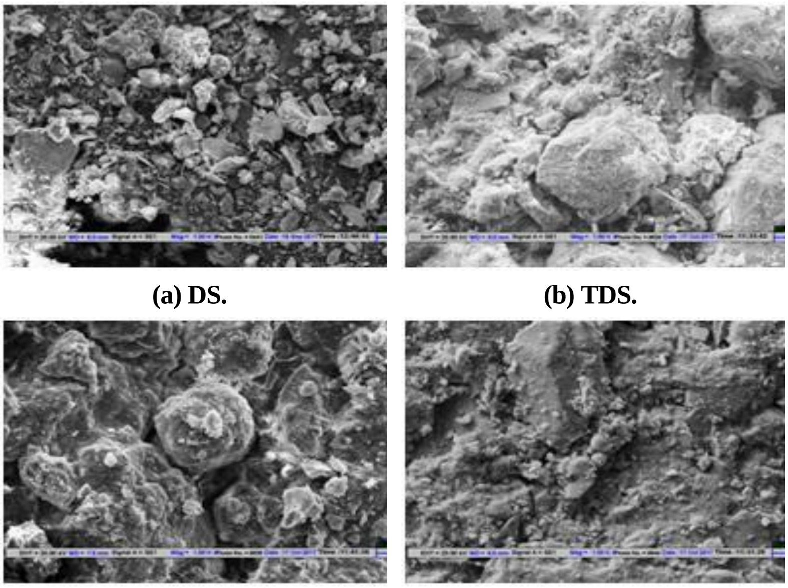


(e) Zinc.

Fig. 9. Concentration of heavy metals for different specimens.

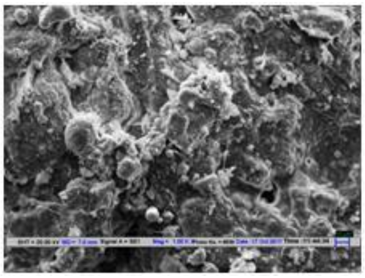
4.7. Scanning electron microscope (SEM) analysis

The SEM images of DS and TDS and 28 days cured specimens of DS-10C, DS-20CBA and TDS-20CBA at 1000× magnification are presented in Figs. 10(a) to (e) respectively. From the figures, it has been observed that after thermal treatment of dredged soil agglomeration of particles occurs. It also revealed that on the addition of cement and cement-bottom ash mix bonding between the particles improved. A strong interaction in between dredged soil and cement-bottom ash mix has experiential on comparison of DS-20CBA with DS-10C as shown in Figs. 10(c) and (d). This interaction may be responsible for the increase in UCS, CBR value and the decrease in soil-cement losses.



(a) DS. **(b) TDS.**

(c) DS-10C. **(d) DS-20CBA.**



(e) TDS-20CBA.

Fig. 10. SEM image of different specimens at 1000× magnification.

5. Application

Results of detailed laboratory investigation were analysed to arrive at the conclusion regarding the suitability of thermally treated as well as stabilized/solidified dredged soil used as construction material in different pavement layers such as subgrade, sub-base, and base layer.

Subgrade

According to IRC:SP:89 [28], the minimum value of soaked CBR for cement stabilized soil should be 15%. Additionally, durability criteria, i.e., maximum soil cement losses for silty soil not more than 10% and heavy metals concentration criteria, i.e., maximum concentration not exceeding 1.0, 5.0, 5.0, 5.0 and 3.0 mg/l for Cd, Zn, Cr, Pb, and Ni respectively [27] should be satisfied. From the test results, it was found that DS-10C, DS-12C, DS-16C, DS-20C, DS-20CBA, TDS-8C, TDS-10C, TDS-12C, TDS-16C, TDS-20C, TDS-12CBA, TDS-16CBA and TDS-20CBA fulfilled the acceptance criteria required for pavement subgrade materials.

Sub-base layer

As per IRC 37 [26], the minimum requirement of 7 days UCS value for cement stabilized soils is 1500 kPa for High Volume Roads (HVR) and 750 kPa for Medium Volume Roads (MVR). However, for low volume roads, the minimum UCS value for stabilized bound sub-base is 1700 kPa as specified in IRC: SP: 72 [29]. Further, durability and heavy metal concentration limits as mentioned in Table 5 should be satisfied by the cement stabilized soil. Specimens, which fulfilled the acceptance criteria to be used as a construction material for the sub-base layer, are illustrated in Table 5.

Base layer

The minimum required 7 days UCS value for base material for HVR is 7000 kPa and for MVR is 4500 kPa [26]. Further, for LVR a minimum laboratory UCS of 3000 kPa is required according to IRC: SP: 72. Also, durability and heavy metal concentration limits should be satisfied by the cement stabilized soil as mentioned in Table 5. From the results, it has been observed that no specimen was able to achieve UCS value required for the base layer for HVR, MVR or LVR.

A comparison of test results with codal provisions has been presented in Table 5. Leachate tests were performed only on those specimens that fulfilled the acceptance criteria of wetting and drying test.

Table 5. Comparison of test results with codal provisions.

Test	Strength							Durability	Leaching characteristic
	CBR, (%) Subgrade	UCS-7 days, kPa sub-base			UCS-7 days, kPa base			Soil cement losses (%)	Regulatory limit, mg/l [27]
Criteria▶		HVR	MVR	LVR	HVR	MVR	LVR		
	> 15	> 1500	> 750	> 1700	> 7000	> 4500	> 3000	< 10	
Specimen▼									
DS-4C	x	x	x	x	x	x	x	x	TNP
DS-6C	x	x	x	x	x	x	x	x	TNP
DS-8C	✓	x	✓	x	x	x	x	x	TNP
DS-10C	✓	x	✓	x	x	x	x	✓	✓
DS-12C	✓	x	✓	x	x	x	x	✓	✓
DS-16C	✓	✓	✓	✓	x	x	x	✓	✓
DS-20C	✓	✓	✓	✓	x	x	x	✓	✓
DS-4CBA	x	x	x	x	x	x	x	x	TNP
DS-6CBA	x	x	x	x	x	x	x	x	TNP
DS-8CBA	x	x	x	x	x	x	x	x	TNP
DS-10CBA	✓	x	x	x	x	x	x	x	TNP
DS-12CBA	✓	x	✓	x	x	x	x	x	TNP
DS-16CBA	✓	x	✓	x	x	x	x	x	TNP
DS-20CBA	✓	x	✓	x	x	x	x	✓	✓
TDS-4C	x	x	x	x	x	x	x	x	TNP
TDS-6C	✓	x	x	x	x	x	x	x	TNP
TDS-8C	✓	x	✓	x	x	x	x	✓	✓
TDS-10C	✓	x	✓	x	x	x	x	✓	✓
TDS-12C	✓	x	✓	x	x	x	x	✓	✓
TDS-16C	✓	✓	✓	✓	x	x	x	✓	✓
TDS-20C	✓	✓	✓	✓	x	x	x	✓	✓
TDS-4CBA	x	x	x	x	x	x	x	x	TNP
TDS-6CBA	x	x	x	x	x	x	x	x	TNP
TDS-8CBA	✓	x	✓	x	x	x	x	x	TNP
TDS-10CBA	✓	x	✓	X	x	x	x	x	TNP
TDS-12CBA	✓	x	✓	X	x	x	x	✓	✓
TDS-16CBA	✓	x	✓	X	x	x	x	✓	✓
TDS-20CBA	✓	✓	✓	✓	x		x	✓	✓

✓: Satisfied, x: Unsatisfied, TNP: Test not performed

6. Conclusion

In this study, sequential treatment of contaminated dredged soil has been done in which, soil was first thermally treated to reduce organic matter followed by stabilization/solidification. The whole process was done to treat and stabilize/ solidified contaminated dredged soil so that it can be used as construction material in different pavement layers. The potential of using bottom ash as partial replacement of cement was also investigated. From the results, the following conclusions have been made:

- After thermal treatment, organic matter in dredged soil reduced to negligible and on further treatment with stabilizers, the value of MDD, UCS and CBR improved. The percentage of soil cement losses and heavy metal concentration also reduced in comparison to dredged soil stabilized/solidified without thermal treatment.
- For the subgrade layer of all category roads, the specimen TDS12CBA is found to be most adequate.
- The specimen TDS-20CBA that consists of 10% cement and 10% bottom ash adequately fulfilled the acceptance criteria of sub-base layer for HVR as well as LVR, whereas the specimen TDS-12CBA that consists of 6% cement and 6% bottom ash adequately fulfilled the required acceptance criteria for MVR.
- Finally, it can be concluded that thermal treatment and use of bottom ash directly influenced the reduction in consumption of cement as well as improved the properties of contaminated dredged soil.

Nomenclatures

C_c	Coefficient of curvature
CAR	California bearing ratio, %
C_u	Coefficient of uniformity
LL	Liquid limit, %
MDD	Maximum dry density, kg/m^3
ML	Silty soil with low compressibility
OMC	Optimum moisture content, %
PL	Plastic limit, %
UCS	Unconfined compressive strength, kPa

Abbreviations

AAS	Atomic Absorption Spectrophotometer
Al_2O_3	Alumina
ASTM	American Society for Testing and Materials
BA	Bottom Ash
C	Cement
DS	Dredged Soil
EDXRF	Energy Dispersive X-ray Fluorescence
Fe_2O_3	Ferric Oxide
HVR	High Volume Roads
IRC	Indian Road Congress
IS	Indian Standard
LVR	Low Volume Roads
MgO	Magnesium Oxide
MVR	Medium Volume Roads
OPC	Ordinary Portland Cement
SEM	Scanning Electron Microscopy
SP	Special Publication
TCLP	Toxicity Characteristic Leaching Procedure
TDS	Thermally Treated Dredged Soil
US EPA	United States Environmental Protection Agency

References

1. Junakova, N.; and Junak, J. (2017). Recycling of reservoir sediment material as a binder in concrete. *Procedia Engineering*, 180, 1292-1297.
2. Kim, J.-O.; Choi, J.; Lee, S.; and Chung, J. (2016). Evaluation of hydrocyclone and post-treatment technologies for remediation of contaminated dredged sediments. *Journal of Environmental Management*, 166, 94-102.
3. Park, J.; Son, Y.; Noh, S.; and Bong, T. (2016). The suitability evaluation of dredged soil from reservoirs as embankment material. *Journal of Environmental Management*, 183(Part 3), 443-452.
4. Amar, M.; Benzerzour, M.; Safhi, A.E.M.; and Abriak, N.-E. (2018). Durability of a cementitious matrix based on treated sediments. *Case Studies in Construction Materials*, 8, 258-276.
5. Huang, Y.; Dong, C.; Zhang, C.; and Xu, K. (2017). A dredged material solidification treatment for fill soils in East China: A case history. *Marine Georesources and Geotechnology*, 35(6), 865-872.
6. Misra, A.K. (2010). A river about to die: Yamuna. *Journal of Water Resource and Protection*, 2(5), 489-500.
7. Central Pollution Control Board. (2000). Water quality status of Yamuna River, New Delhi, India. Retrieved November 11, 2017, from http://cpcb.nic.in/.
8. Delhi.gov.in. (2016). Action plan of desilting 2019. Retrieved June 20, 2016, from http://wcscvv.delhi.gov.in/wps/wcm/connect/2cf1990040f04f6ca083e3a9dc97a204/Desilting+Action+Plan+2019.pdf?MOD=AJPERES&lmod=813163564&CACHEID=2cf1990040f04f6ca083e3a9dc97a204.
9. Aggarwal, K.P. (2016). *Delhi a role model of urban India - Part 1*. New Delhi, India: Educreation Publishing.
10. Gupta, A.; Arora, V.K.; and Biswas, S. (2017). Contaminated dredged soil stabilization using cement and bottom ash for use as highway subgrade fill. *International Journal of Geo-Engineering*, 8(20), 13 pages.
11. Voglar, G.E.; and Lestan, D. (2010). Solidification/stabilisation of metals contaminated industrial soil from former zn smelter in Celje, Slovenia, using cement as a hydraulic binder. *Journal of Hazardous Materials*, 178(1-3), 926-933.
12. Milk, C.M. (2004). Solidification/stabilization treatment and examples of use at port facilities. *Proceedings of the Conference on Port Development in the Changing World.* Houston, Texas, United States, 10 pages.
13. Chen, H.; and Wang, Q. (2006). The behaviour of organic matter in the process of soft soil stabilization using cement. *Bulletin of Engineering Geology and the Environment*, 65(4), 445-44.
14. Onitsuka, K.; Modmoltin, C.; Kouno, M.; and Negami, T. (2003). Effect of organic matter on lime and cement stabilized Ariake clays. *Journal of Geotechnical Engineering*, 72(III-62), 1-13.
15. Sireesh, S.; Srujan, R.C.; Puppala, A.J.; and Harris, P.J. (2010). Effects of organics on stabilized expansive subgrade soils. *Proceedings of the GeoShanghai International Conference on Ground Improvement and Geosynthetics*. Shanghai, China, 155-164.

16. Tremblay, H.; Duchesne, J.; Locat, J.; and Leroueil, S. (2002). Influence of the nature of organic compounds on fine soil stabilization with cement. *Canadian Geotechnical Journal*, 39(3), 535-546.
17. Dia, M.; Ramaroson, J.; Nzihou, A.; Zentar, R.; Abriak, N.E.; Depelsenaire, G.; and Germeau, A. (2014). Effect of chemical and thermal treatment on the geotechnical properties of dredged sediment. *Procedia Engineering*, 83, 159-169.
18. Hessling, J.; Smith, M.L.; Giti-pour, S.; Miller, J.; and Isenburg, J. (1993). Onsite engineering report for solidification/stabilization treatment testing of contaminated soils. Retrieved October 10, 2017, from https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=30003WDA.TXT.
19. Moon, H.; Kim, J.-H.; Lee, J.-Y.; Kim, S.-G.; and Chung, C.-W. (2017). Evaluation of pozzolanic activity for effective utilization of dredged sea soil. *International Journal of Concrete Structures and Materials*, 11(4), 637-646.
20. Cheriaf, M.; Rocha, J.C.; and Péra, J. (1999). Pozzolanic properties of pulverized coal combustion bottom ash. *Cement and Concrete Research*, 29(9), 1387-1391.
21. Google Maps. (2018). Map of New Delhi. Retrieved January 12, 2018, from https://satellites.pro/Delhi_map.India.
22. ASTM International. (2017). Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. *ASTM Standards C618-17a.*
23. Portland Cement Association (PCA). (1995). *Soil Cement Laboratory Handbook*. Skokie, Illinois, United Stats of America: Portland Cement Association.
24. Kogbara, R.B. (2013). A review of the mechanical and leaching performance of stabilized/solidified contaminated soils. *Environmental Reviews*, 22(1), 66-86.
25. United States Environmental Protection Agency (EPA). (1992). Method 1311. Toxicity characteristic leaching procedure. Retrieved August 18, 2017, from https://www.epa.gov/sites/production/files/2015-12/documents/1311.pdf.
26. Indian Roads Congress (IRC). (2012). Tentative guidelines for the design of flexible pavements. *IRC:37-2012*.
27. Environment, Health and Safety Online (EHSO). (2018). The EPA TCLP: Toxicity characteristics leaching procedure and characteristics waste D-codes. Retrieved January 20, 2018, from http://www.ehso.com/cssepa/TCLP.htm.
28. IRC SP 89. (2010). *Guidelines for soil and granular material stabilization using cement, lime flesh*. New Delhi: Indian Road Congress.
29. IRC SP 72. (2015). *Guidelines for soil the design of flexible pavements for low volume roads.* New Delhi: Indian Road Congress