Strength and Compaction Analysis of Sand-Bentonite-Coal Ash Mixes

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Abstract: This paper deals with the strength and compaction characteristics of sand-bentonite-coal ash mixes prepared by varying percentages of sand, bentonite and coal ash to be used in cutoff walls and as a liner or cover material in landfills. The maximum dry density (MDD) and optimum moisture content (OMC) of sand-bentonite mixes and sand-bentonite-coal ash mixes were determined by conducting the standard proctor test. Also, the strength and stiffness characteristics of soil mixes were furnished using unconfined compressive strength test. The results of the study reveal influence of varying percentages of coal ash and bentonite on the compaction characteristics of the sand-bentonite-coal ash mixes. Also, validation of a statistical analysis of the correlations between maximum dry density (MDD), optimum moisture content (OMC) and Specific Gravity (G) was done using the experimental results. The experimental results obtained for sand-bentonite-ash mixes very well satisfied the statistical relations between MDD, OMC and G with a maximum error in the estimate of MDD being within ±1 kN/m³. The coefficient of determination (R²) ranged from 0.95 to 0.967 in case of sand-bentonite-ash mixes. However, for sand-bentonite mixes, the R² values are low and varied from 0.48 to 0.56.

Keywords: Bentonite, Coal Ash, Maximum Dry Density, Optimum Moisture Content.

1. INTRODUCTION

Natural sands are commonly used in place of cohesive soils as a barrier material after amending with admixtures such as bentonite, lime etc. wherever suitable clays of desired permeability characteristics are not available in the vicinity. Generally the low permeability soil (k < 10⁻⁹ m/sec) is used as a barrier material in landfills/containments so that it could resist the infiltration of water into the soil. Several studies have been done to evaluate the hydraulic properties of sand with admixtures. In various geotechnical applications, the amended soil is placed at maximum dry density (MDD) and optimum moisture content (OMC). Therefore, the compaction and strength characteristics of this amended soil are required to be studied. The structure of fine grained soils is highly dependent on the compaction conditions (i.e. as-compacted water content and compactive effort) that directly affect the engineering properties of the compacted material. Several studies have reported the relevant effect of the compaction water content on the soil structure [1] - [2].
The quantity of fly ash generated in India amounts to 200 MT approximately, from 145 thermal power stations, according to the statistics of 2014-15 with the percentage utilization of 55.69% [3]. For successful application of ash in civil engineering practices, knowledge of basic engineering properties such as compaction characteristics, amount of plasticity, compressibility, study of hydraulic behaviour and morphology of the material is essential to achieve the desired requirements in the field. According to [4], with the increase in MDD, hydraulic conductivity decreases for fly ash–montmorillonite clay mixes. By adding 20% of montmorillonite clay in the fly ash–montmorillonite clay mixes, the values of MDD changed from 11.93 to 13.84 kN/m$^3$ and the change in the values of k were from 49.51 to 6.50 x 10$^{-10}$ m/s. [5] reported compaction effort and moisture contents as the major variables to achieve a low permeability (k <1 x 10$^{-10}$ m/s) in case of fly ash or fly ash-sand mixes. This paper reports the experimental results of the compaction tests and unconfined compressive strength tests conducted using the sand-bentonite-coal ash mixtures and discusses about the influence of coal ash and bentonite on the engineering characteristics of the sand-bentonite-coal ash mixes. Also, validation of the experimental results using a statistical analysis of the correlations between maximum dry density (MDD), optimum moisture content (OMC) and Specific Gravity (G) was done. The experimental results obtained for sand-bentonite, sand-bentonite-ash and coal ash-bentonite mixes very well satisfied the statistical relations between MDD, OMC and G with a maximum error in the estimate of MDD being within ±1 kN/m$^3$.

2. MATERIALS

The bentonite used in this study was sodium bentonite obtained from a local supplier. The ashes used in this research are a coal utilization by-product obtained from Ropar Thermal Plant, Punjab. The sand investigated in this study was local fine sand which is typical to that used in local construction. The uniformity ($C_u$) and curvature ($C_c$) coefficients for this sand are 2.82 and 1.21 respectively. Grain size analysis and Hydrometer test were carried out as per Indian Standard IS 2720 (Part 4) – 1985 procedure [6] to determine the grain size distribution of bentonite and coal ash as shown in Fig.1. The index properties of the materials used in the present study including the plasticity characteristics are reported in Table. 1.

![Fig. 1 Grain size distribution curves.](image-url)
Table. 1 Index Properties of Materials Used.

| Property                      | Sand | Bentonite | Coal Ash |
|-------------------------------|------|-----------|----------|
| Specific gravity, G (G)       | 2.66 | 2.82      | 2.17     |
| Liquid limit, LL (%)          | NP   | 363       | NP       |
| Plastic limit, PL (%)         | NP   | 65.2      | NP       |
| Plasticity index, PI (%)      | NP   | 297.8     | NP       |
| Free Swell Index              | 0 %  | 830 %     | 0 %      |
| Unified soil classification system | SP | CH | ML |

3. EXPERIMENTAL STUDY
An experimental program was undertaken for the index properties, compaction properties and unconfined compressive strength characteristics of various mix proportions of sand, bentonite and coal ash using standard IS procedures. The bentonite content was varied in the mixes from 5, 10, 20, 25, 30 and 40% for sand-bentonite mixes while coal ash from 10, 20, 30, 50 and 80% for sand-bentonite coal ash mixes with bentonite content at 10, 15, and 20%. Normal tap water was added to the mixtures to obtain the desired water contents. During sample preparation for compaction tests, a sufficient period (24 hours) as curing time was adopted to homogenize the mix and allow the bentonite to swell and absorb moisture in the sample mix prepared prior to compaction. The main purpose of compaction is to maximize the dry density of soils by expelling air and therefore, to achieve the desired strength and compressibility of the soils used.

4. RESULTS AND DISCUSSION

4.1 Index Properties
The index properties (plasticity characteristics, specific gravity etc.) of different mixes formulated by varying percentages of sand, bentonite and coal ash are tabulated in Table. 2. It can be observed from the tabulated data that the liquid limit and plastic limit values increase as the bentonite content in the mix increases because of increased plasticity. Also, void ratio increases significantly for all sand-bentonite mixes where bentonite content is more than 25%. Addition of coal ash in sand-bentonite mix also tend to increase the void ratio for a particular bentonite content. This can be explained by assuming excessive fines filling up all the spaces and voids within the sand and sand grains are no longer in contact with each other.

Table. 2 Sample Initial Properties and Results.

| Soil Mix | LL % | PL % | PI % | G | e | S % |
|----------|------|------|------|---|---|-----|
| 95S+5B+0F | NP   | NP   | NP   | 2.65 | 0.54 | 65.67 |
| 90S+10B+0F | 33.80 | 17.42 | 16.38 | 2.67 | 0.49 | 82.94 |
| 85S+15B+0F | 41.00 | 26.10 | 14.90 | 2.68 | 0.49 | 78.58 |
| 80S+20B+0F | 53.00 | 27.40 | 25.60 | 2.69 | 0.51 | 81.85 |
| 75S+25B+0F | 60.50 | 31.40 | 29.10 | 2.70 | 0.53 | 79.70 |
| 70S+30B+0F | 72.50 | 42.50 | 30.00 | 2.71 | 0.61 | 83.27 |
| 60S+40B+0F | 118.0 | 66.19 | 51.81 | 2.72 | 0.64 | 80.80 |
| 70S+20B+10F | 57.10 | 18.00 | 39.10 | 2.64 | 0.48 | 78.02 |
| 60S+20B+20F | 65.55 | 21.50 | 44.05 | 2.59 | 0.58 | 85.76 |
| 50S+20B+30F | 74.00 | 25.00 | 49.00 | 2.55 | 0.65 | 80.91 |
| 80S+10B+10F | 35.00 | 25.40 | 9.60  | 2.63 | 0.48 | 83.58 |
70S+10B+20F  39.00  28.00  11.00  2.58  0.53  78.60  
40S+10B+50F  49.00  32.50  16.50  2.43  0.74  75.87  
10S+10B+80F  43.5  20.8  22.7  2.287  0.76  75.31  
75S+15B+10F  45.00  22.50  22.50  2.63  0.56  77.81  
65S+15B+20F  47.00  21.00  26.00  2.59  0.62  76.40  
55S+15B+30F  50.00  20.00  30.00  2.54  0.67  78.11  

Note: S stands for sand, F for coal ash, B for bentonite and the figure preceding the symbol used is the percentage added as a dry % weight of sand. For e.g. 95S+5B+0F stands for a mix with 95% sand, 5% bentonite and 0% coal ash.

4.2 Standard Proctor Test

The compaction characteristics of different mixes were evaluated by Standard Proctor test was carried out as per Indian Standard IS 2720 (Part 7) - 1980 procedure [7] for normal soils. It can be observed in Fig. 2 (a, c) that as the bentonite content increases from 5% to 40%, the OMC increases from 13.4% to 19% with a minor decrease in MDD from 16.86 to 16.27 kN/m$^3$ in case of sand-bentonite mixes. The decrease in MDD may be attributed to the decrease in specific gravity, and the increase in OMC to the higher clay content requiring more water to hydrate the soil particles in the mix. While in case of sand-bentonite-coal ash mixes in Fig. 2 (b, d), the graph suggests that for a constant amount of bentonite in the mix i.e. when bentonite content is fixed at 15% and upon increase of coal ash amount from 10 to 30%, there is decrease in MDD observed from 16.56 to 14.93 kN/m$^3$ while an increase of OMC from 16.5 to 20.5. Generally, bentonite addition in usual soils causes a reduction in the maximum dry unit weight and an increase in the optimum moisture content. As reported in literature as well, as expected, when sand was added to bentonite, optimum water content decreased and maximum dry density increased [8].
Reference [9] gave a relationship between MDD, OMC and G on fly-ash soil mixtures. Statistical analyses were carried out to determine the correlations that satisfied the tests for coefficient of determination ($R^2$), standard error, $F$-test, and $t$-values. The correlations in the form of log-log, exponential, and linear curves are expressed, respectively, as

\[
MDD = a G^{b_1} OMC^{c_1}
\]
\[
MDD = a e R^{b_2} OMC
\]
\[
MDD = a_p G^{b_p} + c_p
\]

where MDD is in kN/m$^3$, and OMC is in percent. The values of constants $a$, $b$, and $c$ are given in Table. 3. These correlations were validated for the experimental results obtained from the compaction tests for different mixes prepared by adding varying proportions of sand, bentonite and coal ash. The analysis reveals that the results satisfy the empirical relations to a great extent with a maximum error in the estimate of MDD being within ±1 kN/m$^3$. It can be observed that the $R^2$ values obtained for sand-bentonite mixes range from 0.48, 0.55, and 0.56 for Eqns. (1) through (3). In case of sand-bentonite-coal ash mixes in Fig. 3 (b), it is observed that the values of MDD obtained from empirical relations match significantly well with the experimental results with $R^2$ values as 0.956, 0.967, 0.967 for Eqns. (1) through (3).

| Constant | $a_g$ | $b_g$ | $c_g$ | $a_e$ | $b_e$ | $c_e$ | $a_p$ | $b_p$ | $c_p$ |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Value    | 25.234| 0.488 | -0.336| 11.086| 1.251 | 0.986 | 11.572| 2.768 | -0.186|
Fig. 3 Comparison between MDD Estimated by Eqs. (1) through (3) and actual experimental results of compaction tests for (a) sand-bentonite mixtures (b) sand-bentonite-ash mixes

4.3 Unconfined Compressive Strength Tests

For any geotechnical project, strength and stiffness are the most important parameters required for design. The strength was measured in terms of unconfined compression strength and the stiffness was measured in terms of initial tangent modulus and secant modulus. The unconfined compression tests were performed as per Indian Standard IS 2720 (Bureau 1973) procedure [10]. Fig. 4 shows the stress-strain curves for different mixes prepared by proportioning sand, bentonite and coal ash in varying percentages.

Fig 4. Stress-Strain diagrams for (a) sand-bentonite-ash mixes (b) sand-bentonite mixtures.

It can be observed that in case of sand-bentonite mixes, the failure occurs at a maximum strain level of 6% in case of bentonite contents ranging from 30-40% as shown in Fig. 4 (b). At low bentonite contents in the range of 5 to 20%, a very early failure is reported at low strain rate ranging from 1.5-2.5 % of the axial strain.

4.4 Elastic Moduli

References [11]-[12] defined a parabolic function that had a peak positioned on the compressive strength of the specimens which helped to predict the behaviour of materials, if the compressive strength and its corresponding strain were determined. The parabolic function was used to
predict the stress-strain relationship before failure and to determine the elastic coefficients namely initial tangent modulus and secant modulus, from the beginning of loading to the maximum stress level, $\sigma_u$. Initial tangent modulus was obtained from the initial portion of the stress-strain curves and secant modulus computed as the ratio of stress and strain at failure as shown in Fig. 5.

![Stress-Strain Curve](image)

Fig 5. Elastic moduli of materials: Initial Tangent, Tangent, and Secant Modulus [13]. The values obtained for Initial tangent modulus and secant modulus for every mix proportioned using sand, bentonite and coal ash are listed in Table 4.

| Mix                     | Bentonite Content (%) | Coal Ash Content (%) | Compressive Stress, $q_u$ (kPa) | Axial Strain (%) | Initial Tangent Modulus, $E_i$ (kPa) | Secant Modulus, $E_{sec}$ (kPa) |
|-------------------------|-----------------------|----------------------|---------------------------------|------------------|-------------------------------------|---------------------------------|
| 95S + 5B+0F             | 5                     | 0                    | 74.07                           | 1.20             | 12372.56                            | 6186.28                         |
| 90S+10B+0F              | 10                    | 0                    | 247.17                          | 2.41             | 20530.19                            | 10265.10                        |
| 80S+20B+0F              | 20                    | 0                    | 271.51                          | 1.97             | 27512.87                            | 13756.44                        |
| 70S+30B+0F              | 30                    | 0                    | 322.00                          | 5.92             | 10874.47                            | 5437.24                         |
| 60S+40B+0F              | 40                    | 0                    | 453.83                          | 5.26             | 17245.68                            | 8622.84                         |
| 70S+20B+10F             | 20                    | 10                   | 403.33                          | 2.49             | 32350.78                            | 16175.39                        |
| 60S+20B+20F             | 20                    | 20                   | 511.59                          | 5.26             | 19440.58                            | 9720.29                         |
| 50S+20B+30F             | 20                    | 30                   | 338.27                          | 5.13             | 13183.97                            | 6591.99                         |
| 80S+10B+10F             | 10                    | 10                   | 420.39                          | 4.08             | 20612.49                            | 10306.25                        |
| 70S+10B+20F             | 10                    | 20                   | 283.83                          | 1.89             | 30028.29                            | 15014.14                        |
| 40S+10B+50F             | 10                    | 50                   | 514.72                          | 3.07             | 33568.57                            | 16784.28                        |
| 75S+15B+10F             | 15                    | 10                   | 445.65                          | 5.43             | 16418.59                            | 8209.30                         |
| 65S+15B+20F             | 15                    | 20                   | 555.89                          | 3.05             | 36428.42                            | 18214.21                        |
| 55S+15B+30F             | 15                    | 30                   | 523.47                          | 4.18             | 25042.51                            | 12521.26                        |

5. CONCLUSIONS
Following conclusions can be drawn from the study of the strength and compaction characteristics of sand-bentonite-coal ash mixes:
1. It can be observed from the compaction test results that as the bentonite content was increased in the sand-bentonite and sand-bentonite-ash mixes, OMC increased while there was a decrease in MDD.
2. The experimental results obtained for sand-bentonite and sand-bentonite-ash mixes very well satisfied the statistical relations given by Kaniraj and Havanagi (2001) between MDD, OMC and G with a maximum error in the estimate of MDD being within ±1 kN/m³.

3. The experimental tests obtained from Standard Proctor test are in good agreement with the statistical analysis results for sand-bentonite-coal ash mixes and coal ash-bentonite mixes with R² values ranging from 0.956 to 0.967 in case of sand-bentonite-ash mixes. However, for sand-bentonite mixes, the R² values are low and vary from 0.48 to 0.56.

4. The stiffness parameters viz. Initial tangent modulus and Secant Modulus were obtained at the appropriate positions of the stress-strain curves for each of the mix proportioned using sand, bentonite and coal ash.

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