Geotechnical and Geo-environmental Properties of Discrete Polyester Fibre-reinforced and RBI Grade-81-stabilized Clay and Sand

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Abstract. The present study evaluated the geotechnical and geo-environmental properties of both clay and sand reinforced with discrete polyester fibre of length 12 mm and stabilized with chemical stabilizer RBI Grade-81. The soils were mixed with RBI Grade-81 content of 1%, 2%, 3% and 4% and fibre content of 0.25%, 0.50%, 0.75% and 1.0% of dry mass of soil for determining their individual and combined effect on different geotechnical properties. Additionally, X-ray diffraction analysis (XRD) and scanning electron microscopy (SEM) tests were also carried out to know the mineralogy and micro-structure of the hydrated products formed during the stabilization. Leachate obtained from the stabilized soils was tested for concentration of heavy metals and were found well within limits prescribed by the United States Environmental Protection Agency for hazardous waste. The results indicated that the mechanical strength parameters of the soils had significantly enhanced with the use of RBI Grade-81 and polyester fibre which was corroborated by XRD and SEM results. The clay showed higher improvement in its mechanical behaviour than that of sand. The inclusion of fibre changed the RBI Grade-81 treated soil’s brittle behaviour into ductile behaviour. The results obtained were indicative of the safe and environment-friendly use of RBI Grade-81 and polyester fibre for use in road construction.

1. Introduction
Construction with weak soils can be uneconomical and non-feasible. Lime and cement are among many chemical soil stabilizers that have proven their potential but have limited applicability. The soil subgrade encountered along the alignment of a road is usually of varying plasticity, and hence lime or cement cannot be used single-handedly. Chemically stabilized soils characterize brittle behaviour and high stiffness which can lead to sudden failure and can be prevented by the use of fibres [1]. The process of reinforcing soils with fibre is easy and improves the mechanical behaviour of natural and cement treated soils. The leachate from chemically treated soils may be hazardous for the environment due to the presence of heavy metals. The present study evaluates the geotechnical and the geo-environmental properties of clay and sand admixed with RBI Grade-81, a patented chemical soil stabilizer and randomly oriented polyester fibre of length 12 mm.
2. Materials
In the present study, four materials namely two soils: clay and sand, RBI Grade-81 chemical stabilizer and polyester fibre were used.

2.1 RBI Grade-81
RBI Grade-81 is a hydration based chemical soil stabilizer, developed and patented by Road Building International (RBI), South Africa. Its scanning electron microscopy (SEM) images with magnification 1500x and 4000x are shown in figure 1. The chemical and physical properties of RBI Grade-81 have been reported in table 1 and table 2.

![SEM images of RBI Grade-81 at 1500x and 4000x magnification](image)

Table 1. Chemical properties of RBI Grade-81

| Material   | Additives |
|------------|-----------|
| CaO        | 52-56%    |
| SiO₂       | 15-19%    |
| SO₃        | 9-11%     |
| Al₂O₃      | 5-7%      |
| Fe₂O₃      | 0-2%      |
| MgO        | 0-1%      |
| Mn, K, Cu, Zn | 0-3% |
| Polypropylene Fibre | 0-1% |
| Additives  | 0-4%      |

Table 2. Physical properties of RBI Grade-81

| Material   | Shape     | Specific Gravity | Length | Effective Diameter | Melting Point | Tensile strength | Young’s Modulus |
|------------|-----------|------------------|--------|--------------------|---------------|------------------|-----------------|
| Polyester  | Triangular| 1.31-1.39        | 12 mm  | 10-40              | 150-          | 4-6 mPa          | >5000 mPa       |

Figure 1. SEM images of RBI Grade-81 at 1500x and 4000x magnification

2.2 Polyester fibre
Though other polyester fibres are also available, in the present investigation polyester fibre Recron-3s was used as these are easily available and have wide application in the field of civil engineering. It is a synthetic fibre derived from air, water, coal and petroleum. Its physical properties have been reported in table 3, and SEM images with magnification 150x and 2000x are shown in figure 2.

Table 3. Physical properties of polyester fibre
2.3 Soils
Two soils, i.e., the clay of intermediate plasticity (CI) and sand with an appreciable amount of silt (SM) used in the present study were obtained from within the limits of Chandigarh, India [2]. Their geotechnical properties are reported in table 4.

| Soil | Specific gravity | Gravel (%) | Sand (%) | Silt (%) | Clay (%) | D_{60} (mm) | D_{30} (mm) | D_{10} (mm) | C_u | C_c | L.L. (%) | P.L. (%) | P.I. (%) |
|------|-----------------|------------|----------|----------|----------|-------------|-------------|-------------|-----|-----|----------|----------|---------|
| CI   | 2.76            | 0.0        | 8.9      | 72.4     | 18.7     | 0.02        | 0.0038      | 0.0015      | 13. | 0.4 | 37.3     | 24.9     | 12.     |
| SM   | 2.65            | 0.0        | 65.1     | 34.9     | 0.0      | 0.23        | 0.064       | 0.021       | 10. | 0.8 | -        | -        | -       |

3. Methodology
Laboratory experiments were performed on both the soils using variable RBI Grade-81 content of 1%, 2%, 3% and 4% and variable fibre content of 0.25%, 0.50%, 0.75% and 1.0% of dry mass of soil. The samples containing RBI Grade-81 were cured for seven days. Geotechnical properties included determination of maximum dry density (MDD), optimum moisture content (OMC), California bearing ratio (CBR) and unconfined compressive strength (UCS) of plain and stabilized clay and sand [3-5]. For the UCS testing of clay, cylindrical specimens of 50 mm diameter and 100 mm height were cast, whereas 100 mm size cubes were cast for sand [6]. X-ray diffraction (XRD) and SEM analysis were performed to understand the mechanism of the proposed stabilization. The stabilized soils were tested for potential leaching of hazardous contaminants in the environment. Leachate obtained through toxicity characteristic leachate procedure (TCLP) was further subjected for determining concentrations of heavy metals namely Arsenic (As), Chromium (Cr), Mercury (Hg), Lead (Pb), Zinc (Zn), Copper (Cu), Nickel (Ni) and Cobalt (Co) through the use of MP-Atomic Emission Spectrophotometer (MP-AES) [7].

4. Results and Discussion

4.1 Compaction characteristics
Figure 3 shows the trend of MDD and OMC for RBI Grade-81 stabilized and fibre reinforced both categories of soil under test. The inclusion of RBI Grade-81 to both the soils decreased the MDD due to flocculation and cementation of soil particles and increased the OMC due to the higher requirement of water for pozzolanic reactions and subsequent hydration of finer RBI Grade-81 particles. The inclusion of fibre in plain and stabilized soils decreased the MDD due to its low specific gravity and increased the OMC due to the trapping of water at the soil-fibre interfaces. These effects were more prevalent in clay than sand.
The CBR increase of plain and RBI Grade 81 were reported from 3.2% and 9.3% to 6.7% and 14.8% respectively. RBI Grade 81 reduced the failure strain of clay treated with 4% RBI Grade 81 further improved from 25.3% to 28.8% to 29.1% and 31.6% respectively.

Table 5. CBR (%) test results for clay and sand

| Soil  | Varying RBI Grade-81 content (%) in soils | Varying fibre content (%) in soils | Varying fibre content (%) in soils stabilized with 4% RBI Grade-81 |
|-------|------------------------------------------|-----------------------------------|---------------------------------------------------------------|
|       | 0 | 1 | 2 | 3 | 4 | 0.25 | 0.5 | 0.75 | 1.0 | 0.25 | 0.5 | 0.75 | 1.0 |
| Clay  | 3.2 | 8.1 | 14.1 | 20.5 | 25.3 | 5.1 | 6.7 | 6.2 | 5.7 | 27.8 | 29.1 | 28.1 | 26.6 |
| Sand  | 9.4 | 13.7 | 21.3 | 27.6 | 28.8 | 11.3 | 14.8 | 13.2 | 12.1 | 30.6 | 31.6 | 29.4 | 28.1 |

4.3 UCS tests

The peak axial stress attained during the UCS tests of clay and sand increased drastically with increasing content of RBI Grade-81. Addition of 4% RBI Grade-81 reduced the failure strain of clay and sand from 2.0% to 0.8% and 0.65% respectively, depicting significant stiffness and brittleness in the stabilized soils. The inclusion of fibre up to an optimized dosage of 0.5% increased the peak stress, of plain and RBI Grade-81 stabilized clay and sand. It is indicated that the role of fibre was critical in imparting ductility as reinforcement with 0.5% fibre content increased the failure strains from 0.8% and 0.65% to 1.75% and 1.5% in clay and sand treated with 4% RBI Grade-81 respectively. RBI Grade-81 soils without fibre reinforcement showed a sudden drop in axial stress beyond peak stress, but on the addition of fibre, the drop in stress was observed to be gradual.
Table 6. UCS (kPa) test results for clay and sand

| Soil  | Varying RBI Grade-81 content (%) in soils | Varying fibre content (%) in soils | Varying fibre content (%) in soils stabilized with 4% RBI Grade-81 |
|-------|-----------------------------------------|---------------------------------|---------------------------------------------------------------|
| Clay  | 0           | 1      | 2     | 3    | 4    | 0.25  | 0.5  | 0.75  | 1.0    | 0.25  | 0.5  | 0.75  | 1.0    |
|       | 147.4       | 267.4  | 437.5 | 514.7 | 720.6 | 219.5 | 283.9 | 256.3 | 230.3  | 920.6 | 1020.3 | 941.3 | 865.0 |
| Sand  | 249.7       | 453.2  | 658.9 | 779.7 | 925.5 | 308.9 | 407.5 | 337.0 | 292.4  | 1105.1 | 1306.0 | 1255.7 | 1227.5 |

Figure 4. Stress-strain curves: (A) clay with varying RBI Grade-81 content; (B) clay with varying fibre content; (C) clay stabilized with 4% RBI Grade-81 and varying fibre content.

Figure 5. Stress-strain curves: (A) sand with varying RBI Grade-81 content; (B) sand with varying fibre content; (C) sand stabilized with 4% RBI Grade-81 and varying fibre content.

4.4 Mineralogical and microstructural characterization

The XRD patterns presented in figure 6 shows that the element of quartz appeared in the XRD pattern generated of clay and sand. A fall in the intensity of the peaks of quartz for the RBI Grade-81 stabilized clay and sand show that during the stabilization process the mineral gets consumed. Also, RBI Grade-81 stabilization leads to the addition of new minerals, muscovite and tri-calcium di-yttrium in the clay and muscovite and albite in the sand, which probably contributed to the increase of capacity to take peak stresses.

Figure 6. XRD Patterns: (A) clay; (B) clay stabilized with 4% RBI Grade-81; (C) sand; (D) sand stabilized with 4% RBI Grade-81.
Figure 7 shows SEM images of clay, clay stabilized with 4% RBI Grade-81 and clay stabilized with 4% RBI Grade-81 and reinforced 0.5% fibre. RBI Grade-81 accounted for the formation of cementation nuclei among the soil micro-aggregates, where there seems to have been SiO₂ and Al₂O₃ solubilization, forming a gel (calcium silicate and aluminates) which after consolidation, cements the surrounding particles. On hydration, RBI Grade-81 flocculates the clay particles into larger particles. The aggregation of fine particles leads to strength and stability to the soil. Following flocculation, an extensive inter-particle matrix of reacted clay particles and RBI Grade-81 was formed, illustrating the linking of the microstructure to the macro-particles.

Figure 8 shows SEM images of sand, sand stabilized with 4% RBI Grade-81 and sand stabilized with 4% RBI Grade-81 and reinforced with 0.5% fibre. It was observed that RBI Grade-81 was effective in filling the pore spaces of soil particles. The extensive inter-particle matrix of the hydration products of RBI Grade-81 got closely bonded with the sand particles. Unlike cement stabilization, RBI Grade-81 was effective in linking inert sand grains to each other without the requirement of an extensive clay fraction. The fibre reinforced soil images (figures 7C and 8C) showed that the hydrated products of RBI Grade-81 got attached to the fibre surface and hence increased the strength at the interface of fibre-reinforced RBI Grade-81 soils. The hydrated products restricted the ability of the fibre to produce relative movement, as a consequence of which, the static friction coefficient between fibre and composite matrix got enhanced. RBI Grade-81 stabilization increased the effectiveness of load transfer from the soil to the fibre.

4.5 Leachate analysis
The concentrations of heavy metals found in the leachate of clay and sand stabilized with 4% RBI Grade-81 are reported in table 7 along with the limiting values for hazardous waste as prescribed by the United States Environmental Protection Agency (USEPA). The concentrations of heavy metals
were well found to be well below the permissible limits, and hence the use of RBI Grade-81 stabilized soils are non-hazardous and do not pose a threat to the environment.

Table 7. Leachate analysis of soils stabilized with RBI Grade-81

|                           | As | Pb | Cr | Cd | Cu | Zn | Hg | Ni |
|---------------------------|----|----|----|----|----|----|----|----|
| Clay + 4% RBI Grade-81    | 0.15 | 0.12 | BDL | BDL | 0.81 | BDL | BDL |    |
| Sand + 4% RBI Grade-81    | 0.12 | 0.11 | BDL | BDL | 0.56 | BDL | BDL |    |
| Regulatory level for hazardous waste, USEPA | 5.0 | 5.0 | 5.0 | 1.0 | NR | NR | 0.2 | NR |

Note: BDL: below detection level with detection limit < 0.1 mg/l, NR: Not reported

5. Conclusion
RBI Grade-81 and polyester fibre emerged effective in enhancing the geotechnical properties of clay and sand, where the former showed more significant improvement than the latter. The increase in the content of RBI Grade-81, fibre or their combination decreased the MDD but increased the OMC. The highest gain in CBR and UCS was obtained at 4% RBI Grade-81 and 0.5% fibre dosage where their combination performed better than their individual counterparts. Where RBI Grade-81 soils characterized brittleness and stiffness, fibre reinforcement was critical in imparting ductility to such soils. XRD and SEM results confirmed the formation of hydrated products that were responsible for bonding the soil particles and eventually increasing the strength of soils. The leaching study results were indicative of the safe and environment-friendly use of RBI Grade-81 as the concentrations of heavy metals were found to be appreciably less than the regulatory limits for hazardous waste issued by the USEPA.

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