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Rockwool as a Potential Alternative to Conventional Geosynthetic Materials in Sustainable Ground Improvement Solutions

Rahul Abhishek[1][0000-0002-8230-044X], Pragati Saxena[2][0000-0002-6760-4947] and

Sowmiya Chawla[3][0000-0002-7552-8366]

[1] Research Scholar, Department of Civil Engineering, IIT (ISM) Dhanbad, Jharkhand-826004, INDIA
[2] M.Tech student, Department of Civil Engineering, IIT (ISM) Dhanbad, Jharkhand-826004, INDIA
[3] Associate Professor, Department of Civil Engineering, IIT (ISM) Dhanbad, Jharkhand-826004, INDIA.

Abstract. Rockwool is an inorganic fibrous furnace product drawn from molten rock and waste slag in the form of interlaced fibers. Owing to its outstanding thermal insulation, durability, non-toxicity, and incombustibility properties, it has found widespread applications in various engineering fields. However, the potential application of this material in the field of ground improvement remains untouched. This study presents an in-depth characterization and review of the potential use of rockwool as a substitute for conventional geosynthetic materials in the field of ground stabilization. The comparison of the mechanical properties of rockwool with commercially available geosynthetics leads to the conclusion that rockwool has mechanical properties lying in the range of natural geosynthetics and can be successfully used as its replacement. To ascertain this, unit cell model tests have been conducted simulating the micropiling ground improvement technique wherein rockwool is provided as an interface between the pile and the expansive clayey soil. These test results have then been validated using the 3D finite element method simulating the model in MIDAS GTS NX, 2021. The laboratory model tests and the finite element simulation results showed that rockwool along with micropiles can be effective in stabilizing weak soil. The micropile with rockwool interface is then simulated as a ground stabilization solution in the subgrade of a 3D railway track model prepared in MIDAS GTS NX, 2021 in order to highlight its benefits.

Keywords: Rockwool, Unit cell model tests, Micropiles.

1. Introduction

Rockwool is an inorganic material obtained by blowing air or steam through molten igneous rock at a temperature of about 1600 °C. The major chemical constituents of the fiber are Si, Al, Ca, and Mg which account for around 82.08 % of its total mass. The presence of high content of oxides like SiO_2 and Al_2O_3 contributes to its better stability. The material is also known to have a high thermal resistance which makes it instrumental in containing and preventing fire spread and toxic smoke emissions. In the past decade, numerous efforts have been made to establish the inherent characteristics and potential applications of rockwool. [1] assessed the effect of factors such as fiber diameter, solid volume fraction (SVF), etc. on properties of rockwool board using GeoDict software. The study showed that the strength of the material is dependent on its mesostructure. [2] analyzed the change in different properties of rockwool boards and rockwool strips produced by Beijing Jinyu Energy Saving and Heat Preservation Technology Co. Ltd. The outcome showed that rockwool was highly durable and easily resisted extreme heat and humidity conditions. [3] conducted laboratory experiments to observe the material properties of stone wool under variable environmental conditions. The study showed that for the same thermal insulation, a lesser thickness of stone wool was required when compared with other conventional materials. [4] summarized the relative merits and application of rockwool as external thermal insulation for walls in the construction field. The study presented rockwool material as an energy-saving standard for buildings abiding by the Civil Construction Energy Efficiency Management Regulation. [5] designed and analyzed the effect of rockwool on vibration with acoustic, coupling muffler with four stoke diesel engine structurally. The study concluded that acoustic sound levels and frequencies are reduced when rockwool material is used.

In the current era, micropiles are one of the most explored ground improvement solutions owing to their immense advantages when compared to other conventional solutions. [6] used FEM to determine the effectiveness of micropiles for clay and silt soil types. [7] presented a case study in which micropiles of 100 mm diameter and 4 m length was used to increase bearing capacity of the foundation soil. [8] in his study assessed the application of micropile wall on a 12 m high railway embankment in southern Ontario, Canada. The results showed an 18 % improvement in the factor of safety for the embankment. [9] conducted experimental and numerical investigations using various arrangements of micropiles of different sizes to check the suitability of micropiles in a railway embankment and concluded that micropiles are suitable for retrofitting existing railway embankments.

From the literature survey, it can be said that rockwool can act as a potential alternative for conventional geosynthetic materials. This can be stated due to the fact that the observed mechanical and thermal properties of rockwool are either at par or better than the presently used natural geosynthetics. The study is also motivated by the reason that till date, the application of this new material which utilizes industrial steel slag waste for its production in the field of ground improvement remains unexplored. Thus, main objective here is to integrate the excellent vibration and shock absorption characteristics and durability of rockwool with the currently trending micropile ground improvement solution and analyze the behavior and the benefits offered. The rockwool sample used in this study is collected from Dhanbad Rockwool Insulation Pvt. Ltd., Dhanbad, Jharkhand – 828109. The basalt rocks which are used for the production and the manufactured samples are depicted in Fig 1 (a) and (b) respectively.

(a) (b)

Fig 1. (a) Basalt material (b) Manufactured Rockwool Sample

2. Comparison of Composite Rockwool Sample with Conventional Geosynthetics

For the laboratory investigations, rockwool was used as a composite material by stitching scaled down geonet material to its faces. Wide width tensile strength test was carried out on the prepared sample and the obtained test results were then compared with other natural geosynthetics data. The bulk density of the rockwool used in the test was 150 kg/m^3. The representative geonet material had an aperture size equal to 1/10 times the actual geonet material aperture size. The prepared samples had dimension of 20 cm x 20 cm x 1 cm, and they were placed between the jaws in such a way that the gauge length came out to be 10 cm. Low strain rate of 3 mm/min was considered to account for the geonet scaling down and representative sample composition. Three samples each were tested in both machine and cross-machine directions, and the mean tensile strength was determined using the method described in IS 13162-5 (1992). The composite sample and the setup in the universal testing machine are shown in Fig 2 (a) to (c).

It is well known that the strength-deformation behaviour of the system is influenced by the shear and normal stiffness, and the interface friction angle between the soil and geosynthetics. The interface friction between different geomaterials is a major attribute to be considered by geotechnical engineers. The interface elements used to model interfaces in the finite element simulation here used Coulomb friction as its constitutive model. To establish the interface parameters between the soil-rockwool composite direct shear experiments were carried out. A small size direct shear apparatus with a box dimension of 6 x 6 x 5 cm was used to conduct the interface test. Using a direct shear test sampler, sample was taken from the constituent geomaterial after it had been compacted using a proctor compaction test to the required dry density. The rockwool composite was bonded to the top of a hardwood block that was specifically sized to fit the lower half of the shear box. The strain rate used was 0.05 mm/min.

(a) (b) (c)

Fig 2. (a) Wide width tensile strength test sample (b) Initial sample setup in UTM (c) Failed sample

3. Laboratory Investigation of Soil

A set of laboratory tests were carried out on the soil sample which was to be used for unit cell test for determination of its strength and mechanical properties. The specific gravity test was performed as per the guidelines of IS 2720 Part 3 (1980) and equation 1 was used for the calculation.

$$G = G_l \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \quad \textbf{1}$$

Where, G_l = Specific Gravity of liquid used at a constant temperature, m_1 = Mass of density bottle in g, m_2 = Mass of density bottle and dry soil in g, m_3 = Mass of density bottle, soil, and liquid in g, m_4 = Mass of density bottle when full of liquid only in g.

Liquid Limit for the soil was determined according to the guidelines of IS 2720-1985 Part 5. Plastic limit for the sample was determined according to the specifications of IS 2720-1985 Part 5. To obtain the maximum dry density and corresponding optimum moisture content of the soil, the proctor compaction test was carried out as per IS 2720 -1980 Part 7. Unconsolidated Undrained Triaxial Compression test was conducted on the soil sample to determine its mechanical property of elastic modulus according to the procedure specified in IS 2720-11 (1993). Elastic Modulus was obtained from the slope of the tangent of deviator stress-axial strain curve. The obtained properties are summarized in Table 1.

Table 1. Properties of Soil

Properties	Value
Specific Gravity	2.4
Liquid Limit (%)	48
Plastic Limit (%)	37.55
Plasticity Index (%)	10.45

Flow Index	30.2
Maximum Dry Density (g/cc)	1.577
Optimum Moisture Content (%)	23.64
Elastic Modulus (kPa)	11560
Cohesion (kPa)	14
Friction Angle (degrees)	16

4. Unit Cell Test and Validation using Finite Element Method

Model tests were carried out to assess the prototype's behavior under simulated conditions. A pneumatic load actuator was used to apply pressure from the compressor using the load cell on the prepared model of pile with rockwool composite interface placed in geomaterial bed. The model's dimensions were determined from the boundary effect study conducted using Finite Element Analysis in MIDAS GTS NX. The entire load cell was connected with a computer system to record the data and load settlement plots. Fig 3 shows the model testing setup and the equipments used. Model dimensions were scaled down based on the similitude ratio so that induced stresses in the model remained the same as those in the prototype. Based on practical consideration, a full panel single pile foundation with a similitude ratio of one-fourth was used. A cylindrical tank of 85 cm height and 55 cm diameter was used. Load was applied from the unit load cell on the pile through a perspex plate 2.5 cm thick, below which there was a sand mat layer of same thickness. A reference test was also performed by loading soil bed without pile for comparison.

Finite Element Analysis discretises the model into a number of elements and nodes. In non-linear analysis conducted in MIDAS GTS NX, hyperbolic Duncan Chang constitutive relationship was used to simulate the soft soil. The input parameters K_l, n, K_b and m were related to a non-linear variation of initial Young’s modulus and Poisson’s ratio, respectively, with respect to confining stress. These were determined from triaxial test results. Pile and perspex plate were modelled as elastic material. Coulomb friction model was used to simulate rockwool composite pile interface. For meshing the model, mesh size for tank, pile, sand mat and perspex plate were determined from mesh sensitivity analysis. The FEM model is shown in Fig 4.

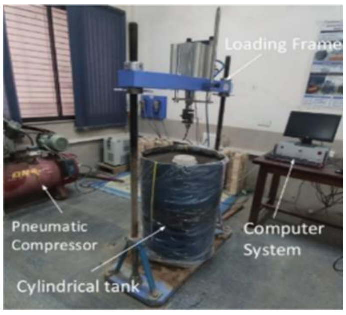


Fig 3. Unit Cell Test Setup

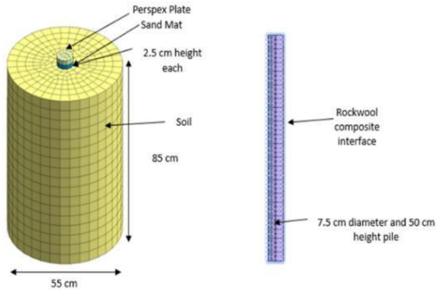


Fig 4. FEM model

5. Finite Element Modelling of Railway Track

Dynamic analysis was also conducted on a three-dimensional railway track model reinforced with micropile-rockwool composite by subjecting it to moving train loads. The geometric configuration, material properties and applied load were taken from [6]. A moving train load resembling the passage of a freight carrier from Indian Railways with BOXN wagons having 32.5 t axle loads was taken as the basis of analysis. [6] showed that the use of micropiles as a retrofitting technique in an existing track resulted in reduced displacement amplitudes. In addition, the rail deflections vs train speed variation for the particular model resulted in the conclusion that the critical speed was around 100 kmph. In the present work, rockwool in MIDAS GTS NX was modelled using the parameters obtained from laboratory investigations as discussed in section 2. Since interface elements cannot be assigned a damping coefficient value, an equivalent damping coefficient for both pile and rockwool was taken as 16%. The properties of other constitutive materials were taken from [6] as summarized in Table 2 and 3. The corresponding interfaces were assigned a strength reduction factor of 0.7. The eigenvalue analysis provided two time periods of vibration as 0.588 and 0.497. The meshed model elements are depicted in Fig 5.

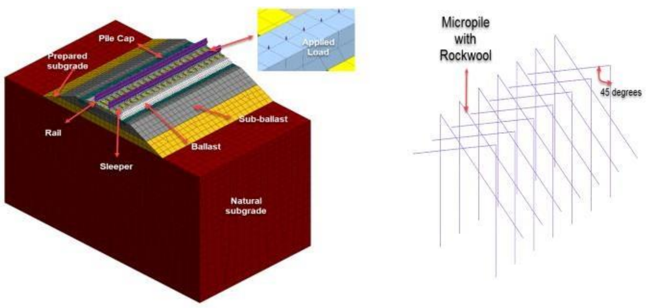
Table 2. General Material parameters [6]

Track Component	Model Type	General parameter				
		E (MPa)	**μ**	**γ (kN/m^3)**	**C' (kPa)**	**Φ'(°)**
Rail	Elastic	200,000	0.27	77000	-	-
Sleepers	Elastic	38730	0.2	25	-	-
Micropile and cap beam	Elastic	38730	0.2	25	-	-

Ballast	DC	140	0.37	16.5	0.1	47.6
Subballast	DC	70	0.37	16	0.1	41.6
Prepared sub-grade	DC	15	0.49	19	6	8
Subgrade (clay)	DC	10	0.49	18	6	8

Table 3. Nonlinear material parameters [6]

Track Component	Model Type	Nonlinear parameters			
		K_L	n	Ks	m
Rail	Elastic	-	-	-	-
Sleepers	Elastic	-	-	-	-
Micropile and cap beam	Elastic	-	-	-	-
Ballast	DC	477.9	0.575	508.6	0.136
Subballast	DC	97.7	0.414	108.7	0.046
Prepared subgrade	DC	48.9	0.5	-	-
Subgrade (clay)	DC	48.9	0.5	-	-



(a) (b)

Fig 5. (a) 3D railway track model, (b) Micropile with Rockwool as 1-D element

6. Results And Discussions

The Tensile force vs Elongation curve obtained from the wide width tensile strength test is converted to the actual scale and is compared with the values obtained from literature as shown in Fig 6. The peak tensile force obtained is around 1.5 kN which is significantly better than the values obtained from literature for the woven, non-woven heat bonded geotextile and Bipolar extruded geonets.

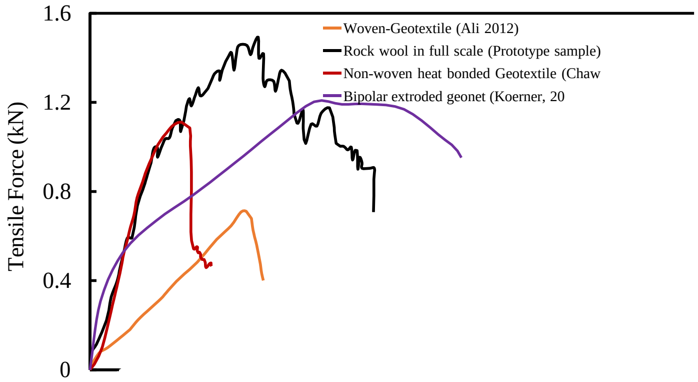


Fig 6. Wide width tensile strength test results

The reference load cell model testing conducted on only soil bed without any micropile improvement resulted in a maximum load of 1.23 kN for a preset maximum settlement of 50mm. The peak load values corresponding to 0, 1, 3, 7, 14, 21 and 28 days obtained from the unit cell test for micropile-rockwool reinforced soil are found to be 1.56, 1.73, 1.77, 1.95, 2.57, 3.855 and 5.14 kN showing a percentage improvement of 26.82, 40.65, 43.9, 58.53, 108.94, 213.41 and 317.88 % respectively when compared to the existing in-situ ground conditions represented in the reference test. The failure load is obtained from the non-linear load-settlement curves using double-tangent method. The failure load for plain soil, 0, 1, 3, 7, 14, 21 and 28 days testing are 0.8, 1.48, 1.5, 1.52, 1.6, 2.3, 2.6 and 4.5 kN respectively. It can be observed that the failure load showed little improvement in case of 1 and 3 days testing but significant improvement can be seen after 7, 14, 21 and 28 days because of gain in compressive strength of reinforced cement pile. Similarly, the failure load obtained from the FEM analysis are 0.96, 1.3, 1.4, 1.48, 1.5, 2, 2.4 and 4.2 kN for models simulating testing done on plain soil bed, 0 day test, 1 day test, 3 days test, 7 days test, 14 days test, 21 days test and 28 days test respectively. The variation in the failure load is 2% for plain clay soil bed, 5% for 0 day, 10% for 1 day, 2% for 3 days, 1% for 7 days, 1.3% for 14 days, 7% for 21 days and 6% for 28 days. Thus, it can be concluded that ultimate failure load obtained from finite element modelling is within 10% of the model testing values, thus validating the model testing results. The obtained load-settlement curves for the unit cell tests are shown in Fig 7. The sectional view of settlement contour for 28 days and the stress variation in the micropile-rockwool composite are shown in Fig 8 (a) and (b) respectively. The comparison of results obtained from unit cell model tests and FEM analysis are summarized in Fig 9.

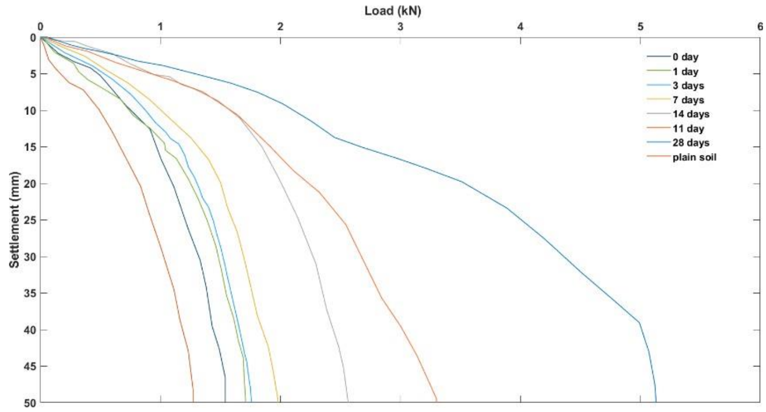
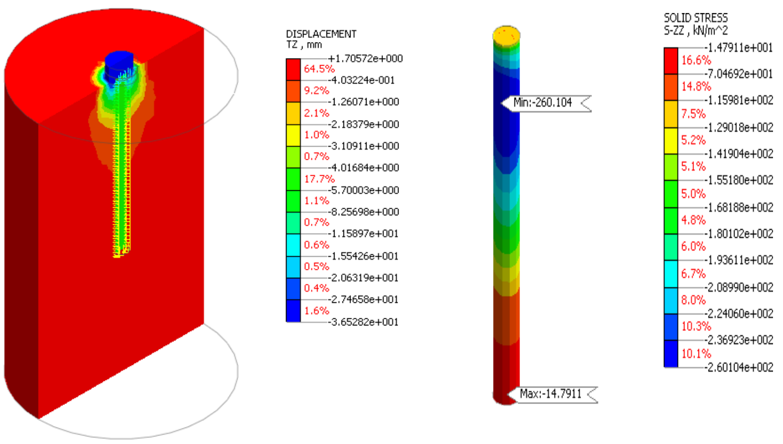


Fig 7. Load-Settlement curves



(a) (b)

Fig 8. (a) Sectional view of settlement contour for 28 days testing (b) Stress variation in the pile for 28 days

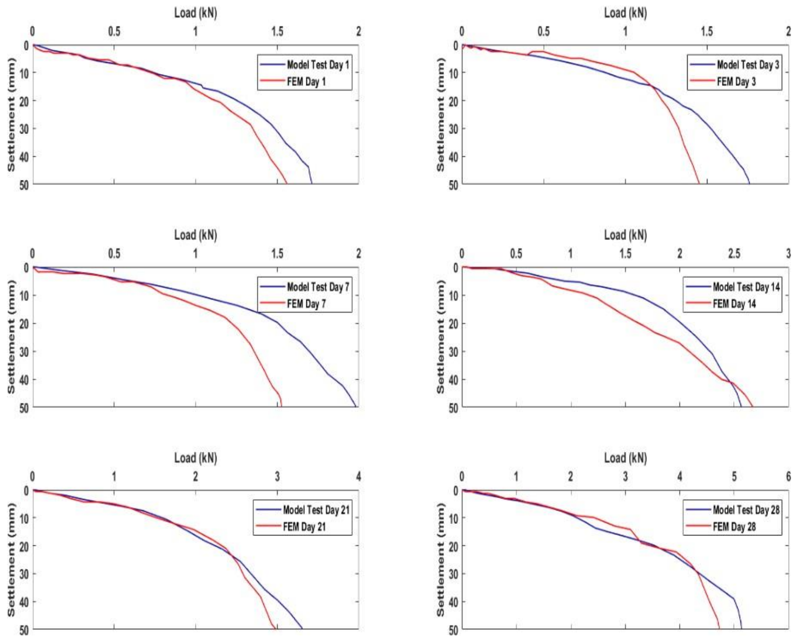


Fig 9. Unit Cell and FEM analysis load-settlement comparison

To assess the results of the moving train load analysis, vertical displacement responses are extracted at the central node of the railway track. The comparison of results obtained from micropile alone and micropile with rockwool composite show a reduction in the vertical displacement amplitude value as shown in Fig 10.

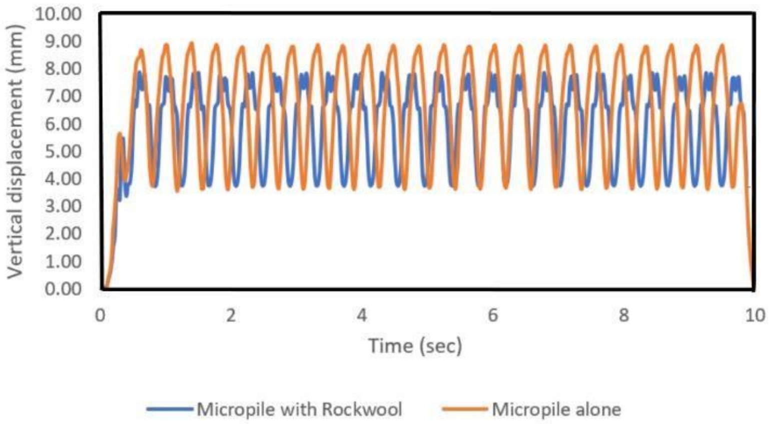


Fig 10. Vertical displacement response because of moving train load at 100 kmph

7. Conclusion

The present study based on the analysis of mechanical behaviour of rockwool, the unit cell model tests conducted and the FEM analysis leads to the conclusion that rockwool prepared by recycling steel slag waste can be used as an alternative to the conventional geotextile materials. The excellent damping characteristics of the material makes it perfectly suitable for use in railway tracks and other transport forms which witness dynamic loads on a large and frequent scale. It is also to be noted that rockwool with geonets when prepared as a composite along with micropiles can be extremely efficient in handling both the static loads as well as the dynamic impacts and can thus become a suitable way of improving and retrofitting the existing ground structures such as railway tracks.

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