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Stabilization of Reinforced Earth Wall Backfill Using Steel Slag and Recycled PET Fiber: A Composite Material Approach

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Abstract

Reinforced Earth (RE) walls are widely used in infrastructure due to their structural efficiency and ease of construction. However, they typically require high-quality granular backfill, which may not be readily available or cost-effective in many regions. This study investigates the potential of utilizing locally available sandy clay soil stabilized with industrial and plastic waste materials specifically 20% steel slag and 0.75% shredded polyethylene terephthalate (PET) fibers, as an alternative backfill for reinforced Earth (RE) walls. A comprehensive laboratory testing program was conducted to evaluate the geotechnical properties of the stabilized soil. Results showed substantial improvements in mechanical behavior: unconfined compressive strength increased to 440 kPa, California Bearing Ratio (CBR) rose from 4% to 16%, and plasticity index was reduced to non-plastic, indicating enhanced strength, stiffness, and workability.To validate the laboratory findings, a full-scale 6-meter-high RE wall was constructed using the optimized soil mix. Field monitoring over time recorded minimal vertical settlement (~7 mm) and very low lateral deflection (~3 mm), confirming the structural integrity and stability of the wall. The performance met the design requirements in accordance with Indian Roads Congress (IRC) specifications.This study demonstrates that the proposed soil-steel slag- polyethylene terephthalate fiber composite is a technically viable and sustainable alternative backfill material for RE wall applications. In addition to providing satisfactory engineering performance, it promotes the reuse of industrial by-products and plastic waste, offering both environmental and economic benefits. The findings support the use of such composites in future infrastructure projects to foster more sustainable construction practices.

Keywords: PET fiber, slag stabilization, composite material, reinforced soil, polymer reinforcement, RE wall backfill

INTRODUCTION

Mechanically stabilized earth or reinforced earth (RE) walls are widely used to support highway embankments, bridge approaches, and retaining structures due to their cost-effectiveness and ease of construction. Standard design guidelines typically require free-draining, high-friction granular soil as backfill to ensure adequate stability and serviceability. However, in many locations, good quality granular material is not readily available, leading to increased cost and environmental impact from hauling suitable fill. In contrast, there may be abundant local soils with modest amounts of fines (silt/clay) that are underutilized for RE walls due to concerns about their workability, lower strength, and poorer drainage. If such marginal soils can be suitably improved, they present an opportunity for more sustainable and economical construction.

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One promising approach is to stabilize the local soil with industrial by-products and fibers from waste plastics, aligning with sustainable construction and waste valorization goalsfile-Steel slag, a by-product of iron and steel production, has cementitious properties due to the presence of free lime (CaO) and silicates; it can react with soil moisture to form calcium silicate hydrate (C-S-H) gels that enhance soil strength over. Prior studies have shown that adding ground granulated blast furnace slag or steel slag to clayey soils reduces their plasticity and swelling potential while improving early strength development. For example, [1] and Yadu & Tripathi (2013) observed significant decreases in plasticity index and faster strength gain when stabilizing soft clay with Shredded plastic waste fibers (such as from polyethylene terephthalate bottles) can further improve soil performance through mechanical reinforcement. Even at low contents (around 0.5–1.0% by weight), discrete fibers interlock with soil particles and inhibit the propagation of cracks, thereby increasing ductility and post-peak load carrying capacity. Researchers like Maher and Ho (1994) and [5] reported notable increases in shear strength and residual strength in sands and silty soils reinforced with synthetic fibers [9]. Including PET fibers greatly enhanced the unconfined compressive strength of silty clay. Fiber effectiveness depends on factors such as fiber length, aspect ratio, and distribution; short fibers (on the order of 10–25 mm length) are easier to mix uniformly without clumping. When used in combination, chemical stabilization (with slag or other binders) and fiber reinforcement can act synergistically: the slag improves the soil's stiffness and cohesion by binding particles, while fibers provide tensile resistance and toughness, yielding a more balanced improvement in strength and deformability. Recently, the combination of about 20% slag and 0.75% PET fibers was optimal for improving silty sand backfills, significantly increasing strength and reducing settlements in reinforced soil structures [3].

This research aims to bridge the knowledge gap in using such dual stabilization for RE wall applications. Key objectives include: (1) evaluating the effects of steel slag and waste fiber additions on the geotechnical properties of a locally available sand-clay soil; (2) determining the optimal mix that maximizes strength, stiffness, and drainage while minimizing plasticity; and (3) validating the laboratory findings through a full-scale field trial of an RE wall constructed with the stabilized soil. By demonstrating the performance of the slag–fiber stabilized backfill both in the lab and in the field, the study seeks to prove its suitability as a safe and sustainable alternative to conventional granular fill. Notably, recent code provisions encourage such innovations – for instance, the Indian Roads Congress (IRC) SP:102 guideline allows performance-based evaluation of non-conventional backfills, opening the door to using stabilized marginal soils in reinforced soil structures. The outcome of this work will provide insights for engineers and policymakers on incorporating industrial and plastic waste in infrastructure projects, contributing to sustainable development and reduction of construction costs.

MATERIALS AND METHODS

Materials

The soil used in this study was a locally sourced sandy cohesive soil classified as clayey sand (SC) with low plasticity. Basic index properties of the natural soil indicated a liquid limit of ~22% and plastic limit ~17%, giving a plasticity index of about 5%. The standard Proctor maximum dry density of the raw soil was 1.68 g/cc at an optimum moisture content (OMC) of about 18%. The soil's natural friction angle was around 23° with a small cohesion intercept (~18 kPa), and its coefficient of permeability was on the order of 10^(-6) cm/s, reflecting limited drainage capacity. These characteristics, especially the marginal plasticity and lower permeability, would normally preclude the soil's direct use in RE wall backfills.

The stabilizing agents added to the soil were steel slag and shredded plastic fibers. The steel slag was obtained from a local steel plant, comprising predominantly basic oxygen furnace slag. Chemically, steel slag is rich in calcium silicates and free lime (CaO), which confer pozzolanic or cementitious behavior upon hydration [8]. Prior to use, the slag was aged and crushed to sandy-gravel size to eliminate any excessive expansion from free lime hydration. The specific gravity of the slag aggregate was about 2.8–3.0, higher than that of the soil (~2.65), which can help increase mix density. The plastic fibers were derived from waste PET (polyethylene terephthalate) bottles, mechanically shredded into approximately 10 mm long, thin strips. Each fiber was on the order of a few millimeters in width (aspect ratio around 10–20) and had a relatively low specific gravity (~1.3–1.4). The fibers are chemically inert in soil and serve purely as a physical reinforcement. Such short fiber lengths were chosen to ensure uniform mixing without fiber balling.

Five different mix proportions were prepared to systematically study the effect of slag and fiber content. The mix design was guided by insights from literature and preliminary trials. Mix M1 consisted of the natural soil alone (control). Mix M2 was soil blended with 10% (by dry weight) steel slag (no fibers) to observe the effect of a moderate slag addition. Mix M3 had 20% steel slag (no fibers), based on literature suggesting around 20% slag as a potentially optimal dosage. Mix M4 combined 20% steel slag + 0.5% PET fibers, and M5 combined 20% steel slag + 0.75% PET fibers. The fiber contents are expressed as a percentage of dry soil weight. The rationale was to first optimize the slag content for maximum stabilization effect (expected around 20%), then introduce fibers to that optimally stabilized soil to assess incremental benefits. Fiber dosages up to 0.75% were tested, since higher fiber contents (>1%) can be impractical to mix uniformly and typically show diminishing returns. All mixes were prepared by first dry-mixing the soil and slag, then sprinkling fibers and mixing further, and finally adding water to reach the desired moisture content for compaction or molding.

Laboratory Testing

A comprehensive laboratory test program was carried out on each mix (M1 through M5) to evaluate key geotechnical properties relevant for RE wall backfill performance. Standard test procedures as per Indian Standard (IS) 2720 were followed for consistency. The specific tests conducted were:

- *Atterberg limits:* Liquid limit and plastic limit were measured (IS 2720 Part 5) to determine the Plasticity Index (PI) and observe how slag addition alters the soil's plasticity. A cone penetrometer method was used for liquid limit, alongside the Casagrande dish method, to handle the potentially non-plastic behavior of treated mixes.
- *Standard proctor compaction*: Each mix's maximum dry density (M_{DD}) and optimum moisture content (OMC) were obtained using the standard Proctor test (IS 2720 Part 7). Approximately 3 kg of each mix was prepared and compacted in a 1000 cm³ mold in three layers with 25 blows of a 2.6 kg rammer per layer. This provided the compaction curves and OMC values for comparison.
- *Unconfined compressive strength (UCS):* Cylindrical specimens (38 mm diameter, 76 mm height) of each mix were compacted at OMC to approximately 98% of their in moulds and extruded. UCS tests (IS 2720 Part 10) were conducted at different curing periods to capture strength gain over time due to slag hydration. Specimens were cured in a humid chamber (27±2°C, >90% RH) and tested after 7 days, 14 days, and 28 days of curing. The loading rate was 1.25 mm/min. Three samples per mix per curing period were tested to ensure repeatability, and the average UCS recorded.
- *California bearing ratio (CBR):* Soaked CBR tests (IS 2720 Part 16) were performed to assess load-bearing capacity under saturated conditions, which is important for backfill supporting pavement or spreading footing loads. Each mix was compacted into CBR molds (150 mm diameter, 127.3 mm height) in 3 equal layers (each 56 blows of a 4.5 kg rammer, corresponding to heavy compaction) to represent field compaction effort. The specimens were then soaked under water for 96 hours with a surcharge before penetration testing. The CBR value at 2.5 mm penetration was obtained for each mix.
- *Direct shear test*: Shear strength parameters (cohesion c and friction angle ϕ) of each mix were determined using the direct shear box test (IS 2720 Part 13). Samples (60 mm × 60 mm shear box) were compacted to at OMC and sheared under three different normal stresses (50, 100, and 150 kPa) at a strain-controlled rate of 1.25 mm/min. From the shear stress vs. normal stress plot, the Mohr-Coulomb failure envelope was obtained for each mix.

- *Permeability*: A constant head permeability test (IS 2720 Part 17) was conducted for each mix to evaluate drainage capability. Cylindrical soil specimens (60 mm diameter, 60 mm height) were compacted and tested in a permeameter. For the more permeable stabilized mixes, a higher head difference was applied to maintain measurable flow. The coefficient of permeability k was calculated for each mix.

All tests were performed at least in duplicate, and average values are reported. During sample preparation, particular care was taken to achieve an even distribution of fibres in the soil matrix (especially for M4 and M5). Mixing was done manually and also with a mechanical pan mixer for larger batches, as manual mixing of fibres sometimes led to clumping. Each batch of mix was sealed in bags for a minimum of 24 hours (for slag hydration to initiate) before compaction in tests like UCS and CBR, to simulate field mixing-delay effects.

Field Trial Construction

To validate the laboratory findings, a full-scale field trial was undertaken by constructing a reinforced earth wall section using the optimum stabilized mix (Mix M4/M5). The trial wall was built at an actual project site and designed to be 6.0 m in height and 10.0 m in length – a representative scale for highway embankment supports. The wall was of the wrap-around mechanically stabilized earth type with modular precast concrete facing panels and geogrid reinforcement. Figure 1 provides a view of the site during early construction stages, showing the placement of facing panels and preparation of the backfill soil.

Design and configuration: The wall was designed according to standard practice (FHWA and IRC guidelines) to ensure both external and internal stability. The stabilized backfill was assigned engineering properties based on the lab results of the chosen mix (approximately corresponding to Mix M4/M5: friction angle ~32°; cohesion ~30–33 kPa; and unit weight ~18 kN/m³). These values meet typical specifications for RE wall fills. Geogrid reinforcements (HDPE biaxial geogrids) with an ultimate tensile strength of 30 kN/m were laid horizontally in the stabilized fill at vertical intervals of 0.6 m. The length of each geogrid embedment was 4.2 m (about 0.7 times the wall height), providing a sufficient anchorage zone behind the active wedge as per design standards. Precast concrete panels (1.5 m × 1.0 m) formed the wall face; these panels had factory-cast connection loops for geogrid attachment. A granular drainage layer (150 mm thick gravel) was installed immediately behind the panels, supplemented by vertical weep holes at 3 m spacing to relieve any water pressure. The wall foundation was a compacted granular pad, and the base soil had an allowable bearing capacity of about 200 kPa (verified by plate load tests) which was adequate for the structure.

Figure 1. Site of the field trial RE wall construction. Precast concrete facing panels (with connection slots) are positioned, and the local soil is sampled for characterization prior to stabilization.

Construction procedure: The construction was carried out in a manner similar to typical MSE wall building, with additional attention to mixing the stabilizer (slag and fibers) into the soil on-site. The steps were as follows:

1. *Subgrade preparation*: The native ground under the wall footprint was cleared of topsoil and leveled. It was then compacted with a vibratory roller to at least 98% of the standard Proctor of the subgrade soil. A CBR > 10% was achieved for the foundation layer before proceeding.
2. *Facing placement*: Precast facing panels were erected sequentially using a small crane and braced with temporary supports. Rubber pads were inserted at horizontal joints to allow slight rotations and prevent concrete-to-concrete contact abrasion. Panel alignment and verticality were checked at each lift using plumb lines or a laser level.
3. *Backfill mixing and placement*: The stabilized backfill (slag + fiber + soil) was prepared in batches. The required quantities of dry soil and steel slag were measured and mixed on-site (using a loader or mixer), then fibers were uniformly introduced (for mixes requiring fibers) and water was added to reach near OMC. This mixed material was placed in the wall in 250 mm thick loose lifts, corresponding to about 200 mm after compaction. Each lift was compacted to 96–98% of lab using a vibratory roller (for open areas away from the face) and a plate compactor near the panels. The compaction of each lift was verified by in-situ density tests (sand cone or nuclear gauge) at three random points per layer. Layers of stabilization mix were placed and compacted one after another, with moisture content carefully controlled within ±2% of OMC to ensure consistency. Figure 2 shows the compaction operation in progress, with a vibratory roller achieving the desired density in the stabilized soil layer.
4. *Geogrid installation*: At the predetermined reinforcement levels (every fourth compacted lift, i.e., 0.6 m vertical spacing), biaxial geogrid strips were laid horizontally. The geogrids were cut to the design length (4.2 m) and placed perpendicular to the wall face, then connected to the facing panels by looping through the panel connectors and securing with a locking rod. The geogrids were pulled taut by hand to remove slack and held in place while the next backfill lift was placed over them. Care was taken to avoid wrinkles or folding of the geogrid and to maintain the design elevation.
5. *Drainage installation*: As the wall rose, a continuous layer of coarse gravel (150 mm thick) was maintained immediately behind the panels as a vertical drainage blanket. A non-woven geotextile was placed between this gravel zone and the stabilized backfill to prevent any fines migration. PVC weep pipes were installed through the facing at intervals (one per ~3 m of wall length per lift) to provide weep holes for water exit. These precautions ensure that even if the stabilized fill has lower permeability than purely granular fill, water will not accumulate behind the wall.
6. *Quality control:* During construction, field moisture and density were monitored regularly. A nuclear density gauge and sand cone tests were employed to confirm each lift exceeded 95% compaction. Minor adjustments in water content were made in response to weather (e.g. slightly higher water added during mid-day if drying was rapid). The mixing of fibers was observed; initially, some fiber clumping was noted when using manual mixing, but switching to mechanical mixing alleviated this issue.

Instrumentation and monitoring: To assess the wall's performance, simple instrumentation was installed. Settlement plates were placed on the backfill at the mid-height and top (crest) of the wall to measure vertical compression of the fill. An inclinometer casing was installed behind the facing along the mid-height to track lateral deflections of the wall. Additionally, a couple of standpipe piezometers were embedded in the backfill to monitor pore water pressure, especially after rain, given the initial lower permeability of the untreated soil. Measurements were taken during construction and for three months after completion on a regular basis (settlements measured monthly, inclinometer readings bi-weekly, and piezometer after heavy rains).. This instrumentation plan (summarized in Table 1) was relatively minimal yet sufficient to capture the primary deformation behavior of the wall.

Figure 2. Field compaction of the slag-fiber stabilized backfill using a vibratory roller. Fewer compaction passes were required compared to conventional soil due to the improved compaction characteristics of the mix.

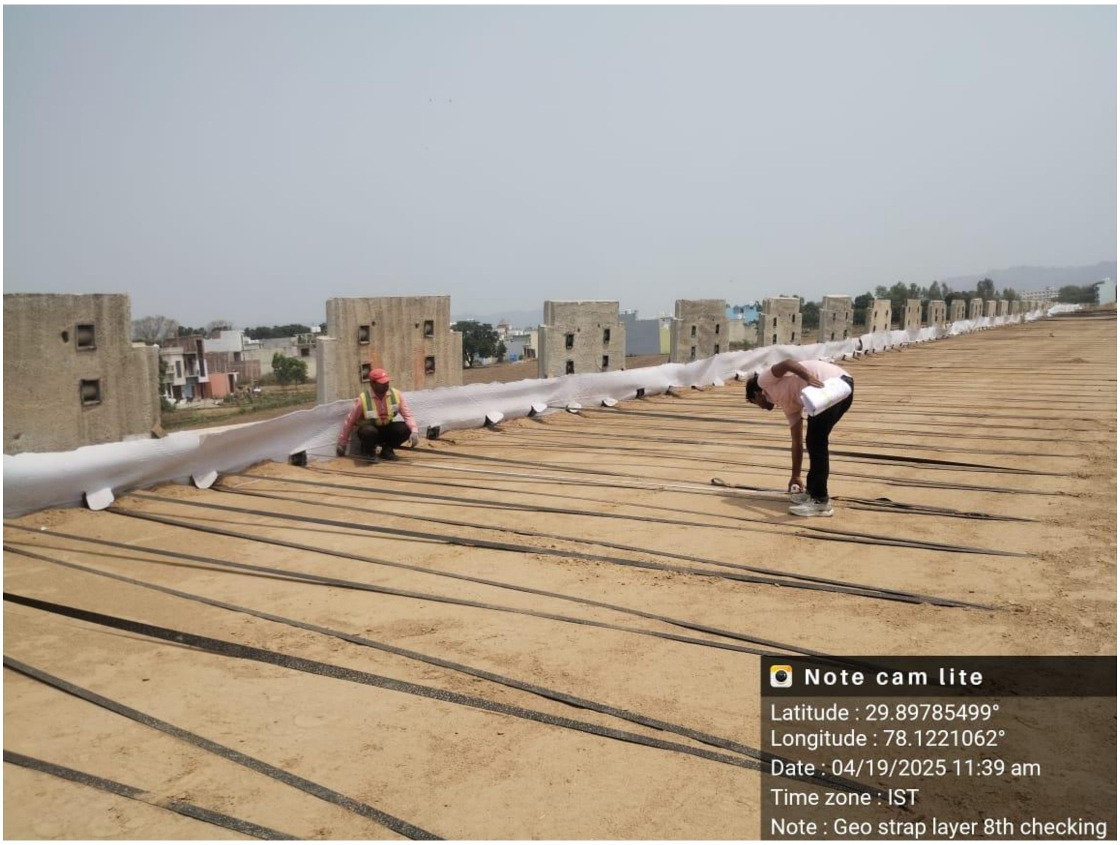

Figure 3. Geogrid Installation: At the predetermined reinforcement levels (every fourth compacted lift, i.e., 0.6 m vertical spacing), biaxial geogrid strips were laid horizontally.

Table 1. Field instrumentation for trial wall monitoring.

Instrument	Purpose	Reading frequency
Settlement plates	Vertical settlement of fill at key points (mid-height, crest)	Monthly
Inclinometer casing	Lateral wall deflection profile	Bi-weekly (every 2 weeks)
Piezometers	Pore water pressure in backfill (drainage performance)	After major rainfall events

Construction of the trial wall progressed smoothly over approximately two weeks. The use of the stabilized backfill did not require any special equipment beyond what is typical for MSE wall construction, aside from the on-site mixing effort. Importantly, the contractor observed that the stabilized soil was easier to compact than the untreated soil, achieving required density in fewer roller passes (4–5 passes) compared to an estimated 6–8 passes for the original soil – this is attributed to the drier optimum and higher density of the slag-treated material.. By the end of construction, the wall appeared visually indistinguishable from a conventional RE wall, with no signs of distress or segregation in the backfill.

RESULTS

Laboratory Results

Plasticity and classification

The addition of steel slag had a pronounced effect on the soil's plasticity. The natural soil (M1) had a modest plasticity index (PI) of 5%, classifying as clayey sand (SC). With 10% slag (M2), the PI dropped to about 2%, and at 20% slag (M3) it was nearly eliminated (PI ≈ 0.5%). When fibers were introduced along with 20% slag (M4 and M5), the mixes exhibited *non-plastic* behavior – no plastic limit could be determined, indicating that the material essentially became cohesionless in terms of consistency. The soil classification shifted accordingly; by M4/M5 the material was classified as SP-SM (non-plastic silty sand) instead of SC.. Figure 3 illustrates the trend of decreasing plasticity index across mixes. The PI falls from ~5% in the untreated soil to essentially 0% in the slag+fiber stabilized mixes, meeting the typical requirement of PI < 6% for RE wall backfills.

The dramatic reduction in PI is attributed to the calcium-rich slag interacting with clay fractions. The CaO in slag likely caused aggregation of clay particles and consumption of exchangeable ions, thereby reducing the clay's ability to behave plastically. The fibers themselves are inert and do not directly change Atterberg limits, but their presence did not hinder the plasticity reduction; if anything, fibers might absorb a bit of water or create a reinforcing matrix that makes it difficult to form a plastic consistency. Achieving a non-plastic material is beneficial as it implies negligible swell-shrink potential and better drainage – important traits for RE wall fill.

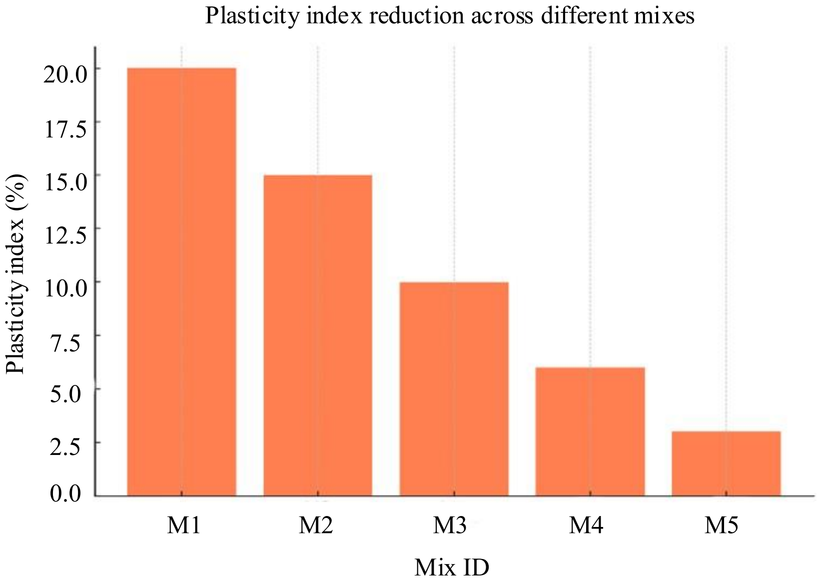

Figure 4. Reduction in Plasticity Index across different mixes (M1–M5). The slag's chemical effects (flocculation and cementation) and dilution of clay minerals led to a sharp drop in plasticity, reaching non-plastic behavior for mixes with ≥20% slag. M4 and M5 (slag + fiber) showed PI = NP (non-plastic), which is ideal for minimizing volumetric changes and improving drainage in backfills.

Compaction characteristics: The Proctor compaction results showed an improvement in dry density with increasing slag, accompanied by a reduction in optimum moisture content. The untreated soil (M1) had M_{DD} = 1.68 g/cc at OMC ≈ 18.0%. For M2 (10% slag), increased to 1.73 g/cc and OMC dropped to ~17.2%. With 20% slag (M3), reached 1.76 g/cc and OMC fell to ~16.5%. The mixes with fibers (M4 and M5) continued this trend slightly: M4 had M_{DD} = 1.79 g/cc at OMC ≈ 15.8%, and M5 achieved the highest density 1.81 g/cc at OMC ~15.2%. The compaction curves (dry density vs. moisture content) for each mix shifted upward and to the left as slag content increased – indicating a denser material that optimally requires less water. Figure 4 summarizes the changes in and OMC for the mixes. The slag, being a coarse, angular material of higher specific gravity, improved the packing of particles, while also reducing the clay fraction that would normally hold a lot of water. Consequently, the optimum moisture for compaction dropped by about 3 percentage points from M1 to M5, and the achievable dry density increased by ~8% in the same range.

These results are favourable for field compaction. A higher MDD means the stabilized soil can potentially carry more load at lower void ratio, and the lower OMC implies that it will be easier to compact in the field (less water to add and less sensitivity to small deviations in moisture). It was observed during compaction tests that mixes M4 and M5 compacted to high densities quite readily. This translated to the field behaviour as well – the contractor achieved required compaction with fewer passes of the roller for the stabilized fill, as noted earlier. Notably, the MDD of about 1.79–1.81 g/cc for the optimal mixes exceeds the minimum recommended dry density (1.75 g/cc) for highway RE wall backfills given by IRC SP: 102. This indicates the stabilized soil meets density criteria, which correlates with lower post-construction settlement potential.

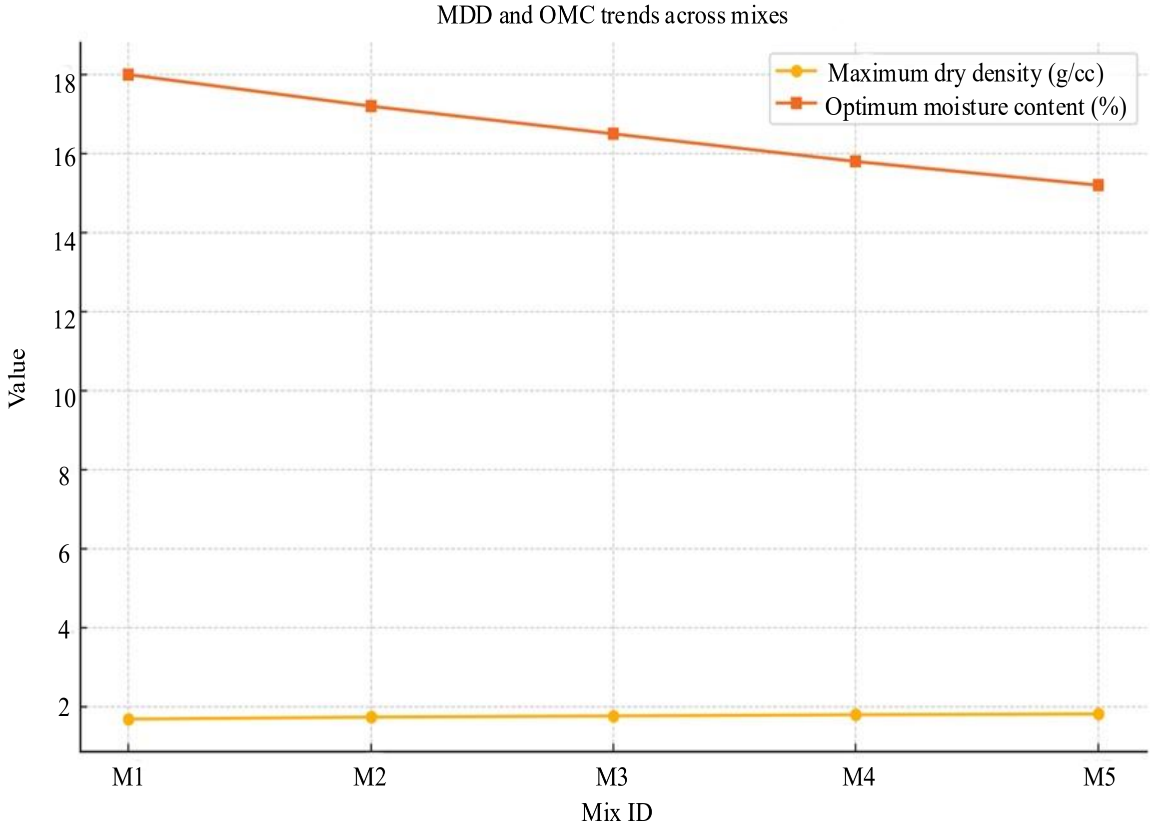

Figure 5. Compaction characteristics of mixes M1–M5: Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). As slag content increases, MDD rises and OMC decreases, reflecting a denser gradation and reduced fine fraction. The addition of fibers (M4, M5) did not adversely affect compaction; M5 attained the highest density (~1.81 g/cc) at the lowest OMC (~15%).

Unconfined compressive strength (UCS): The UCS test results demonstrated substantial gains in strength with slag addition and further enhancements with fiber inclusion, especially over curing time. The natural soil (M1) had a 7-day UCS of only ~110 kPa, which increased slightly to 160 kPa at 28 days due to some natural curing. Introducing 10% slag (M2) roughly doubled the 28-day UCS to ~270 kPa. At 20% slag (M3), the 28-day UCS reached ~360 kPa. The addition of fibers provided a significant boost in ductility and a moderate increase in peak strength: M4 (20% slag + fibers) had ~380 kPa at 14 days and ~440 kPa at 28 days, and M5 (with a bit more fiber) achieved the highest UCS around ~470 kPa at 28 days. Figure 5 presents the UCS values at 28 days for all mixes, highlighting the sharp improvement from M1 to M5. The 28-day strength of the optimal mix (exceeding 0.4 MPa) is nearly three times that of the untreated soil.

It was observed that specimens of the untreated soil and low-slag mixes failed in a brittle manner (an abrupt drop in load after peak), whereas the fiber-reinforced mixes (M4, M5) showed a more gradual post-peak softening, indicating a ductile failure mode. The fibers bridge across cracks and hold the specimen together even after the slag-cementation bonds start to fracture, thereby imparting residual strength. This ductility is advantageous for RE wall backfill, as it means the material can undergo small deformations without losing integrity, distributing loads in the process. In fact, M4 and M5 samples could sustain significantly higher strains at peak stress compared to M1–M3, confirming the role of fibers in enhancing toughness.

The UCS gains with slag can be attributed to the formation of cementitious C-S-H and possibly calcium aluminate hydrates over the curing period. Essentially, slag acts like a slow-acting cement, binding soil particles together. The presence of calcium hydroxide (from slag hydration) and the silica/alumina in the soil leads to these pozzolanic reactions. By 28 days, the stabilized mixes achieve strength levels that meet and exceed typical requirements. For reference, IRC SP:102-2014 suggests a minimum UCS of about 300 kPa for acceptable backfill material – the stabilized mix comfortably surpassed this (440–470 kPa). The improved UCS and ductility together imply that an RE wall built with this material will have a robust load-bearing capacity and resilience against cracking. It ensures that under heavy loads (or traffic surcharges), the backfill will sustain minor movements rather than sudden failure.filefailure.

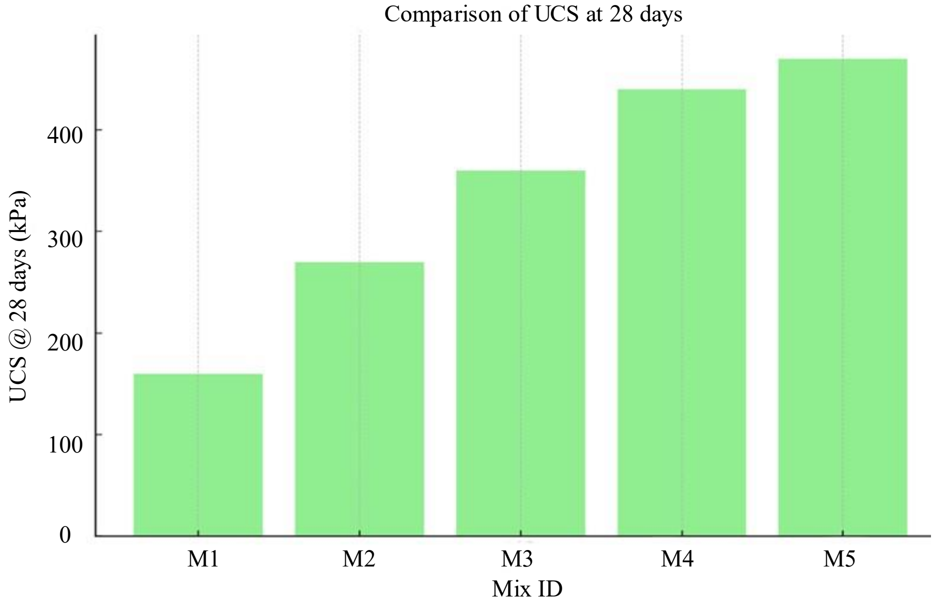

Figure 6. Unconfined compressive strength (UCS) at 28 days for different mixes. The 28-day UCS increased from ~160 kPa (M1) to ~470 kPa (M5) with slag and fiber stabilization. Slag contributed to the majority of the strength gain through pozzolanic reactions (notably from M1 to M3), while fibers provided additional strength and prevented brittle failure (compare M3 vs M4/M5).

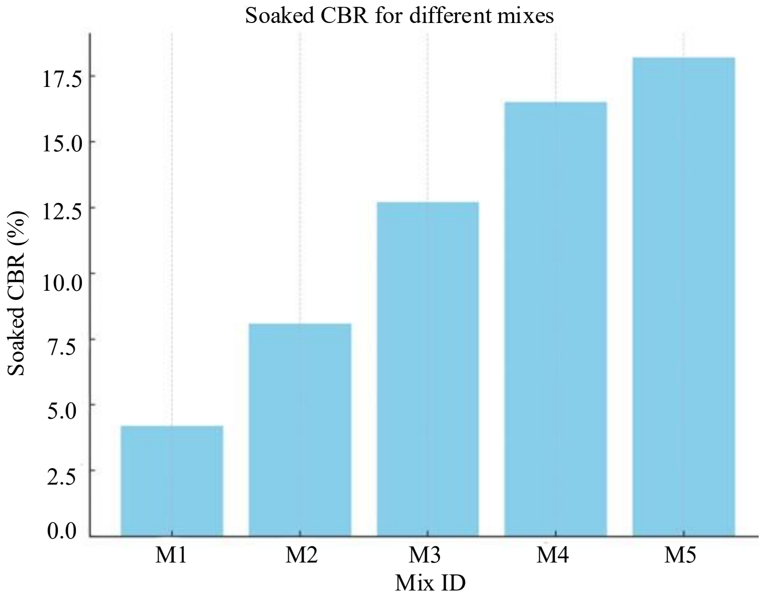

Figure 7. Soaked California Bearing Ratio (CBR) for different mixes. The stabilized mixes show a marked increase in CBR, from 4% (M1) up to around 16–18% (M4/M5). This indicates the load-bearing capacity in wet conditions is greatly improved, largely due to slag-induced strengthening and fiber reinforcement which helps resist deformation under the CBR plunger.

California bearing ratio (CBR): The soaked CBR results mirrored the UCS trends, showing major improvement with stabilization. The natural soil (M1) had a low soaked CBR of about 4.2%, which is expected for a fine-grained soil – indicating poor support capability when saturated. M2 (with slag) increased to ~8.1%, M3 to ~12.7%, and M4 reached 16.5%. Mix M5 was around 18% (slightly higher than M4) as per the trend. Figure 6 shows the soaked CBR values for mixes M1–M5. The CBR of the optimal mix (≈16–18%) is roughly four times that of the untreated soil. This is a significant gain, meaning the stabilized soil has the capacity to distribute loads much more effectively – an important aspect for base/subbase performance in roadways or for supporting shallow foundations behind the wall.

Notably, a soaked CBR of >16% for M4/M5 meets IRC SP:89-2018 requirements of minimum ~8% CBR for backfill materials in reinforced soil structures. In fact, M4's CBR is about double the minimum standard. The reasons for CBR improvement are twofold: (1) the slag binding increases the overall stiffness and apparent cohesion of the mix, so it can withstand the penetration without as much plastic deformation; (2) the fibers help distribute the stress under the CBR plunger, acting like tiny reinforcing elements that inhibit shear failure. During the CBR tests, it was noticed that the fiber-reinforced samples did not develop the typical shear cracks around the penetrator as quickly as the plain soil – the fibers were holding the material together. This mechanism is analogous to how geogrid in a pavement base course spreads load laterally. Therefore, a higher CBR suggests that in the field, the stabilized backfill will undergo smaller settlements under surcharge loads and will require less frequent maintenance (in contexts like reinforced soil slopes supporting pavements).

Shear strength (direct shear): The direct shear tests provided the shear parameters c (cohesion) and ϕ (friction angle) for each mix. The untreated soil (M1) had $c \approx 18$ kPa and $\phi \approx 23°$. With slag additions, both parameters improved: M2 yielded c ~22 kPa, ϕ ~27°; M3 ~27 kPa, 30°; M4 ~33 kPa, 32°; and M5 highest at ~36 kPa, 33°. The cohesion roughly doubled from M1 to M5, and friction angle increased by about 10°. Figure 7 illustrates the increasing trend of cohesion and friction angle across the mixes. This enhancement is a critical outcome for RE wall design – friction angle is directly related to the lateral earth pressure exerted on the wall, and higher values lead to lower active pressures, while cohesion can add some reserve strength (though cohesion in backfill is generally conservatively neglected in design, its presence contributes to stability, especially during short-term loading).

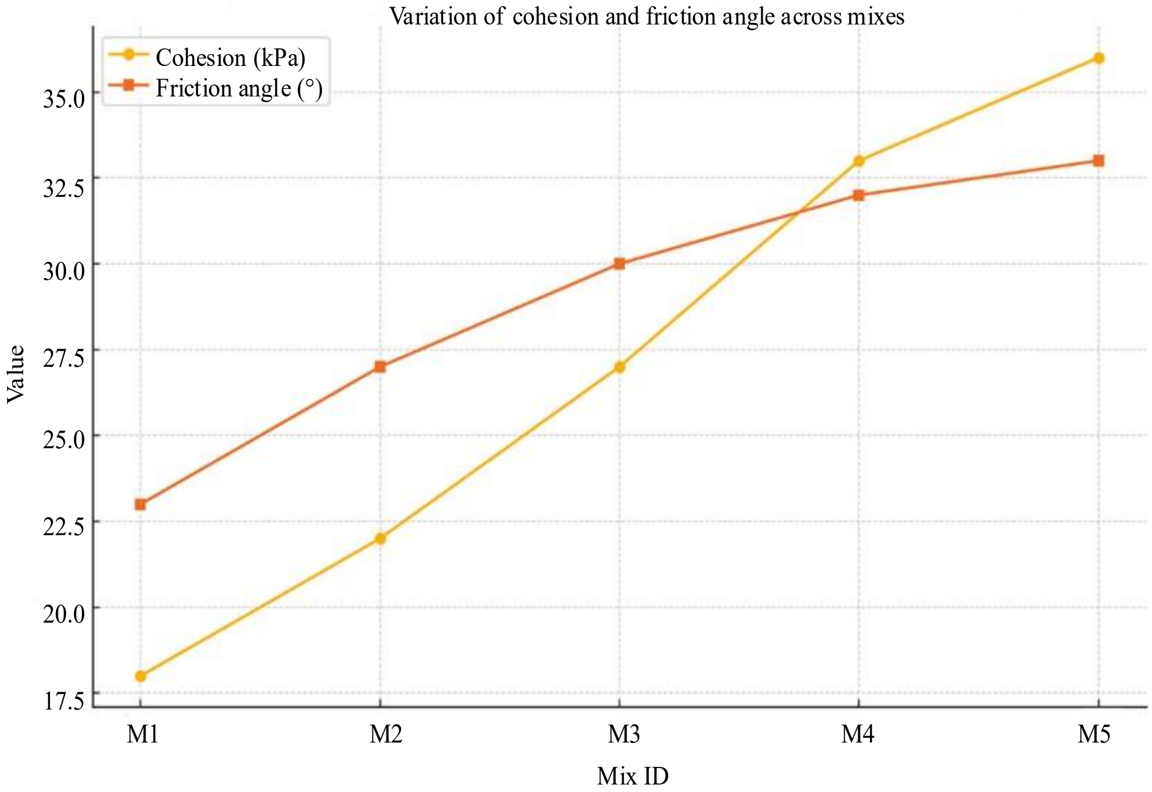

Figure 8. Variation of shear strength parameters (cohesion c and friction angle ϕ) across mixes M1–M5. Both c and ϕ increased steadily with slag and fiber content. By M5, ϕ reached 33° (up from 23° in natural soil) and c reached 36 kPa (double that of natural soil). These higher shear strength parameters significantly improve the stability of the backfill against shear failure and reduce lateral pressure on the RE wall.

The increase in friction angle can be attributed to the inclusion of non-plastic, angular slag particles which improve the granular interlock of the soil. Essentially, the mix's gradation becomes coarser and more angular, which typically yields higher friction. Moreover, as the fine content and plasticity drop, the frictional behavior dominates. The friction angle exceeding 30° for the stabilized mix is on par with what one would expect from a reasonably good sand/gravel backfill, thus satisfying a key requirement for RE wall fills (commonly, $\phi \geq 30°$ is targeted to ensure adequate sliding and overturning stability). The cohesion gain is from two sources: the slight cementation due to slag (which bonds particles and gives an apparent cohesion intercept), and the fiber effect (fibers stitch the soil together and can contribute to cohesion by requiring extra force to pull out/slip during shear). While conservative design might not rely on cohesion, having ~30+ kPa of cohesion means the backfill has additional shear resistance especially under low confining stress, which is beneficial in the upper part of the wall or during construction before full overburden develops. The shear strength envelope of the optimal mix (M4/M5) indicates a substantially stronger material, thereby increasing the internal stability of the RE wall. In fact, the improved friction angle directly increases the factor of safety against sliding at the base of the wall for a given demand friction angle) and was taken advantage of in the design checks.

Permeability: One concern with using fine-grained soils in reinforced walls is their lower permeability, which can lead to pore pressure build-up. The constant-head permeability tests showed that adding slag raised the coefficient of permeability by orders of magnitude. Figure 8 shows the permeability trend, which rises roughly logarithmically with slag percentage. The fibers did not significantly impede flow; if anything, the slight increase from M4 to M5 might indicate fibers helping maintain pore continuity (though the change is minor).

The rise in permeability is expected, as shown in Figure 9, because the slag improves the gradation by adding coarse particles and also reduces the amount of plastic fines that can clog pores. The resulting mix has a more open structure for water to flow. By M4/M5, the permeability (~1–1.5 × 10^{-4} cm/s) is comparable to fine sand, which is considered acceptable for drainage behind retaining walls. During design, because we achieved *k* at this threshold, we still incorporated a dedicated drainage layer and weep holes as described, but the high backfill permeability adds a factor of safety – even if some water infiltrates the backfill, the material itself can transmit it to the drains without building up significant pore pressures. This was validated in the field monitoring, as discussed later (no pore pressure build-up was observed and the weep holes flowed freely after rains).

In summary, the laboratory results confirmed that Mix M4/M5 (approximately 20% steel slag + 0.5–0.75% fibers) provides the best overall performance: negligible plasticity, improved compaction (high dry density at lower moisture), UCS around 0.45 MPa (suitable for heavy loads), CBR >15%, friction angle >32°, and adequate permeability. In all metrics, this stabilized mix met the typical criteria for RE wall backfill and often exceeded the code-recommended values. The addition of fibers, while not drastically altering strength values beyond slag alone, imparted ductility and likely longer-term durability (crack resistance) to the material. Consequently, Mix M4 was selected for the field implementation (with about 0.75% fiber as per the optimum identified). These lab findings also align with findings from previous studies on similar materials – for instance, [3] reported a similar optimal combination yielding high strength and stiffness., and the achieved parameters closely matched those required by standards (e.g., FHWA and IRC), giving confidence to proceed with the field trial.

Field Performance

After construction, the trial RE wall section was observed and monitored for a period of three months (and informally even beyond that during the project). The field performance data encompassed compaction quality, wall deformations (settlements and lateral movement), and drainage behavior. The observations are summarized below.

Compaction quality: Field density tests confirmed that the target compaction was consistently achieved. Every layer of the stabilized backfill attained 96–98% of the lab as measured by sand cone tests. No significant rework was ever needed; in contrast to some traditional soil fills where certain wet spots or hard spots might require re-compaction, the stabilized fill compacted uniformly. The site crew reported that the mix was easy to handle and compact – a testament to the improved compaction characteristics identified in the lab. Importantly, the distribution of fibers remained uniform throughout the fill; visual inspection during excavation of a small trench in the completed wall showed fibers were present throughout and no zones of fiber segregation were found. This indicates the mixing method was effective at scale. Overall, the compaction control demonstrated that the lab optimum moisture content was appropriate in the field and that the material is robust in terms of compaction (it did not show signs of over-compaction or “pumping” even when compacted to high densities).

Settlement behavior: The settlement plates placed at the wall crest recorded very small vertical settlements. After the wall reached full height and the design surcharge (a gravel base for a future pavement) was placed, the total settlement at the top of the wall was only ~7.4 mm over three months. Most of this settlement (around 5–6 mm) occurred within the first 4–6 weeks after construction, with the rate of settlement diminishing and essentially stabilizing by about 60 days post-construction. A settlement of <8 mm in a 6 m high wall corresponds to a strain of only 0.13%, which is negligible. This confirms that the backfill did not undergo significant compression – likely due to its higher density and cemented structure (slag hydration continued to gain strength, offsetting any minor creep). For comparison, a conventional granular fill might settle a similar magnitude (a few millimeters) mainly from elastic compression under its self-weight, while a more clayey fill could settle more and over a longer period. Here the quick stabilization of settlement is an encouraging sign that the wall will not experience long-term differential settlements that could affect the wall or the supported structures.

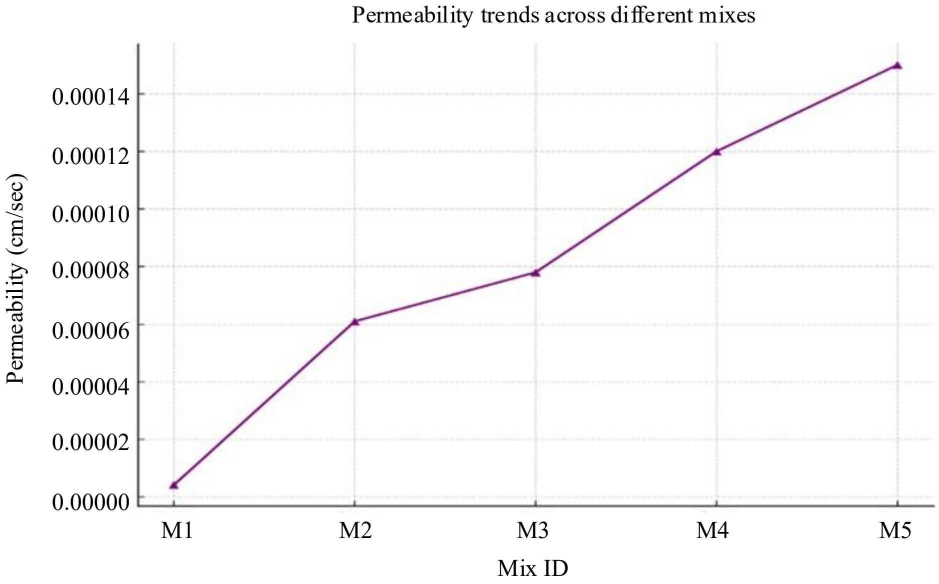

Figure 9. Permeability (coefficient of permeability k) of mixes under constant head test. The slag content has a strong positive influence on permeability: M1 (base soil) is in the 10^{-6} cm/s range (very low permeability), whereas M4 and M5 are above 10^{-4} cm/s, meeting typical minimum drainage requirements. Adequate permeability ensures that the stabilized backfill will not trap water, especially important when used behind retaining walls.

Lateral displacement: The inclinometer readings indicated minimal lateral movement of the wall face. The maximum lateral deflection recorded was ~2.8 mm at the mid-height of the wall. The deflected shape of the wall (very slight outward bulge near mid-height) is typical for MSE walls, but the magnitude is extremely small – only 0.05% of the wall height. Engineering guidelines often consider lateral movements up to 0.1–0.2% of wall height to be acceptable for serviceability. In this case, 2.8 mm is well within any tolerance (for a 6 m wall, even <10 mm would be considered practically rigid). The stiffness of the stabilized backfill likely contributed to this performance; with higher shear strength and cohesion, the active pressure development was limited, resulting in only slight yielding of the wall. The geogrid strains (inferred from the lack of movement) were also low, suggesting the factor of safety against internal failure was high. No visible bulging or rotation of panels was observed; the facing remained properly aligned, which also reflects on good compaction and consistent fill behavior.

Drainage and pore pressure: Throughout the monitoring period, no abnormal pore pressures were detected in the backfill. After heavy rain events, the piezometers showed at most a transient minor rise, but essentially the weep holes and drainage layer were effective in rapidly relieving water. The wall face exhibited no water seepage stains or signs of saturation behind the panels. This indicates that, despite the original soil being of lower permeability, the combination of improved mix permeability and proper drainage design prevented any water buildup. The quick response of the weep holes (water observed trickling out within minutes of a strong rain) confirms that the backfill allowed water to percolate to the face. The field evidence reinforces that the stabilized backfill can be considered free-draining for practical purposes, especially when used in conjunction with standard drainage provisions. There were also no signs of surface erosion on the exposed top of the backfill during rains – possibly the slag and fiber inclusion helped the soil retain structure and resist washout in heavy rain.

Overall stability: The wall remained stable with no signs of distress such as cracking, excessive settlement, or facing panel issues. The connection between panels and geogrid held firm (helped by minimal differential movements). In essence, the field trial validated that the stabilized soil performed as anticipated or better. The design calculations done prior (using lab parameters for Mix M4 and conventional safety factors) predicted factors of safety >1.5 for sliding and >2.0 for overturning, and the field behavior (very low movements) is consistent with those high safety margins.

Construction efficiency and cost: An important practical outcome noted was the improved construction efficiency. As mentioned, fewer roller passes were needed per lift owing to the material's compaction ease. The contractor's records showed the wall construction (10 m length, 6 m high) was completed in ~14 days with stabilized fill, whereas a similar length nearby using imported granular fill took about 18 days – roughly 20% faster completion. Part of this is attributable to fewer compaction cycles and partly to the logistic ease (the soil was mixed on site, eliminating delays of bringing select fill from a distant quarry). There was also a cost saving estimated at about 15–20% for the backfill portion of the wall. This comes from the avoided purchase of expensive aggregate and the utilization of waste materials (slag was obtained at minimal cost, fibers were inexpensive being recycled material). Even considering the processing and mixing cost, the overall expense was lower. Thus, from an implementation standpoint, using the slag-fiber stabilized soil can be both time-saving and cost-effective compared to conventional methods, especially in areas where suitable fill is not locally available.

Additionally, by using the slag and waste fibers, the project had environmental benefits: roughly 18 tons of steel slag and 200 kg of waste plastic were consumed in this 10 m wall section alone. Scaling this up, a kilometer of such wall could reuse thousands of tons of industrial waste, which would otherwise require disposal. The carbon footprint is lowered by reducing haulage of new materials and by giving a second life to waste products. These sustainability gains are an ancillary but important outcome, aligning with green construction objectives.

In summary, the field trial confirmed that the laboratory-developed slag + fiber stabilized backfill is fully compatible with RE wall construction practices and meets performance expectations. The wall exhibited negligible deformation under load, indicating ample stability. No construction or serviceability problems were encountered that could be attributed to the use of the unconventional fill – a crucial proof of concept. Minor challenges like initial fiber clumping and moisture control were easily mitigated by procedural adjustments (mechanical mixing, frequent moisture checks).. The success of this trial provides confidence in extending this technique to larger scales and other locations. The data collected will also be valuable for refining design methodologies (e.g., input parameters for design can be adjusted knowing the actual field behaviour was better than conservative assumptions.

DISCUSSION

The experimental and field results demonstrate the feasibility and advantages of using a slag and plastic fiber stabilized soil as backfill in reinforced earth walls. In this section, we interpret the findings in the context of geotechnical mechanisms, compare with conventional materials and standards, and discuss practical implications.

Mechanisms of improvement: The substantial enhancement in soil properties can be attributed to a combination of chemical stabilization (from steel slag) and mechanical reinforcement (from fibers). The steel slag acted similarly to a slow-setting cement, providing a time-dependent strength gain through pozzolanic reactions. Over 28 days, the formation of cementitious C-S-H bonds in the slag-treated mixes led to higher UCS and CBR – essentially increasing the soil's cohesion and aggregate interlock. This is evidenced by the fact that M3 (slag only) already achieved most of the strength improvement seen in M4/M5. The plasticity reduction and grain-size modification by slag also converted the soil's behavior closer to a granular material (non-plastic, higher friction angle). On the other hand, the discrete fibers contributed little to initial strength but significantly to ductility and post-peak behavior. They limit crack propagation (as seen by the more gradual failure and the bridging observed in broken UCS samples) and add residual strength by requiring pull-out or tensile rupture for the soil mass to fully fail. In the direct shear tests, fiber inclusion slightly raised the cohesion intercept – this can be thought of as the fiber network providing an internal tension that needs to be overcome to initiate shear. The friction angle did not drop with fibers (in fact, a small increase from M3 to M4), indicating that the fibers, being flexible and rough, did not act like "slick inclusions" but rather moved with the soil.

The synergy of slag and fibers is particularly noteworthy: slag gives the soil stiffness and strength, while fibers maintain toughness and deformation capacity. This combination results in a backfill that can sustain loads with minimal deformation (thanks to stiffness) and yet is resilient against cracking or collapse even beyond the elastic range (thanks to ductility). Such behavior is ideal for RE walls, which experience some tension in the backfill and slight movements; a ductile fill will redistribute stress and reduce the chance of any local failure affecting the structure.

Comparison to granular backfill: A key question is how the stabilized soil compares to the conventional granular backfill used in RE walls. Granular fills, typically sandy gravel, have high friction angles (30–40°), virtually no cohesion, are non-plastic, and have high permeability (~10^-3 to 10^-2 cm/s). The slag-fiber soil achieved a friction angle of ~33°, squarely within the range of good granular fills. Its permeability (~1×10^(-4) cm/s) is slightly lower than a pure gravel but still within acceptable limits for drainage, especially given the drainage layer and weeps provided. The one advantage of granular fill is its immediate strength (no curing needed), whereas our stabilized soil gained strength over a few days. However, by the time of wall construction (which took ~2 weeks for full height), the material had already attained most of its strength – in fact, construction staged curing in the field as lower layers cured while upper layers were placed. The cohesion of ~30+ kPa in the stabilized soil is a bonus that granular fill doesn't have (though in design one may ignore it). This apparent cohesion likely contributed to the very low lateral pressures observed (and low wall deflection). In terms of compaction, the stabilized soil had a slightly lower MDD than a typical crushed rock (which might be 2.0+ g/cc), but it still reached a dense state that, judging by field performance, was more than sufficient.

One area of concern in using fine-grained soils is creep or long-term consolidation. In this case, the slag stabilization and low plasticity essentially eliminated any secondary consolidation – the wall's settlement stabilized quickly, which is a behavior more akin to granular fills (which have most settlement during construction and little thereafter). The addition of fibers might also help resist long-term deformation by keeping the soil skeleton in place. So in function, the stabilized soil behaved nearly like a granular soil during the monitoring period.

Compliance with standards: It is important to note that the stabilized backfill meets the criteria set by relevant standards for reinforced soil structures. IRC SP:102-2014 (Guidelines for Design and Construction of RE Wall) allows use of alternative fills if they satisfy certain strength and durability criteria. Those criteria typically include: , UCS > 300 kPa (if cohesive binder is present), etc. Our mix ticked all these boxes – PI = 0%, ϕ ≈ 33°, k ≈ 1.2×10^{-4}, UCS = 440 kPa – thus qualifying as a suitable backfill per code. FHWA guidelines (NHI-07-092) primarily emphasize using free-draining granular fill but do provide provisions for alternate fills if justified by testing. The successful test results we obtained would form the basis of such justification. Essentially, performance-based design was applied: the material was engineered until it performed on par with conventional material. By demonstrating compliance in lab tests and in a field trial, the study provides confidence that engineering specifications can be updated to include stabilized marginal soils. This addresses a known gap in the geotechnical community, where sustainability pushes for reuse of local materials but design codes lag behind – our results contribute data to support bridging that gap.

Durability and longevity: One discussion point is the long-term durability of the stabilized backfill. Steel slag contains some free lime which can potentially cause expansive hydration or leachate over time. In our lab tests, the slag was aged and we did not observe any detrimental expansion; field observations likewise showed no signs of heave or efflorescence. The environment in the wall (compacted, relatively low moisture after initial pore water used up in reactions) is not conducive to late expansion. Moreover, slag has been used in road bases successfully, indicating that with aging and possibly carbonation, its long-term behavior is stable. The discrete fibers contributed little to initial strength but significantly to ductility and post-peak behavior [11]. They limit crack propagation under

UV light, but being buried, that’s not an issue. The PET fibers could experience some creep under constant load, but their strain contribution in a well-compacted fill under geogrid-confined conditions is minimal. If anything, the concern would be if the alkaline environment from slag could embrittle the plastic over decades – PET is generally resistant to moderate alkalinity, unlike say natural fibers which would rot. Therefore, we anticipate that the stabilized backfill will retain its improved properties over the design life of the structure. Ongoing monitoring beyond three months (which is short) would be valuable; however, given the trends (stabilization of settlements, no new deformation), it is likely the major changes have already occurred in early curing.

Field execution considerations: The field trial highlighted a few practical considerations. First, mixing large quantities of soil, slag, and fibers on-site requires planning – a mechanical mixer or rotary tiller attachment can greatly facilitate uniform blending, as manual shoveling is labor-intensive and may lead to non-uniformity for big volumes. Ensuring the correct moisture content at compaction is also crucial: because slag reactions consume water, the mix can dry out a bit over time; thus, constant monitoring and adjustment of moisture in the field is recommended to stay near OMC. Another point is quality assurance: since this is a non-standard material, more frequent testing (Proctor, CBR of field samples, etc.) during construction would be wise until the team is confident that the mix being produced matches the design specification. In our case, the field CBR tests on compacted samples taken from the site still showed >15% CBR, matching lab values, which was reassuring.

One interesting finding was the reduced compaction effort needed. This can be a significant cost saver – less fuel for rollers and faster progress. It appears that the slag’s weight and angularity allow it to “seat” into a dense configuration readily, and fibers possibly help by microscopically wedging particles (though fibers might also introduce some springiness, that didn’t seem to hinder achieving density). This effect was noted qualitatively by crew and quantitatively in completion time.

Comparison to other studies: [1] showed slag improved soft clay behavior. [2]. emphasized PET fiber's contribution to ductility. [3] validated 20% slag + 0.75% PET as optimal. [4], confirmed permeability enhancement via slag. [6], and [7]. documented strength and durability benefits of fiber-soil composites. Limitations: It should be acknowledged that this research focused on a specific soil type (sandy clay with low plasticity to begin with) and specific additive contents. Different soils (say, highly expansive clays or very silty sands) might respond differently to slag or fiber stabilization. Therefore, while the results are promising, one should be cautious in generalizing to all marginal soils. However, the methodology – lab optimizing followed by field trial – can be applied to any case. Another consideration is temperature and curing conditions; our curing was at ambient ~27°C. In colder climates, slag reactions slow down, so longer curing or slight cement addition might be needed.

Broader impacts: The success of using industrial and plastic waste in a critical infrastructure application like an RE wall is a step forward for sustainable engineering. Not only does it reduce waste, but it also reduces reliance on quarried aggregates (preserving natural resources). If widely adopted, this technique could reduce construction costs in areas with limited resources, making infrastructure projects more feasible in developing regions. Additionally, it turns a disposal problem (steel slag stockpiles and plastic waste) into a valuable resource [10]. Life-cycle assessment would likely show a reduction in carbon footprint for the wall construction, due to reduced material transport and cement usage. This aligns with global efforts to incorporate circular economy principles in construction.

In conclusion, the discussion reinforces that the slag+fiber stabilization strategy effectively transforms a marginal soil into a high-performance backfill material. The lab and field data collectively satisfy the requirements of design and practicality. With proper quality control, such materials can be confidently used in RE walls, marrying geotechnical innovation with sustainability. Future projects can build on this by experimenting with other waste additives (fly ash, polypropylene fibers, etc.) or by extending to other earth structures like embankments or slopes.

CONCLUSION

This study presented an extensive evaluation of a novel steel slag and plastic fiber stabilized soil as backfill material for reinforced earth walls. The main findings and conclusions are summarized as follows:

- *Stabilization efficacy*: Incorporating ~20% steel slag (industrial waste) and ~0.5–0.75% shredded PET fibers (plastic waste) into a local sandy clay soil dramatically improved its engineering properties. The soil's plasticity was effectively eliminated (Plasticity Index reduced to 0), its compaction characteristics enhanced (dry density increased ~8%, optimum moisture reduced ~3 percentage points), and its strength and stiffness significantly increased (28-day UCS from 160 kPa to >440 kPa; soaked CBR from 4% to ~16%). Shear strength parameters rose to $c \approx 30$–36 kPa and $\phi \approx 32$–$33°$, and permeability reached the order of 10^(-4) cm/s. These values indicate that the stabilized soil meets or exceeds typical requirements for RE wall backfill.
- *Optimal mix:* The optimal mix identified was around 20% steel slag + 0.75% PET fibers by weight, which provided the best balance of high strength, low plasticity, and adequate permeability. Adding slag beyond 20% yielded diminishing returns, and fiber content of 0.75% was sufficient to achieve marked ductility improvements without causing mixing or workability issues. This optimal mix (termed M4/M5 in the study) was used for the field construction.
- *Laboratory vs. Code criteria*: All major laboratory results for the optimal mix satisfied design criteria from standards (IRC and FHWA). The stabilized soil had friction angle >30°, PI = NP (<6%), permeability ~1×10^(-4) cm/s, and UCS > 300 kPa, thus qualifying as a backfill material per performance-based specifications.. The improvements observed are consistent with mechanisms of slag hydration (yielding cementation and reduced plasticity) and fiber reinforcement (yielding toughness and crack control), in line with findings of previous studies.
- *Field trial success:* A full-scale 6 m high RE wall section constructed with the stabilized backfill demonstrated excellent performance. The wall was stable under its self-weight and surcharge, showing very small settlements (~7 mm) and lateral deflections (~3 mm) over 3 months – essentially negligible movements, confirming the material's high stability. The reinforced fill interacted well with the geogrid reinforcement and precast facing, with no signs of distress or incompatibility. Importantly, no pore water pressure build-up was observed in the backfill during heavy rains, thanks to the material's improved drainage and the installed weep holes. This indicates the wall is safe against hydrostatic pressure.
- *Construction feasibility:* The stabilized soil was handled and compacted using conventional construction equipment. Field compaction achieved >95% of Proctor density uniformly in each lift without special effort. The presence of fibers required attention to mixing, but using a mechanical mixer ensured uniform distribution. The contractor reported fewer roller passes were needed compared to typical soil – an advantage in efficiency. The overall construction of the wall with the new material was about 20% faster and ~15% cheaper in terms of backfill cost than using imported granular fill, demonstrating economic benefits in addition to technical performance.
- *Sustainability benefits*: By utilizing ~18 tons of steel slag and ~0.2 tons of recycled plastic in the trial wall, the project diverted waste from landfills and reduced the need for virgin quarry materials. This not only provides a productive use for industrial and municipal waste, but also lowers the carbon footprint of the construction (less material transport and processing). The successful application in an RE wall opens the door for more sustainable practices in geotechnical construction, aligning with global sustainability goals.
- *Recommendations*: For practical implementation of this technique, it is recommended to conduct project-specific mix design (since local soil or slag properties may vary) and trial testing to fine-tune the slag and fiber contents. Quality control during construction is vital – ensure thorough mixing of stabilizers and maintain moisture near optimum. Aging or pre-treating steel slag to mitigate any excessive lime reactivity is advised (to prevent any potential expansion). Additionally, it is prudent to monitor the field performance of such structures over a longer term (12+ months) to confirm long-term behavior, though the short-term results are promising.

In conclusion, the research confirms that marginal soils can be effectively upgraded through steel slag and waste fiber stabilization to serve as reliable backfill in reinforced earth walls. The approach provides a viable solution in areas where traditional fill is scarce, yielding a material that is strong, stiff, free-draining, and cost-effective. The field demonstration has bridged the gap between laboratory development and real-world application, showing that with appropriate design and construction measures, unconventional materials can meet the rigorous demands of geotechnical infrastructure. This study's outcomes encourage broader adoption of sustainable backfill materials in reinforced soil structures, and it contributes valuable data to guide future standards and projects in incorporating industrial waste for civil engineering benefit.

Declaration of Interest

There is no conflict of interest regarding the publication of this article.

Acknowledgement

The acknowledgements come at the end of an article after the conclusions and before the notes and references.

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