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Farklı Katılım Oranları ve En Boy Oranları ile Çimento Kaplanmış Tekstil Atığı (CCTW) Kullanılarak Karayolu Alt Taban Zemini Mukavemetinin Artırılması

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ÖZ

Zemin stabilizasyonu, özellikle zayıf zeminlerin taşıma kapasitesini artırmada, geoteknik ve ulaştırma mühendisliğinin kritik bir yönüdür. Geri dönüştürülmüş malzemeler kullanılarak yapılan sürdürülebilir güçlendirme yöntemleri, ekonomik ve çevresel faydaları nedeniyle ilgi görmektedir. Bu çalışma, çimento kaplı tekstil atıklarının (CCTW) Kaliforniya Taşıma Oranı (CBR) testi aracılığıyla kötü derecelenmiş kumun dayanımını artırmadaki etkinliğini araştırmaktadır. Çalışmanın temel amacı, CCTW'nin farklı en/boy oranlarında (AR1, AR2, AR4) ve katılım oranlarında (kuru ağırlıkça %2, %4 ve %6) zemin dayanımı üzerindeki etkisini değerlendirmektir. CCTW, tekstil atıklarının Portland çimento hamuru ile kaplanıp 28 gün kürlenmesi ve ardından belirlenen oranlarda zemin ile karıştırılmasıyla hazırlanmıştır. Sonuçlar, tüm güçlendirilmiş numunelerin CBR değerlerinde, güçlendirilmemiş zemine kıyasla önemli bir artış olduğunu göstermektedir. En iyi iyileşme, AR2 ve AR4 liflerinin en yüksek güçlendirme etkisini sağladığı %4 katılım oranında gözlemlenmiş olup, CBR değerleri sırasıyla %6.97 ve %6.87'ye ulaşmıştır. Ancak %4'ün üzerindeki aşırı katılım oranı, zemin performansında düşüşe yol açmıştır. İyileştirme faktörü analizi de güçlendirmenin etkinliğini doğrulamış olup, AR4-%4 ve AR2-%4 en yüksek kazançları sağlamıştır. Bu çalışma, CCTW'nin çevre dostu bir zemin stabilizatörü olarak potansiyelini vurgulayarak sürdürülebilir atık yönetimi ve maliyet etkin mühendislik çözümlerine katkı sağlamaktadır. Bulgular, maksimum zemin güçlendirme faydalarını sağlamak için optimal lif dozajının ve geometrik özelliklerin kritik öneme sahip olduğunu göstererek önemli çevresel, ekonomik ve mühendislik avantajları sunmaktadır.

Enhancement of Highway Subgrade Soil Strength Using Cement-Coated Textile Waste (CCTW) with Varying Inclusion Rates and Aspect Ratios

Research Article

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ABSTRACT

Soil stabilization is a critical aspect of geotechnical and transportation engineering, particularly in enhancing the load-bearing capacity of weak subgrade soils. Sustainable reinforcement methods using recycled materials have gained attention due to their economic and environmental benefits. This study investigates the effectiveness of cement-coated textile waste (CCTW) in improving the strength of poorly graded sand via California Bearing Ratio (CBR) testing. The main objective of this study is to evaluate the impact of incorporating CCTW at varying aspect ratios (AR1, AR2, AR4) and inclusion rates (2%, 4%, and 6% by dry weight) on soil strength. CCTW was prepared by coating textile waste with Portland cement paste, curing for 28 days, and then mixing with the soil at designated ratios. The results indicate a significant enhancement in the CBR values of all reinforced specimens compared to unreinforced soil. The optimal improvement was observed at a 4% inclusion rate, where AR2 and AR4 fibers provided the highest reinforcement effect, with CBR values reaching up to 6.97% and 6.87%, respectively. However, beyond 4%, excessive inclusion rate led to a decline in soil performance. The improvement factor analysis further confirmed the efficiency of reinforcement, with AR4-4% and AR2-4% yielding the highest gains. This study highlights the potential of CCTW as an eco-friendly soil stabilizer, promoting sustainable waste management and cost-effective engineering solutions. The findings suggest that optimal fiber dosage and geometric properties are crucial in maximizing soil reinforcement benefits, offering significant environmental, economic, and engineering advantages.

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1. Introduction

Textile and apparel products are fundamental necessities for humans, with the global textile industry playing a crucial role in ensuring consumer comfort since its inception. However, due to the accelerated expansion and transformation of fashion trends over the past century, the rates of textile manufacturing and waste accumulation have significantly escalated (Uddin, 2019; Ruuth et al., 2022). The waste generated throughout the energy-intensive manufacturing processes of new garments primarily consists of fibrous residues and discharged chemical compounds. These solid fibrous materials comprise a mixture of natural and synthetic polymer-based substances, including cotton, polypropylene, nylon, polyester, and various others (Rahman et al., 2022). The escalating environmental challenges arising from the excessive accumulation of non-biodegradable textile waste, coupled with the diminishing availability of landfill space, have necessitated a shift toward sustainable practices within the textile and fashion industries. In response, these sectors are increasingly adopting and implementing eco-conscious strategies at every stage of a product's lifecycle, including raw material selection, manufacturing processes, consumer usage, and end-of-life disposal (Haawley, 2009). These efforts aim to mitigate environmental impact, promote circular economy principles, and enhance resource efficiency in the long run.

The improper disposal of hazardous textile waste into municipal landfills is primarily driven by economic constraints and a general lack of public awareness regarding its detrimental environmental consequences. This uncontrolled accumulation of textile waste poses significant sustainability challenges, necessitating developing and implementing innovative solutions that integrate environmental responsibility, economic feasibility, and material performance optimization. Sustainable strategies must be explored across various sectors to mitigate the negative impact of excessive waste generation from the rapidly expanding textile industry.

In the field of civil engineering, particularly within the domains of transportation and geotechnical engineering, various soil and pavement improvement techniques have been widely adopted to enhance the performance and durability of infrastructure systems. Among these techniques, the incorporation of materials such as geosynthetics (Kaplan et al., 2022; Kayadelen et al., 2023; Önal et al., 2023; Öztürk et al., 2023; Öztürk et al., 2024; Öztürk, 2024), fibers (Serin et al., 2023a), as well as recycled and industrial waste products (Bora et al., 2022; Önal et al., 2022; Serin et al., 2023b; Öztürk, 2024), has proven effective in addressing critical challenges. These methods are commonly employed to improve the structural stability and crack resistance of asphalt concrete layers, as well as to enhance the static and cyclic behavior of subgrade, subbase, and base layers used in highway construction. Furthermore, such reinforcement strategies contribute to the improvement of shear strength, bearing capacity, and overall mechanical properties of different soil types, offering sustainable and cost-efficient solutions for modern infrastructure development.

In geotechnical engineering, textile waste has shown potential for diverse applications that contribute to both waste reduction and infrastructure enhancement. Notable utilization areas include improving the strength and load-bearing capacity of subgrade soils (Abbaspour et al., 2019; Fareghian et al., 2023), stabilizing rammed earth structures and engineered slopes (Abbaspour et al., 2019; Zare et al., 2020; Nouri et al., 2023), and enhancing the physical and mechanical properties of engineered backfill materials (Rahman et al., 2022). By repurposing textile waste in these applications, it is possible to reduce environmental pollution, lower raw material consumption, and promote circular economic principles within the construction and engineering industries.

Numerous studies in the literature investigate the impact of incorporating waste materials on the California Bearing Ratio (CBR) values and shear characteristics of soils exploring the potential benefits of various waste by-products for soil stabilization and strength enhancement (Miraftab and Lickfold, 2008; Abbaspour et al., 2019; Habibi et al., 2021; Önal et al., 2022). Habibi et al. (2022) have demonstrated the effectiveness of waste tire textile fibres (WTTFs) and lime in enhancing the mechanical properties of low-plasticity clays. Experimental results indicated that the inclusion of 1.5% WTTFs improves soil strength parameters, while lime stabilization enhances cohesion and internal friction angle. The combined addition of 1.5% fibres and 6% lime significantly increased unconfined compressive strength (UCS) by up to 10.66 times and California bearing ratio (CBR) by more than 100%. Furthermore, fibre reinforcement mitigated the brittleness induced by lime treatment, improving soil ductility and durability. These findings highlight the potential of WTTFs and lime as an effective soil stabilization technique for geotechnical applications. Abbaspour et al. (2019) have investigated the reuse of WTTFs as a soil reinforcement material through a series of laboratory tests, including compaction, direct shear, UCS, CBR, and split tensile strength (STS) tests. Experimental results indicated that WTTFs effectively enhance the strength and ductility of sandy soils, while in clayey soils, they primarily improve ductility and tensile strength despite reductions in UCS and CBR. The distinct behavior of WTTFs in different soil types has been further analyzed using an optical microscope. These findings suggest that rather than being discarded, WTTFs can be effectively repurposed to enhance the mechanical properties of various soils, offering a sustainable solution for soil stabilization. Ghiassian et al. (2004) were investigated the reuse of fibrous carpet waste as a sustainable material for soil reinforcement through drained triaxial tests on compacted silty sand specimens. Key parameters, including the aspect ratio and weight percentage of fibrous strips, were examined to assess their influence on shear strength. The findings demonstrate that fibrous inclusions derived from carpet waste significantly enhance the shear strength of silty sands. Furthermore, a predictive model accurately simulated the effects of strip content, aspect ratio, and confining pressure on reinforced sand, highlighting the potential of carpet waste fibres in geotechnical applications. In their study, Miraftab and Lickfold (2008) investigated incorporating carpet fibrous waste into clayey and substandard soils to improve their mechanical properties by conducting triaxial compression tests. They concluded that up to 10% fibre inclusion enhances internal cohesion, shear strength, compressive strength, and load-bearing capacity, with soil moisture content playing a crucial role in optimizing these improvements.

Numerous studies in literature have investigated the treatment of soil reinforcement materials with cement to enhance their load-bearing performance (Ouria and Mahmoudi, 2018; Öztürk et al., 2023; Öztürk et al., 2024). In their study, Öztürk et al. (2023) conducted an experimental study to investigate using cement-coated geotextile as soil reinforcement material via CBR tests. They also utilized conventional geotextile to compare the performance of cement-coated geotextile on the CBR values. The inclusion of geotextile and cement-coated geotextile as reinforcement in sand soil resulted in CBR enhancements of 1.68 and 3.25 times, respectively. While the geotextile-reinforced base material exhibited a 4% reduction in CBR, the cement-coated geotextile reinforcement led to a significant 59% increase in CBR performance. Ouria and Mahmoudi (2018) investigated both experimental and numerical analyses of cement treatment at the geotextile-sand interface and its impact on the bearing capacity of foundations on reinforced sand. Laboratory findings revealed that cement treatment enhances bearing capacity by 6%–17%, depending on the reinforcement length.

In this study, the influence of cement-coated textile waste (CCTW) on improving the strength of poorly graded sand is evaluated through California Bearing Ratio (CBR) testing. To analyze the effects of aspect ratios and inclusion rates of CCTWs on load-bearing capacity, a total of ten CBR tests were performed. The results of this study underscore the potential of CCTW as an effective and sustainable reinforcement material for use in geotechnical engineering applications.

2. Materials and Method

2.1. Sand Soil

The soil used in this study is classified as SP (poorly graded sand) according to the Unified Soil Classification System (USCS), as described in ASTM D2487 (2006). A poorly graded sand, selected intentionally to represent a conservative soil condition that is often encountered in arid and semi-arid regions. This type of soil is characterized by low cohesion and high permeability, which can lead to reduced load-bearing capacity and increased deformation under loading. These properties make it particularly suitable for evaluating the effectiveness of soil reinforcement techniques. Additionally, the uniformity of particle size distribution in poorly graded sand allows for more controlled and repeatable testing conditions, thereby enhancing the reliability of the comparative analysis between reinforced and unreinforced samples. The sand samples were prepared under controlled laboratory conditions to ensure homogeneity. The samples were air-dried and sieved through a series of standard sieves to obtain the required grain size distribution as specified in ASTM D6913 (2006). The grain size distribution of the sand was determined through sieve analysis. The resulting data were plotted to produce the grain size distribution curve, as shown in **Figure 1**. Basic physical properties of the sand, such as the specific gravity, maximum and minimum dry densities respectively were measured and recorded in **Table 1**.

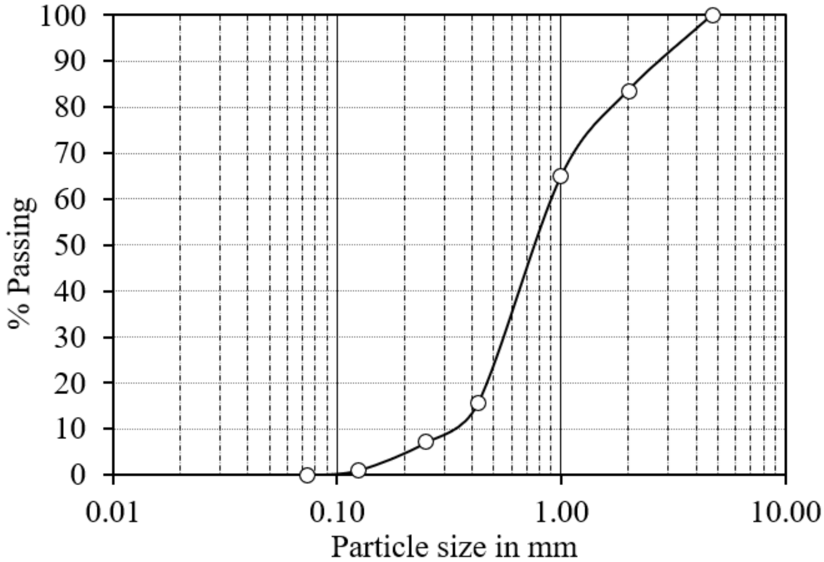

Figure 1. The soil's particle size distribution curve

Table 1. Main properties of the soil

Properties	Value
Specific gravity	2.73
D_{10} (mm)	0.35
D_{30} (mm)	0.55
D_{60} (mm)	0.90
Coefficient of uniformity, C_u	2.57
Coefficient of curvature, C_c	0.96
Minimum dry density (kN/m^3)	15.24
Maximum dry density (kN/m^3)	17.69
Maximum void ratio, e_{max}	0.757
Minimum void ratio, e_{min}	0.514

2.1. Cement-Coated Textile Waste

The waste textiles used in this study were sourced from a local tailor shop and primarily consisted of cotton and polyester blends, which are typical of off-cuts and remnants generated during garment manufacturing. These textiles were clean and free of contaminants, such as adhesives or finishes, which could interfere with the cement coating or soil interaction.

The waste textiles were cut into three different dimensions to achieve varying aspect ratios: 12 × 12 mm (Aspect Ratio 1; AR1), 12 × 24 mm (Aspect Ratio 2; AR2), and 6 × 24 mm (Aspect Ratio 4; AR4). These dimensions were selected to explore the influence of aspect ratio on reinforcement efficiency guided by findings from previous studies (Pinho-Loopes, 2022). The textiles were coated with Portland cement paste prepared with a water-to-cement ratio of 0.5. Prior to coating, the textile pieces were lightly moistened to enhance adhesion with the cement matrix. The coated textiles were allowed to dry under laboratory conditions for 1 day to ensure initial cement setting. The dried, coated textiles were then submerged in a standard curing tank and left to cure for 28 days to achieve proper cement hydration. At the end of the curing process, the cement-coated textile waste (CCTW) was ready for incorporation into the sand matrix for further testing. The final thickness of the CCTW after curing was approximately 2.5 mm, and their surface exhibited a rough, textured finish due to the cement layer, which may enhance mechanical interlocking with surrounding soil particles. The prepared CCTW are illustrated in Figure 2.

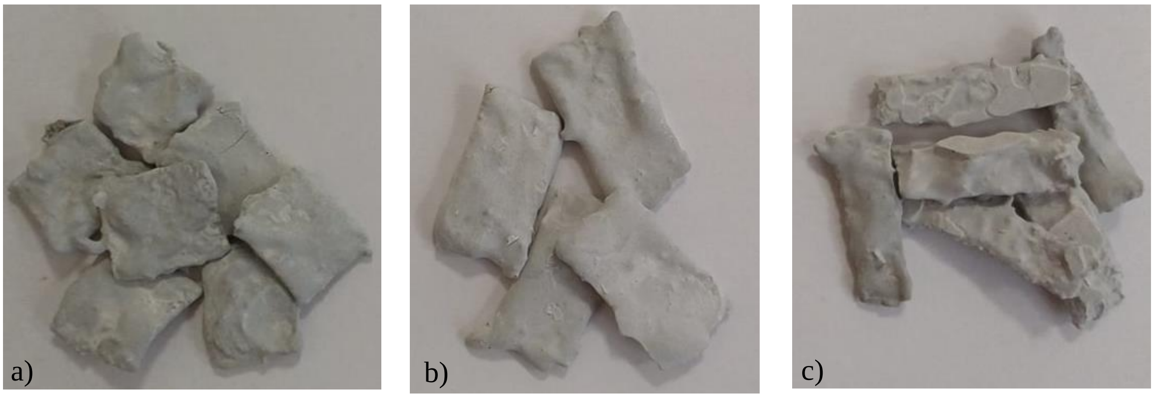

Figure 2. Cement coated waste textiles a) AR1 b) AR2 c) AR4

CBR tests were conducted on a dense sand subgrade material, which was prepared at a relative density of 90% to represent field compaction conditions typically encountered in practice. This density level was achieved through a standardized compaction procedure to ensure uniformity and repeatability across all samples. To compare the effects of reinforcement, an unreinforced California Bearing Ratio (CBR) test was initially conducted as a control. For the reinforced tests, the soil reinforcement was applied only to the upper H/3 depth of the CBR mold. The CBR test setup is illustrated in Figure 3 to provide visual confirmation of the experimental configuration and procedures. CCTW were incorporated into the soil at varying percentages of 2%, 4%, and 6% by weight. All tests were conducted in accordance with ASTM D1883 (2016) to ensure consistency and reliability of the results. For comparison purposes, the unreinforced soil was labeled as UR, while the soil reinforced with Aspect Ratio 1 (AR1) textiles at a 2% inclusion ratio was labeled as AR1-2%.

Figure 3. CBR test setup

3. Results and Discussion

Figure 4 illustrates the load-displacement behavior of both unreinforced and cement-coated textile waste (CCTW)-reinforced CBR specimens under the same waste inclusion rates. The results clearly demonstrate a substantial improvement in the load-bearing capacity of reinforced soils compared to unreinforced specimen, regardless of the variation in waste content. This improvement highlights the potential of CCTW as an effective soil stabilizer, provided that the appropriate waste type and dosage are selected. Reinforced soils exhibit similar behavior in terms of load-displacement behavior. According to Figure 4a, the trends of the reinforced soils are almost identical. The better load-displacement behavior of the reinforced soil is due to the stress distribution of the CCTW to the underlying soil and the compaction and strengthening of the underlying soil. Compared to the unreinforced soil, the reinforced soil suffered a sudden loss of load bearing capacity after about 6 mm of deformation. This is due to the failure of the compressed soil under CCTW. Additionally, although CBR values are conventionally determined at 2.5 mm and 5.0 mm penetrations, in this study, the tests were extended to a penetration depth of 8.0 mm. This extension was intended to observe the post-peak behavior of the reinforced and unreinforced samples. It also enabled a better comparison of the residual strength performance beyond the conventional limits, thereby offering deeper insights into the deformation resistance of each configuration.

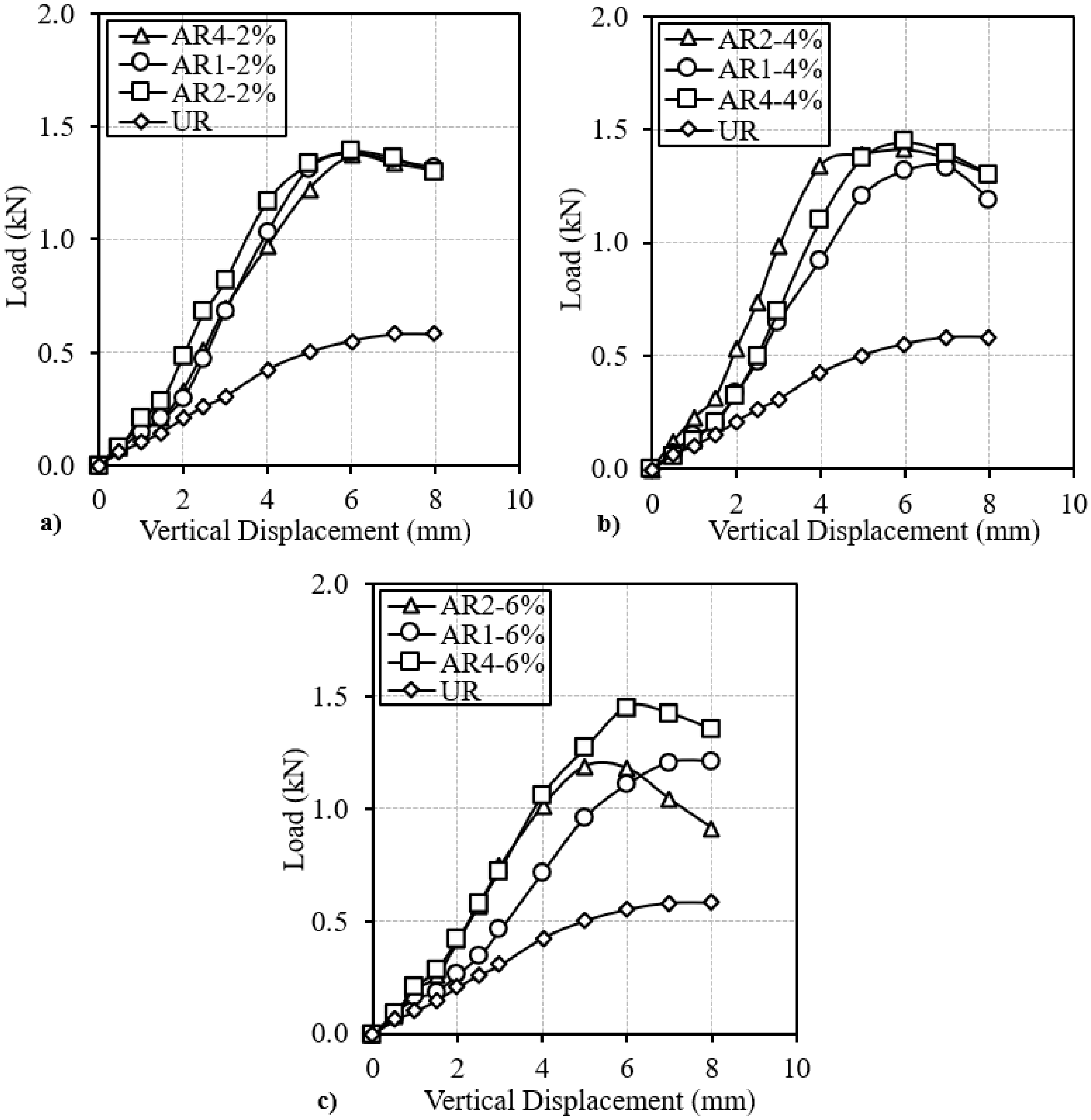

Figure 4. Load-displacement curves of UR and CCTW-reinforced CBR specimens at a) 2% b) 4% c) 6% waste rate

Figure 5 illustrates the load-displacement behavior of both unreinforced and CCTW-reinforced CBR specimens under varying waste inclusion rates. From Figure 5a and Figure 5b, it can be inferred that the inclusion of CCTW at 2% and 4% waste rates for AR1 and AR2 resulted in similar load-displacement behavior. However, it can be said that the inclusion of CCTW at a 6% waste rate led to a deterioration in load-displacement performance. In contrast, Figure 2c shows that varying the waste rate for AR4 had less impact on the load-displacement behavior compared to AR1 and AR2, with similar load-displacement behavior observed.

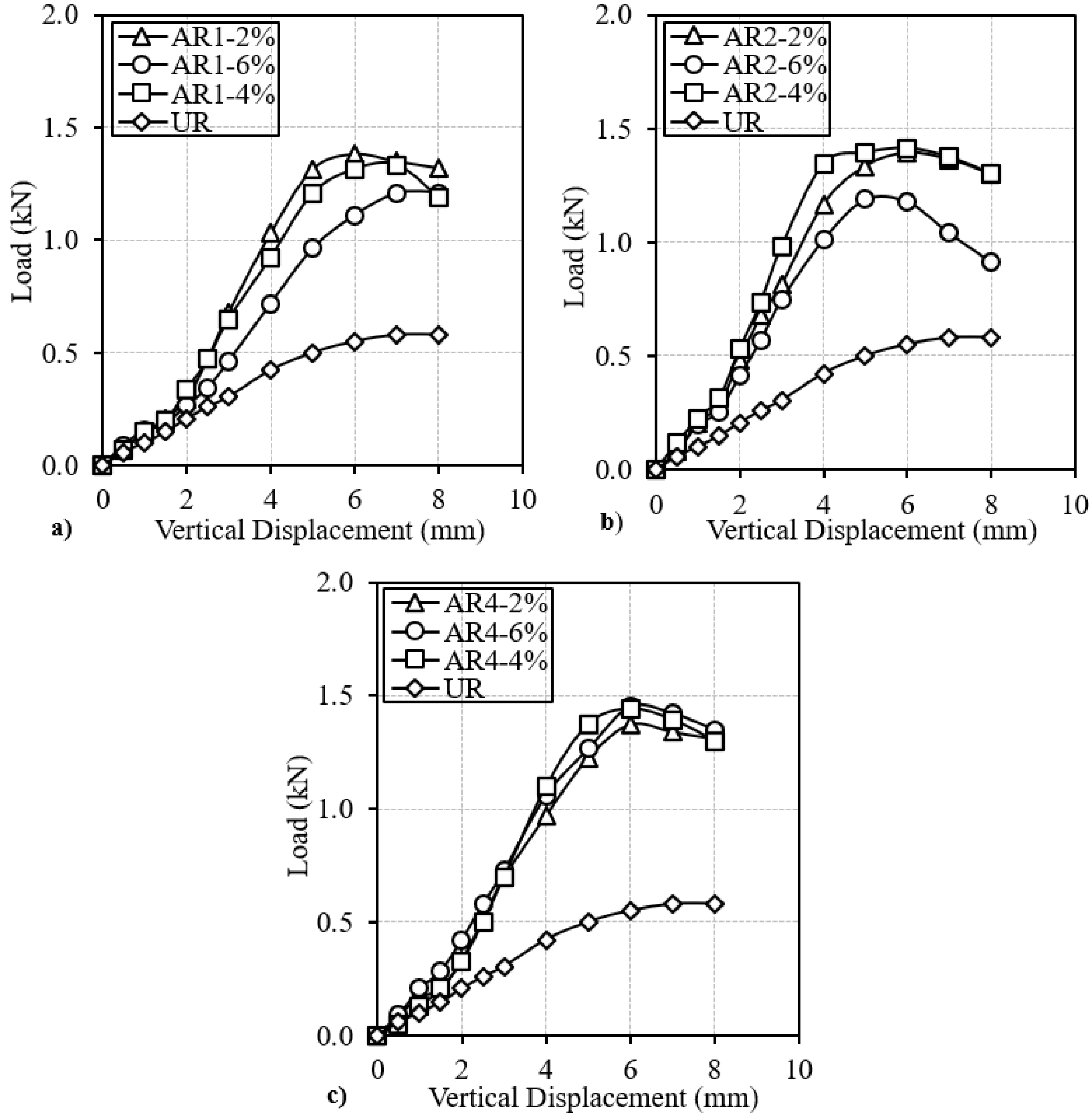

Figure 5. Load-displacement curves of UR and CCTW-reinforced a) AR1 b) AR2 c) AR-4 CBR specimens

Figure 6 presents the corresponding changes in CBR values. When AR2 was incorporated at a 2% waste rate, the CBR value was measured at 6.67%, demonstrating an initial improvement in load-bearing capacity compared to unreinforced soil, which had a CBR value of 2.50%. As the waste rate increased to 4%, a further enhancement in soil strength was observed, with the CBR value reaching its peak at 6.97%. This suggests that at moderate fiber inclusion levels, AR2 fibers effectively contribute to soil stabilization by improving inter-particle bonding and increasing resistance to deformation under loading conditions. However, beyond the 4% waste content, the reinforcing efficiency of AR2 fibers exhibited a declining trend. At a 6% waste rate, the CBR value decreased to 5.94%, indicating that excessive fiber content may negatively affect soil performance. A similar behavior was obtained when AR4 was used as fiber. When AR1 fibers were used as reinforcement, the highest CBR value was recorded as 6.57% at a waste inclusion rate of 2%, indicating an initial improvement in the soil's load-bearing capacity.

However, as the waste rate increased to 4%, a decline in CBR performance was observed, with the value decreasing to 6.03%. This downward trend became more pronounced at a 6% waste rate, where the CBR value further dropped to 4.81%.

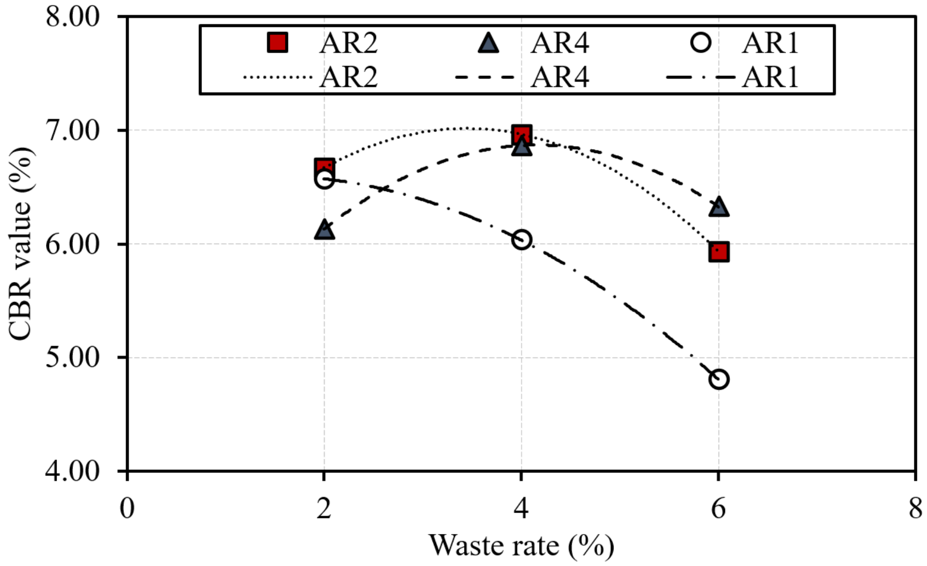

Figure 6. CBR values for all waste types with varying waste rates

At a waste rate of 2%, the highest CBR value was recorded as 6.67% when AR2 was used, indicating its superior reinforcing capability at this specific dosage. A similar result was obtained with AR1, where the CBR value was measured as 6.57%. However, when AR4 was employed at the same waste content, a reduction in CBR performance was observed, with the value dropping to 6.13%. This suggests that the effectiveness of reinforcement is highly dependent on the aspect ratio and fiber distribution within the soil matrix. Fibers with certain geometrical properties may contribute more effectively to interlocking mechanisms and load transfer, while others may create discontinuities or excessive voids, leading to performance reductions. At a waste rate of 4%, the trend remained consistent, with AR2 yielding the highest CBR value of 6.97%. Interestingly, AR4, which had shown a lower CBR at the 4% waste rate, exhibited a significant increase in effectiveness at this higher waste inclusion rate, achieving a CBR value of 6.87%. In contrast, AR1 demonstrated the lowest CBR value of 6.03% at this waste content. These variations indicate that an optimal balance between fiber dosage and geometric characteristics is crucial to maximizing soil reinforcement benefits. The improved performance of AR4 at 4% suggests that, while it may be less effective at lower dosages, its reinforcing ability becomes more pronounced as the fiber content increases, possibly due to enhanced inter-fiber bonding and particle confinement. At the highest waste rate of 6%, the results exhibited a different trend. The maximum CBR value was observed when AR4 was used, reaching 6.33%, followed by AR2, which provided a slightly lower CBR of 5.94%. However, a substantial reduction in reinforcement efficiency was noted when AR1 was used, with the lowest CBR value dropping to 4.81%. This finding suggests that beyond a certain threshold, excessive waste inclusion may lead to diminishing returns, possibly due to fiber clustering, increased void formation, or inadequate particle interlock. Such effects could compromise the overall integrity of the soil structure, reducing its capacity to sustain higher loads. The reduction in CBR with increasing fiber content suggests that while AR1 fibers provide reinforcement at lower inclusion rates, excessive fiber addition may lead to adverse effects on soil performance.

Figure 7 illustrates the improvement factor in CBR values for different reinforcement types and percentages. Improvement factor can be expressed as the CBR value of reinforced soil to that of the unreinforced soil. All reinforcement types significantly enhance the CBR value, with improvement factors consistently exceeding 1.5. The highest improvement factors are observed for AR4-4% and AR2-4%, both exceeding 2.5. AR1-6% shows the lowest improvement factor among the tested configurations, yet it remains above 1.5. A general trend suggests that reinforcement at 4% concentration AR4, AR2, and AR1 yields a higher CBR enhancement compared to 2% or 6% concentrations. The variation in improvement factors of all reinforcement types suggests that these reinforcements play a role in CBR enhancement.

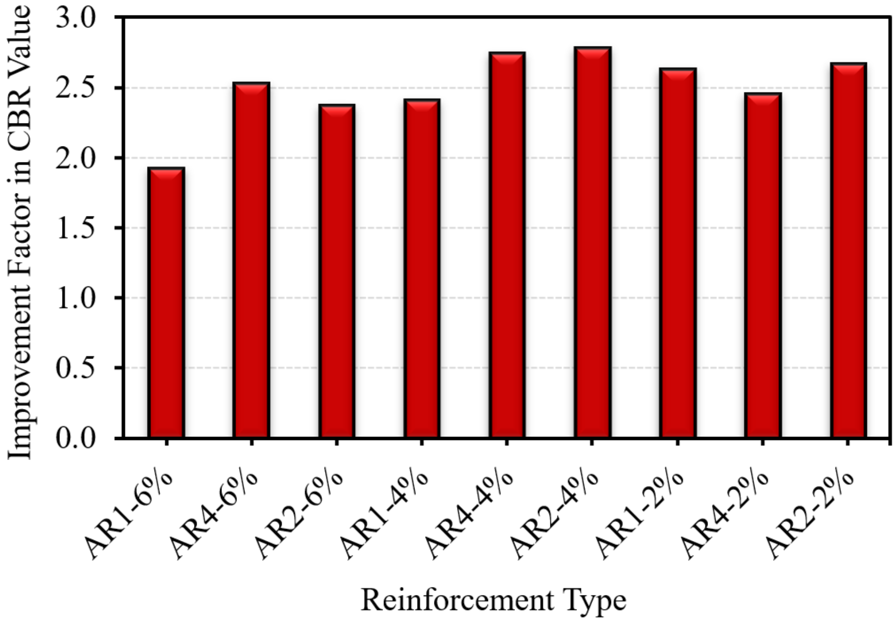

Figure 7. Improvement Factor in CBR Value for all waste types with varying waste rates

4. Limitations and Recommendations

This study was limited to experimental evaluations using California Bearing Ratio (CBR) tests conducted on dry, non-cohesive, poorly graded sand. Due to the cohesionless nature of the soil, unconfined compressive strength (UCS) testing was not applicable, as the specimens could not maintain their shape without confinement. Therefore, UCS tests were not included in this study. Additionally, the tests were performed under dry conditions, and the influence of moisture content and the associated compaction characteristics (e.g., dry density vs. water content relationship) were not investigated. These factors may significantly influence the mechanical performance of soil-reinforcement mixtures and should be explored in future research.

Furthermore, the anisotropic nature of CCTW-reinforced soils, especially due to varying aspect ratios, was not examined in this study. Anisotropy effects are expected to influence the mechanical response of the reinforced soil and warrant separate experimental analysis in future studies.

To broaden the understanding of CCTW's reinforcing potential, it is recommended that future work investigate the behavior of CCTW in cohesive soils such as clays, where UCS testing is applicable, and explore the impact of different moisture contents on compaction and strength behavior.

4. Conclusions

This study examines the effectiveness of cement-coated textile waste (CCTW) in enhancing the mechanical properties of poorly graded sand, with a particular focus on its influence on strength improvement. The evaluation was carried out using California Bearing Ratio (CBR) tests to quantify the impact of CCTW inclusion. Additionally, to better understand how different aspect ratios and inclusion rates of CCTWs affect the load-bearing capacity of the sand, a series of ten CBR tests were systematically conducted. The findings aim to provide insights into the potential use of CCTW as a sustainable reinforcement material in geotechnical applications.

- The inclusion of CCTW significantly enhanced CBR values of unreinforced condition (2.50%), with the highest performance observed at a 4% waste content for AR2 (6.97%) and AR4 (6.87%), while AR1 achieved its peak value of 6.57% at a 2% waste content.
- At a 6% waste content, excessive fiber inclusion resulted in diminishing returns, leading to fiber clustering, increased void formation, and a decline in soil integrity, as evidenced by the reduction in CBR value for AR1 to 4.81%.
- The incorporation of CCTW has led to significant improvements in CBR values. When expressed as improvement factors, the maximum enhancements are observed to be 2.78 and 2.75 for AR2 and AR4, respectively, at a 4% waste inclusion rate, while AR1 at a 2% waste inclusion rate shows an improvement factor of 2.63.
- The improvement factor analysis confirmed that a moderate reinforcement level of 4% provides the most effective and stable soil performance.
- CCTW offers a sustainable, cost-effective, and environmentally friendly alternative for soil stabilization and waste management. This method supports circular economy initiatives by repurposing textile waste in geotechnical applications.
- Future studies should explore the long-term durability, large-scale field applications, and varying curing conditions to further validate CCTW's geotechnical performance.

Conflict of interest

The authors declare that there is no conflict of interest.

Summary of Researchers' Contribution Rate Declaration

The authors declare that they have contributed equally to the article.

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