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Shear Performance of Recycled Pavement Materials Reinforced with Geogrids : A Comprehensive Review

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ABSTRACT

Reuse of recycled asphalt pavement (RAP) has generated immense interest in pavement design because it stands out in terms of performance, economy, and the environment when compared to virgin aggregate. RAP is an eco-friendly alternative to natural aggregates, as about 97 percent of the material is recycled to form new pavement, and the remaining portion is used as foundation course material for the construction of roads. Researchers have looked at RAP's mechanical characteristics, including its stiffness, resilience modulus, and deformation behavior, in great detail. Its behavior in unbound layers is not always the same. Even though RAP has a lot of material and causes more permanent deformation, the research suggests that RAP-VA blends may have the same or even higher modulus and stability. RAP is useful right away, but it has also been shown to improve the performance and stability of subgrade and subbase courses in soils. Geogrids and other geosynthetics are two of the most significant components that improve the mechanical properties of RAP and other recycled materials. Geogrids promote load distribution, bearing capacity, and stiffness while decreasing rutting and settling via interlocking, shear transfer, and the tensioned membrane effect. They are mostly used to build tunnels, keep railways stable, make retaining walls, and make pavements. MSE walls are considered to be cost-effective, long-lasting, and a substitute for retaining walls and embankments. Some researchers have demonstrated improved interface shear strength and long-term performance in geogrid-RAP interaction. In this regard, geosynthetics and RAP are viable alternatives and offer a sustainable solution for new highway construction in a way that reduces raw material requirements and pavement infrastructure strength and durability.

1. Introduction

Reclaimed asphalt pavement (RAP) exceeds virgin aggregates and provides economic and environmental advantages when used to build pavements [1]. Pavement replacement accounts for over 97% of RAP waste, with base course material accounting for the remaining 3%. Using RAP as a base course material on unpaved roads could decrease the workload on civil engineers caused by the excessive usage of virgin aggregates or natural aggregates.

Reusing reclaimed asphalt pavement (RAP) has been shown to be an environmentally responsible, energy-efficient, and sustainable alternative. This review provides a comprehensive overview of RAP and its use as a base course material in unpaved or paved roads, and also explores the influence of RAP as a sustainable solution. In addition, this research introduces the effect of using geosynthetic materials with RAP in pavement layers. Moreover, an overview of mechanically stabilized earth (MSE) uses in many applications, especially in embankment or retaining walls in highways, and a review of

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the interface shear strength parameter between geogrid, RAP, and MSE.

2. Recycled Materials in Pavement Engineering

There are financial and ecological advantages to using recycled materials in engineering. Costly and possibly toxic to air and groundwater, these materials are best disposed of in landfills [2]. In civil engineering, reused materials such as bottom and fly ash, RAS, foundry sand, and recycled concrete aggregate are often employed.

When it involves concrete pavements, RAP is a significant potential resource. Road aggregates and reclaimed pavement materials (RAP) ultimately compose roads. The collected RAP is used in a variety of repair and rebuilding operations after the milling or removal of old asphalt pavement [3]. When asphalt pavements are removed for reasons such as repair, resurfacing, or rebuilding, or to get access to underground utilities, these materials are produced [4]. Concrete mixtures have made employing RAP in a variety of fractional forms, including coarse, fine, and blended fractions. Highway building materials have disposal issues; using RAP helps reduce these [5]. When compared to virgin materials, RAP is more cost-effective and helps preserve the environment, according to sustainable development techniques [6]. Roller compacted concrete pavements (RCCP), pervious concrete pavements (PCP), cement mortar, precast concrete paver blocks (PCPB), and self-consolidating concrete (SCC) are all possible applications for the various RAP fractions [7].

2.1 Mechanical Properties of RAP

In order to define RAP aggregates, mechanical processes such as grinding, heating, ultrasonic cleaning, oxidation of asphalt, densification of ITZ, and acid pre-soaking are executed. In order to substitute the natural coarse aggregate in dry thin concrete foundation, Singh et al. [8] categorized RAP aggregates into dirty reclaimed asphalt pavement (DRAP) and washed reclaimed pavement (WRAP).

Likewise, the presence of an asphalt film over the RAP aggregate was exploited by Singh et al. [9] to classify the RAP aggregates into DRAP, WRAP, and AB&AT-treated RAP. The various RAP aggregates were sorted by Guduru and Kuna [10] based on experimental index criteria for cohesion tests and fragmentation tests.

The variation of the geometric distinctive index in the mechanical performance of the concrete pavements was applied to sort the matured RAP materials based on angularity, sphericity, and texture attributes [11].

The majority of researchers used RAP as a reference material and conducted MR tests. There were studies that showed that 100% RAP samples showed greater MR than a natural aggregate; examples include Bennert et al. [12] and Song et al. [13], both of which drew this conclusion. McGarrah [14] concluded that virgin aggregates showed greater bearing capacity than those with 100% RAP. Last but not least, there is further research that has established that base and subbase courses comprising unbound base containing a given percentage of RAP materials are sustainable and a viable substitute for 100% virgin aggregate mixes of equivalent or greater MR and stiffness [15-17]. RAP aggregates gained less stress compared to normal limestone aggregates [17].

MR values for four different types of RAP and three different types of RAP-VA mixes were higher than VA alone, even under the same loading conditions, a study conducted by [18].

As far as deformation properties of RAP are concerned, there are reports that have indicated specimens containing RAP exhibit more permanent deformation when compared to naturally occurring aggregates [19,20].

Arshad and Ahmed [21] also reinforced the findings by concluding there was no notable rise in residual cumulative strain for 0% to 50% concentration of RAP. However, when the residual cumulative stresses of the strong modulus test were brought into perspective with new granular samples, it became evident that at 75% RAP concentrations, there was a significant increase.

Ullah et al.[22] also illustrated that other variables had an impact on the performance of the material and that the inclusion of RAP in VA tended to increase permanent deformation overall. In this instance, the binder content of RAP did show that portions of the mixtures performed as well as VA alone, even though the amount of RAP in the VA mix remained unchanged. Ullah and Tanyu [23] examined what happened when the RAP-VA mixes were exposed to increases in moisture content of 2% and 4% over OMC, respectively. The results showed that the RAP-VA mixes outperformed the VA group according to how well they drained excess moisture. For determining proper thresholds for RAP-VA blends, Ullah et al. [22] examined how different particle size distributions impacted the permanent deformations of the blends. Researchers found that VA with supplementary RAP needed strain reduction levels similar to 100% VA samples. Based on recent research by Al-Shujairi et. al. [24], RAP percentages suitable to be used in base and subbase courses of highway construction vary between 10% and 50%.

While RAP integration in unbound layers of pavement has been the point of study for many years, the results appear to be contradictory worldwide. When it comes to permanent deformation, some writers speculate that permanent strains developed by RAP-VA mixtures have implications if considered in comparison to those developed by VA alone [20,22], but others are opposed to the above results. The dispute implies a necessity for additional research. The present study thus investigates RAP as an unbound material, employing a laboratory setting to evaluate the physical and mechanical characteristics of RAP and VA mixes, with the aim of determining the ideal quantity of materials within the mix. Tests performed are adhering to regular protocols in VA material testing.

2.2 Benefits of Using RAP in Pavement Layers

Compared to nature-derived materials, RAP aggregates are associated with environmental and economic advantages. Savings can be substantial with the utilization of locally available recycled products compared to landfill disposal [25]. RAP has extensive application in asphalt mix due to its green characteristics of resource conservation and reducing waste [26-28]. Although it is predominantly utilized, RAP has difficulties being used when mixed with asphalt. For instance, there can be heterogeneity of the quality of RAP in terms of binder content and particle size that can impact the performance and durability of the resultant asphalt mixtures [29-30].

Kim et al. [19] reported that, taking into account greater confining stresses, combinations of 50% aggregate and 50% RAP were more rigid than 100% aggregate blends. Hoppe et al. [16] highlighted how adding up to 50% RAP made the underlying course material stiffer overall. Dong and Huang [31] analyzed and contrasted the characteristics of RAP, crushed limestone, and crushed gravel that had a similar gradation and level of compaction. On the contrary, Jeon et al. [32] tested 100% RAP and 100% VA in multistage permanent deformation tests and discovered that at low stresses, RAP showed more deformation than VA, but under high stresses, the reverse was true. Additionally, Pradhan and Biswal [33] combined two grades of RAP and VA and used the CBR value at optimal moisture to assess the mixture's effectiveness. They found that RAP-VA mixes with a ratio of 45-55% enhanced the CBR value from 32% to 100%, and they recommended these blends for use in the subbase layer. According to Attia [34], who conducted triaxial repeated loading tests on three separate specimens (100 percent RAP, 50 percent RAP, 50 percent VA, and 100 percent VA), a combination of the two types of materials showed less permanent deformation than a specimen made entirely of Va. Using the California Bearing Ratio (CBR), Taha et al. [35] studied and assessed RAP's utility as an unbound aggregate. Neither of the samples reached the target minimum CBR value of 80% for a base course, and the CBR value dropped as the proportion of RAP went from 20% to 100%. As a result, they concluded that RAP should not be employed in more than 60% of subbase courses and no more than 10% of base courses.

Reclaimed Asphalt Pavement (RAP) may enhance the strength and performance of problematic soils, rendering it very beneficial for soil stabilization, particularly in pavement applications [36].

Hasan et al. [37] discovered that the robust modulus of subgrade soil enhanced with the use of RAP, achieving 300 MPa at 75% RAP content. Suebsuk et al. [38] discovered that a 50% RAP mixture attained the maximum dry density of 21.90 kN/m³ and the minimum optimal moisture content in the compaction of lateritic soil. Lima et al. [36] discovered that the inclusion of Reclaimed Asphalt Pavement (RAP) into sedimentary soil from the Guabirotuba Formation in Brazil enhanced both unconfined compressive strength and splitting tensile strength. The use of eighty percent of RAP led to an 18.62% enhancement in CBR values and a decrease in expansion from 1.19% to 0.88%. A blend of 40% Reclaimed Asphalt Pavement (RAP) and 3% cement satisfied sub-base layer specifications, exhibiting expansion less than 1% and California Bearing Ratio (CBR) more than 20%. A fifty percent RAP combination attained the maximum dry density of 21.90 kN/m³ and the minimum optimal moisture content.

3 Geogrid and Its Role in Engineering

Because of the lack of suitable raw materials, roads have been built on mechanically or chemically treated marginal soils. As illustrated in Figure (1), geosynthetics is one example of a mechanical treatment.

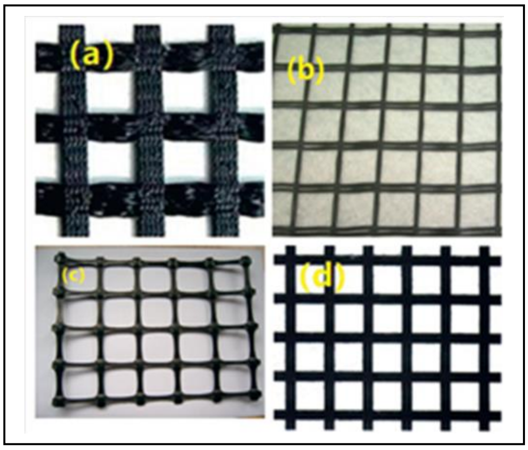


Figure 1. (a) warp knitted polyester geogrid, (b) glass fiber geogrid, (c) bidirectional plastic geogrid, (d) steel plastic geogrid

According to Saberian [39], using geogrids may enhance the efficiency and mechanical qualities of marginal materials used in base and subbase courses. Employing a geogrid inside an unbound layer of a pavement structure might enhance the stiffness of pavement layers, particularly those located below and above the geogrid [40]. By lowering the pavement structure's inclined movement and raising aggregate bonding and confinement, geogrids stabilize the aggregate layer and reduce deformation.

Reducing the overall thickness of the pavement structure layers and increasing the road structure's lifespan are two benefits of using geogrids in building roads. Rutting, pavement material fatigue, thermal and reflective cracking, and other issues have been claimed to be avoided by using geosynthetic reinforcement in asphalt layers. To improve drainage systems and road performance, geocomposite materials like geotextiles sandwiched between geogrids may be used as a separation layer to stop small particles from moving into open-graded foundation layers [41].

In order to sustain the initial building work on temporary roadways, geogrids are employed inside the weak foundation. In order to get the big equipment onto the building sites, the geogrid-reinforced aggregates serve as a platform. According to Shirazi et al. [42], geogrids may be used for subgrade stabilization purposes by reinforcing soft subgrades and reducing the extreme deformation of pavement structures caused by traffic loads. A flexible road's bearing capacity against cyclic loads may be enhanced by installing geogrids beneath or inside unbound layers for basal reinforcement applications [43]. According to Mirzapour Mounes et al. [44], geogrids are embedded in the asphalt layer for pavement surface reinforcement. This helps to reduce fatigue and rutting caused by the marginal amount of aggregate.

Though there is limited work available for geogrid-strengthened recycled aggregates, in addition to design procedures and construction practices widely accepted, commercial geogrid-strengthened recycled aggregates have been of interest to some researchers over the last few years [45]. In order to promote the use of natural geotextiles with recycled aggregates for environmentally friendly road construction and sustainable development, Suddeepong et al. [46] investigated interface shear behavior between natural kenaf geotextiles and RCA. Geogrid stiffness and shape, geogrid depth and installation location, particle size of aggregate, and other factors all influence geogrid-reinforced recycled aggregates' performance [46].

3.1 Mechanisms of Reinforcement Using Geogrid

Geogrids can help keep the soil stable by allowing particles to connect within the grid in the soil. This improves the lifting capacity and stiffness of the gravel layer. There is less horizontal spreading because the geogrid holds everything together. Vertical stress is passed to the subgrade, and it can form a tension barrier when loaded, moving, and holding loads. This makes it easier for loads to be transferred, lessens lasting damage, and improves the general performance of the strengthened earth structure, like in sidewalks and retaining walls [47].

3.1.1 Interlocking and shear transfer

Soil reinforcement mechanisms where the geogrid's structure physically engages with soil particles, creating an interlocking effect that increases shear strength and stability. The geogrid's openings allow soil to penetrate and interact, while the rigid grid prevents lateral soil movement and transfers stress, resulting in enhanced soil performance through both confinement and the physical locking of soil particles [48].

When soil particles move relative to the geogrid, some particles can pass through the geogrid's apertures (openings), effectively "keying" into the grid's structure. This creates a mechanical interlock that resists further movement and increases the shear resistance of the soil mass [49].

In addition, the grid's robust structure provides confinement to the surrounding soil, as soil particles attempt to move laterally under load, they are restrained by the geogrid. This confinement prevents excessive deformation and enhances the soil's overall shear strength. Also, geogrids improve shear strength through friction between the geogrid's surface [50].

3.1.2 Tensioned membrane effect

The tension membrane effect is a geogrid reinforcement mechanism where the geogrid stretches and absorbs forces perpendicular to its surface through tension, acting like a flexible sheet to hold soil together and improve load distribution. This creates a stabilizing tension membrane over a weak soil foundation, helping to prevent issues like settlement and subsidence. The effect is most significant in flexible, deformable structures, requiring some strain in the soil to activate, and is a key design consideration for applications like piled embankments [51].

When a load is applied, the geogrid stretches slightly this deformation causes the geogrid to develop tensile forces, which absorb stresses that would otherwise be concentrated on the weaker soil below. Also, the geogrid acts like a tensioned membrane, distributing the applied loads over a larger area of the soil. This enhanced load distribution increases the soil's effective strength and stability, preventing issues such as differential settlement and subsidence [52].

3.1.3 Bearing capacity enhancement

Using geogrid layers significantly enhances soil bearing capacity by improving load distribution and reducing settlement through confinement and interlocking mechanisms. The effectiveness of geogrid reinforcement depends on factors such as the number and depth of layers, geogrid type and length, and soil properties. For optimal results, specific parameters like the depth of the first geogrid layer and the vertical spacing between layers need to be carefully selected [53].

Geogrids spread the load from a foundation over a wider area of soil, reducing the pressure on the underlying soil, preventing lateral displacement, and increasing the shear strength of the soil mass, also improving load distribution and soil confinement. Geogrids effectively mitigate settlement, leading to a more stable foundation [54].

3.1.4 Dynamic/cyclic stabilization

Geogrids achieve dynamic and cyclic stabilization through minimizing cumulative settlement and augmenting the dynamic elastic modulus of soil under cyclic load. Use geogrids in applications involving repeated or vibrational stresses, like railway ballasts and reinforced retaining walls, to improve stability and prevent deformation. The specific choice of geogrid and reinforcement layout also affects performance, with elements like double reinforcement and the right aperture size (matching soil grain size) enhancing interlocking and stabilization [55].

Geogrids are effective in reducing permanent deformation and settlement caused by repeated traffic or vibrational loads. They are used to improve the performance of railway track beds by reducing permanent deformation in the granular ballast. Also, geogrids are employed in geogrid-reinforced soil (GRS) structures subjected to long-term cyclic vehicular loads or even short-term seismic loads. In addition, geogrid reinforcement increases the dynamic elastic modulus of the soil, indicating better resistance to deformation under cyclic stress [56].

3.2 Common Applications of Geogrid in Highway.

As shown in Figure (2), geosynthetics are used in a wide range of civil engineering, construction, and environmental tasks. Numerous technical problems might be resolved because of their adaptability and advantageous qualities. There are common applications of geosynthetics

3.2.1 Pavement construction

Roads and other paved surfaces may benefit from geosynthetics because they increase their utility, durability, and longevity. Geosynthetics are significant in reinforcement, which involves using geogrids and geotextiles for strengthening the pavement layers' structural integrity [57]. Pavement lifespan is extended, rutting is reduced, and loads are distributed more effectively.

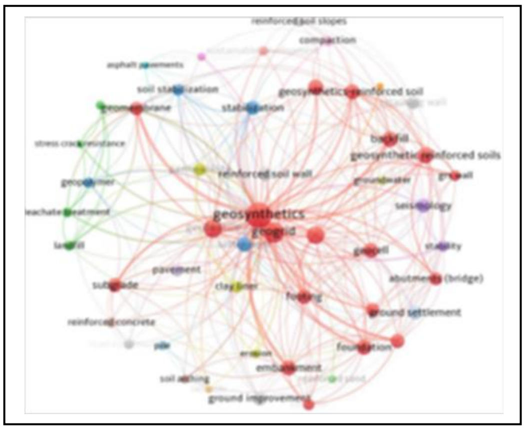


Figure (2): Uses of geosynthetics as eco-friendly construction material

It is common practice to place geogrids in the spaces between the pavement layers. On the other hand, geotextiles are often used to separate and filter different pavement components, which helps to keep materials from mixing and allows for better drainage. In order to prevent water from damaging the subgrade and eventually causing pavement collapse, geogrid may be used to seal the pavement layers. Another use for geotextiles is as a barrier against moisture. Pavement may also benefit from the use of a geo-composite, which can enhance it while decreasing the chances of water damage [57].

Using geogrids might improve traffic conditions by reducing pavement thickness. It lessens the strain or pressure of cracking by creating a buffer zone. In addition to protecting the layers from water seepage and fatigue cracks, geosynthetics may also aid in reflecting cracks. These serve as a fluid barrier that prevents surface water, capillary, and groundwater from penetrating the pavement and damaging the layers underneath.

3.2.2 Retaining walls

Retaining walls rely heavily on geosynthetics for a number of reasons, including enhanced performance, longevity, and stability. load for this to happen. Improved effectiveness and efficiency cannot be achieved without geosynthetics. It is important to consider specific locations, including turns, switches, and train crossings. Geosynthetics are based on the principle of separation, which is to say that they act as a barrier to keep soil and new ballast from mixing. Because vibration causes ballast to infiltrate into subgrade soil, track efficiency is reduced [60]. Stability in the long term is ensured by the drainage function. Soil pore water rises and reaches the soil subgrade via capillary action; so, the driving wheel might pump mud, weaken the soil, and diminish its load-bearing capacity [61]. Side drains allow water to flow away from the geosynthetic.

3.2.4 Tunnel construction

In spite of improving structural integrity and making surfaces watertight, geosynthetics also Geogrids and geotextiles are frequently employed to stabilize soil and reinforce retaining wall systems. Geogrids are rigid structures that stabilize soil by being embedded in it. Geogrids are commonly constructed of steel or polymers and increase the tensile strength and lateral stress resistance of soil. By causing loads to be transferred more evenly and minimizing soil movement, geogrids behave against the movement of the retaining wall and structurally enhance its stability [58].

Geotextiles are also employed as drainage layers and as filtering layers so that water accumulation and soil erosion outside the retaining wall are avoided. By creating a physical separation between the backfill soil and the structural components of the wall, they retard the flow of soil and make the wall long-lasting. To further improve, minimize hydrostatic pressure below the wall, and drainage, geo composite materials like geo composite drains can be implemented in retaining wall design [59].

3.2.3 Railway track stabilization

Trains generate enormous vibrations and stresses; therefore, railway rails need to be strong and durable. Ballast, rails, and sleepers must all function properly under guarantee long-term durability. When building tunnels, geosynthetics like geotextiles and geomembranes are often used. To prevent material mixing and promote proper drainage, geotextiles are often used as filter layers and separation between various tunnel building materials [62]. They shield the waterproofing membranes and other tunnel components from destruction while building is underway. According to Robertson et al. [63], geomembranes are crucial for waterproofing because they stop water from getting into the tunnel. They provide an impermeable barrier that prevents groundwater from seeping in and causing damage to tunnel walls, floors, and ceilings.

4 Mechanically stabilized earth (MSE)

As a means of defense against Nile River floods, retaining walls have an extensive and fascinating past in ancient Egypt. The erosion that resulted from the floods was minimized by constructing retaining structures utilizing reeds in the gabion style. These walls were effective flood control measures because they let streams on land flow through them and because they diverted Nile floods into reservoirs. Much of the material used in the construction of such retaining walls is massive boulders, drums filled with small stones, seasoned wood, cast-in-place concrete, and slabs of concrete. Henri Vidal was one of the earliest advocates for mechanically stabilized earth (MSE) walls during the 1960s; they were established in the United States by the 1970s [64].

Compared to other retaining wall structures, they possess several benefits including being cost-effective, simple to build, stronger to seismic forces, and inherent stability, which can withstand settlement without being destroyed. These advantages have made MSE walls the Favorite option for use in a wide range of applications [65].

Soil may be held on steep, unstable slopes with crest loads in Mechanically Stabilized Earth (MSE) walls [66]. Their ease of construction, architectural flexibility, and affordability have made them very popular in the past ten years. MSE walls need to be monitored to avoid collapse during and post-construction based on transportation asset management principles. This will ensure that the walls are achieving their expected levels of functionality and assist in diagnosing design or construction faults. Visual inspection and observation are some of the qualitative methods of monitoring MSE walls that are available.

4.1 Advantages and Disadvantages of MSE Retaining Walls

Mechanically stabilized earth (MSE) walls come in a range of sizes and types; their compatibility with the environment and suitability for use will determine their optimal application. They are resistant to seismic forces, water pressure, and lateral earth pressure by tapping into their inherent gravitational load. The net effect is the value of bearing pressure of a large area being evenly dispersed.

In comparison to concrete walls, MSE retaining walls are less expensive and are able to tolerate more overall settlement and movement differences before collapse. Since they do not require any form of external support, e.g., scaffolding or curing time, the construction of MSE retaining walls is also faster and simpler.

As stated by Coduto [67], MSE walls can withstand static and complex dynamic stresses, like earthquakes. The strength and affordability of MSE structures have contributed to their popularity among both architects and builders. They are simpler to construct than traditional concrete barriers, require less heavy equipment, and can be constructed significantly faster. They also have the potential to occupy more land for construction. There is no longer any need for skilled labor, wall finishing, or considerable site preparation when using MSE walls. They are ideal for places where constructing a concrete wall would be difficult, such as in confined spaces. Nevertheless, this method might reduce land requirements. Even though MSE walls are very resistant to seismic stresses, they may be damaged by elastic materials. When reinforced with other materials, MSE walls may be as tall as 60 feet, or around 18 meters, making them comparable to other types of tall retaining walls. Because MSE walls may come in many shapes and sizes, they can be used in places with shallow ground without having to drill foundation holes [68]. There are a few downsides to the design of MSE walls. The first is that stability requires a minimum diameter. An additional is that in areas where granular material is scarce, the construction process might not be economically viable due to the high cost of obtaining coarse-grained soil for the reinforced soil mass. It is also necessary to install proper drainage systems. The mechanical benefits of the composite structure may be reduced with time; hence, it is important that the reinforced parts can resist weathering and degradation.

4.2 MSE Wall Applications

Bridge abutments, embankments, and excavations are just a few examples of places where MSE walls have been used as retaining structures. This is because these areas often do not have adequate space to build stable side slopes. Installation of inhibition dikes, dams (including the heightening of dams), seawalls, and detours for highway repair projects all make extensive use of MSE walls. For more examples of MSE walls in practice, see the illustrations in Table (1).

4.3 MSE Wall Components

When constructing an MSE wall, the backfill and reinforcements that are chosen are the two most important parts. Even though it does not do much to support the MSE wall system as a whole, the facing component is crucial for aesthetic reasons. Below, we shall proceed to the parts of the MSE walls:

4.3.1 Selected Backfill

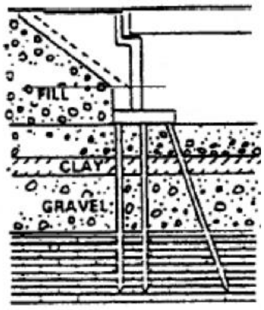
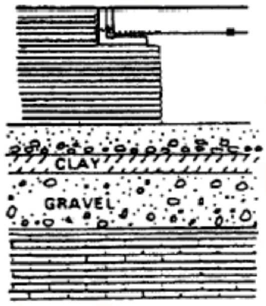
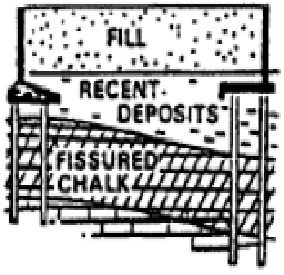
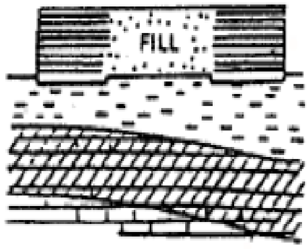
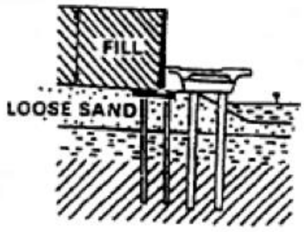
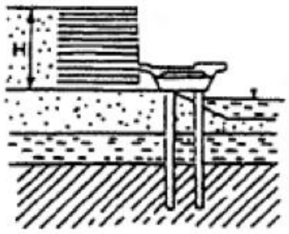
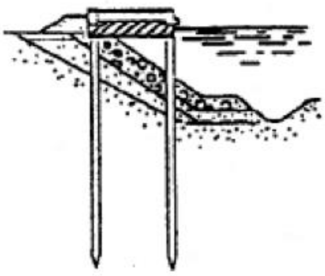
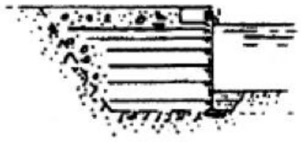
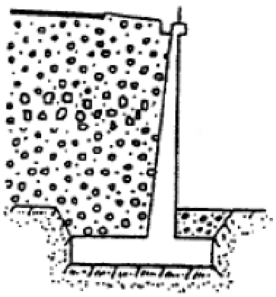
Regulatory organizations such as AASHTO, FHWA, state DOTs, etc., define specifications for design that might be met by either natural or recycled materials used as backfill. Materials having a small fines content (less than 15%), as specified by Anderson et al. [70], are utilized as backfill in MSE walls.

The wall system's functionality over time is taken into account while choosing the backfill material. Water must be able to percolate freely through the backfill; hence, the material's hydraulic permeability must be high enough to provide adequate drainage when there are too many fine particles in a coarse material, its hydraulic conductivity drops, which can affect the wall's performance in over time [2]. According to Berg et al. [71], who reviewed the AASHTO T-27 criteria, in order to achieve acceptable drainage, the reinforced fill material chosen must contain no more than 15% fines (as measured by particles passing a No. 200 sieve) and 60% fine sand size particles (as measured by particles passing a No. 40 sieve). The material's plasticity index must be below 6.

Backfill that does not drain well might increase the possibility of corrosion of metal reinforcements. Backfill materials with a high capacity to absorb water, including silt and clay, should therefore be avoided [71]. Because corrosion might cause the MSE wall system to suddenly fail, it is important to avoid using metal reinforcements in MSE wall systems [70]. The backfill's mechanical characteristics also contribute to the wall's mechanical stability. According to Berg et al. [71], the material should have a sufficient internal friction angle to provide high shear strength when subjected to horizontal pressures from the soil mass. It is important that the chosen backfill provide enough friction at the reinforcement's interface. The dry unit weight is increased during compaction of materials that are well-graded and have fewer sharp edges [1]. According to Berg et. al. [71], materials that are compacted with a low water content and dry unit weight can undergo substantial settling when wetted.

If the backfill is constructed of a material with a substantial creep potential, like RAP or RAS, another deformation process to be concerned about in MSE walls is creep [72]. At higher temperatures, this tendency will be even more pronounced. It is generally advised against using creepy materials for backfill as they impact the wall's long-term stability and cause the MSE wall system to bend excessively [2].

Table (1): The applications of Mechanical Stabilized Earth wall (Elias et al. [69].

	The exact infrastructure	Mechanical Stabilized Earth wall
Bridge Abutment		
Bridge Approach Fill over Compressible Foundation		
Interchange with Access Ramps		
Marine Wall		
Retaining Wall		

4.3.2. Reinforcements

In order to protect the backfill from the lateral earth pressure, reinforcements are used to increase its shear strength. According to Das [73], there are two types of reinforcements utilized in MSE walls: extensible and inextensible. When they fail, inextensible reinforcements indicate significantly less deformation than the soil itself. Certain types of reinforcement cannot be stretched, such as steel strips and bar mats. Conversely, the deformability of the soil is less than or equal to the deformation that extensible reinforcements exhibit at failure. Two examples of extendable reinforcements are geotextiles and geogrids [71].

A porous, elastic fabric woven from geosynthetic strands is called a geotextile. There are two main types of geotextile patterns: woven and nonwoven [74]. Weaved geotextiles are created by methodically interlacing two sets of parallel threads into a flat surface. In contrast, geosynthetic fibers are either randomly or systematically matted together to create nonwoven geotextiles. Chemical, thermal, or mechanical bonding of these filaments occurs after fiber implantation [73]. Woven geotextiles are often employed as reinforcement in MSE wall applications because of their much-increased tensile strength. According to Berg et al. [71], nonwoven geotextiles are often used to facilitate drainage in reinforced zones, both above and below the surface. A geogrid is a large, grid-like structure constructed from high-modulus plastics such as polypropylene (PP) or polyethylene (PET). Soil may move freely between the geogrid's perforations, which are big enough to accommodate the spacing between the ribs moving longitudinally and transversely. Das [73] and Koerner [74] state that geogrids may be manufactured using a variety of procedures, including extrusion, weaving, and welding. It is possible to design geogrids in either a uniaxial or biaxial strength direction. When discussing geogrids, the terms MD and XMD are used in a manner similar to when discussing geotextiles [75]. Geogrids may be rigid and interlock with the backfill material around them because of their holes [73]. Figure (3) displays samples of several geosynthetics.

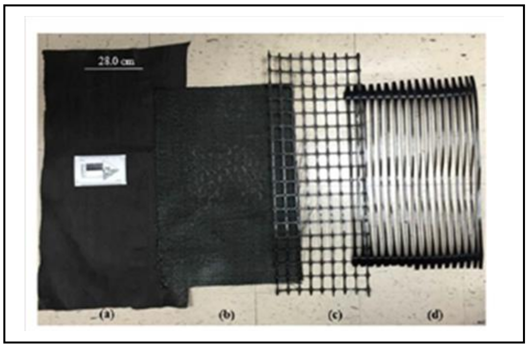


Figure (3): Geosynthetic reinforcement samples: (a) nonwoven geotextile, (b) woven geotextile, (c) biaxial geogrid, and (d) uniaxial geogrid

.5 Indirect Tensile Strength of RAP

According to Qais S. Banyhussan et al. [76], they tested the selected subbase in a number of subgrade soil types, including clay and sandy soil, and conducted a number of extensive direct tests using four different kinds of geosynthetics. They came to the conclusion that, in comparison to sand-subbase, the installation of geosynthetics diminishes the materials' apparent cohesiveness as well as their friction and adhesion angle.

As the normal applied stress at the clay-subbase and sand-subbase interfaces increased, so did the interaction coefficient for all of the geosynthetics utilized in this investigation. Subbase-Rectangular Apertures Geogrid-clay interaction coefficient behavior, however, seems to follow a distinct pattern, with a reduction in interaction as normal stress increases.

Biaxial geogrid rectangular aperture geogrid has the best behavior for both subbase-clay and subbase-sand, according to the experiment results. Its interface shear coefficient factor is more than unity and is 1.05 and 1.02, respectively.

Geogrids often produce more interaction with the shear stress than geotextiles when the impacts of the four distinct types of geosynthetics evaluated on contact shear strength are compared. Because of the geotextiles' flat surface, which significantly lowers interface shear stress, the soil-geotextile interaction is less than the soil-soil contact. Therefore, when sliding along contact is more likely to occur, special attention should be paid to the geotextile-reinforced soils.

6 Interface Shear Strength

The soil is not strong enough to support any kind of tension load. Incorporating a tensile material into the designed soil would improve the soil's weakness, according to a comprehensive investigation. Geogrid is a tensile material that is widely used to strengthen deficient soil due to its affordability, simplicity of manufacturing, and ecologically favorable characteristics. A high-stiffness-ratio geogrid reinforcement combines with soil to improve the system's performance and load-carrying capability. A mechanism often referred to as the stiffening effect enhances the shear strength of reinforced soil, caused by a variation in stiffness between the soil and the geogrid. This effect is crucial for shear stress mobilization along the geogrid [77].

Using prestressing geogrid fundamentals allows for an even greater rise in the geogrid's tensile force. According to Lackner, Bergado, and Semprich [78], the soil utilized, the size of the aperture, and the mechanical qualities of the geosynthetic product all have a beneficial impact on the enhanced load-carrying capacity and decreased irrecoverable deformation.

In most cases, the area where the soil and reinforcement meet is the weakest. Progressive failure owing to substantial post-construction deformations is possible if the interface's peak shear strength is higher than the residual shear strength [79]. In addition, fine-grained reinforced soil has a lower common interface strength than coarse-grained soil, which causes the common surface to collapse before the reinforcement's entire strength can be mobilized [80]. According to Jotisankasa and Rurgchaisri [81], the surface strength of the soil-reinforcement interface must be studied for the design and stability of geosynthetic-reinforced soils.

6.1 Factors Influencing Interface Shear Behavior

Scholars have undertaken numerous experimental investigations on geosynthetic-reinforced soil and fiber-reinforced soil. The findings indicate that variables, including the quantity of reinforcement layers, the kind of reinforcement, cross-sectional geometry of the reinforcement, and arrangement of the reinforcement strips, affect the reinforcing efficacy in geosynthetic-reinforced soil. In fiber-reinforced soil, the fiber type, quantity, length, and dry density all influence the strength of the reinforced soil. Nonetheless, these investigations have concentrated on particular reinforcement materials, and a systematic assessment approach for determining the reinforcement-soil interface characteristics has yet to be devised.

7 Previous Studies on Interface Shear Strength Between Geogrid and Different Materials

Artit Udomchai et al. [82], performed a large direct shear test (LDST) to examine the interface shear strength (τreinforced) between recycled asphalt pavement (RAP) and kenaf geogrid (RAP-geogrid) as a sustainable base course material. The impact of RAP particle gradation and geogrid aperture diameters (D) on the reinforcement of RAP-geogrid was assessed under varying normal loads.

Jakub STACHO et al. [83] conducted experiments with three distinct geosynthetic reinforcements: Thrace WG80 black woven geotextile, Tencate Miragrid GX55/30 woven geogrid, and Thrace TG3030S rigid polypropylene geogrid. The measurement findings indicate that the interface coefficient α is often bigger in vital shear strength compared to peak shear strength.

Anubud Liangsunthonsit et al. [84], propose sand, lateritic soil, and clay, together with RSS geogrid and RCS geogrid, as reinforcing materials. A large-scale direct shear test was conducted to determine the Rin to validate the efficiency of geogrid reinforcement. The RSS geogrid and RCS geogrid effectively enhanced the shear strength of the soil.

David H. Marx et al. [85] demonstrated the effective integration of deep learning-based segmentation with triaxial testing on transparent soil to assess the lateral support offered by geogrids. The geogrids were modeled using geosynthetic inserts. The insertions were included in triaxial specimens subjected to cyclic loading.

Suddeepong et al. [86] did a lot of direct shear tests to find out how strong the interface is between recycled concrete aggregate (RCA) and kenaf-based geogrids. They came to the conclusion that larger apertures and angular RCA particles made the interlocking stronger and the interface shear resistance stronger.

Zhang et al. [87] tested geogrid interfaces with foam made from recycled glass. Their studies showed that particle shape, compressibility, and density had a big impact on interface friction and cohesion, especially when the fill was light.

Adhikari et al. [88] concentrated on the examination of the base and sub-base layers of the pavement employing RAP, geopolymer, and soil. Two kinds of soil were examined and categorized as A-7-5 and A-7-6 according to the TRB technique. Hasan et al. [37] examined varying quantities of crushed material combined with fine soil obtained from a roadway subbase. The resilient modulus was shown to rise with the incorporation of milled material.

Other studies are shown in Table (2).

Table (2): Previous Studies on Interface Shear Strength Between Geogrid and Different Materials

No.	Author(s)	Year	Country	Materials Used	Test/Analysis Method	Key Findings
1	Sweta et al. [89]	2019	India	RCA + Ballast + Geogrid	Cyclic direct shear	Long-term strength degradation under simulated train loads
2	Suddeepong et al. [90]	2020	Thailand	Recycled Concrete Aggregate (RCA) + Geogrid	Large-scale direct shear	Interface shear strength α increases with particle size and aperture size
3	Kang et al. [91]	2020	USA	Unbound Aggregates + Geogrid	Triaxial + Bender element	Geogrid increases stiffness and resonance frequency under cyclic loads
4	Udomchai et al. [82]	2021	Thailand	RAP + Kenaf Geogrid	Large-scale shear test	Higher adhesion (ca), linear α vs D/F_D relationship
5	Xu et al. [92]	2022	China	Calcareous Sand + Geogrid	Large-scale direct shear	Significant improvement in cohesion and internal friction
6	Suddeepong et al. [86]	2022	Thailand	RCA + Kenaf Geogrid	Large-scale direct shear	Suggested α–D/F_D relationship; better friction with large D
7	Sarkar & Hegde [93]	2022	India	Geogrid + recycled marginal backfill	Triaxial tests	Geogrid reinforcement improved strength and plastic hardening behavior.
8	Anda et al. [94]	2023	China	RCA + Geogrid	Cyclic direct shear	Increased shear strength and friction angle after cyclic loading
9	Liangsunthonsit et al. [84]	2023	Thailand	Sand, Clay, Lateritic Soil + Recycled Rubber Geogrid	Shear test under 3 normal stresses	Rubber-based geogrid (RCS) shows superior performance
10	Marx et al. [85]	2023	USA	Transparent Sand + Geogrid	Triaxial test + DIC + AI image analysis	Quantified zone of particle confinement and mobilized stress zone
11	Shireen et al. [95]	2023	India	Bottom Ash + Recycled Tire Granules + Polyester Geogrid	Large-scale direct shear under varying normal stresses	Geogrid reinforcement improved interface shear strength by up to 11 %; interaction coefficient ranged 0.90–1.1
12	S. Maramizonouz et al. [96]	2023	UK	Crushed glass + Crumb rubber + Geogrid	Tribological tests + high-pressure torsion	Recycled glass granules are effective in adhesion; recommended for full-scale tests
13	Feiyu et al. [97]	2023	China	RCA + Rocks + Geogrid	Direct shear + DEM simulation	Optimal performance at 75% rock; higher compaction improves strength
14	Ok et al. [98]	2023	Turkey	Recycled aggregates +	Direct shear tests	Shear strength exceeded natural aggregate; bricks

				geogrid		added benefit.
15	Stacho et al. [83]	2023	Hungary	Soil + geogrid (ash, sand, gravel)	Large-scale shear test	Alpha values between 0.87–1.19; highest in ash and sand.
16	Marwa et al. [99]	2023	Turkey	Geogrid + RCA for embankments	Numerical modelling (FEM)	Enhanced stability and reduced erosion in embankments.
17	Alam et al. [100]	2023	India	Rubber-coated ballast + geogrid	Direct shear tests	Improved shear performance in mixed ballast conditions.
18	Ho et al. [101]	2023	USA	Geogrid in unpaved aggregate roads	DCP, Plate Load Tests	Reduced rutting and improved load resistance over long-term.
19	Zhang et al. [87]	2024	China	Sand + Recycled Fillers + 4-Way Geogrid	Cyclic direct shear	Observed shear strength fluctuations under cyclic loads
20	Tan et al. [102]	2024	China	Geogrid reinforced C&D waste	DIC-based experimental tests	Reinforcement increased bearing capacity in waste embankments.

8 Conclusions

Reclaimed asphalt pavement (RAP) offers economic and environmental advantages over virgin aggregates when used to build pavements. Reusing RAP as a base course material on unpaved roads can decrease the workload on civil engineers caused by excessive usage of virgin aggregates or natural aggregates. Geogrid, a sustainable alternative, can be used with RAP in pavement layers. Mechanically stabilized earth (MSE) is also used in many applications, especially in embankment or retaining walls in highways. RAP is more cost-effective and helps preserve the environment compared to virgin materials. RAP aggregates have mechanical properties that vary, with some exhibiting higher residual modulus (MR) than natural aggregates.

Geogrids, a type of geosynthetic, can enhance the efficiency and mechanical qualities of marginal materials used in base and subbase courses. They can reduce the overall thickness of pavement structure layers and increase the road structure's lifespan.

RAP and geogrid are tensile materials used to strengthen deficient soil due to their affordability, simplicity, and ecologically favorable characteristics. They often produce more interaction with shear stress than geotextiles.

The interface shear coefficient factor is more than unity for a biaxial geogrid rectangular aperture geogrid. Factors influencing interface shear behavior include the quantity of reinforcement layers, the type of reinforcement, the cross-sectional geometry of the reinforcement, and the arrangement of the reinforcement strips.

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