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Pullout testing of recycled construction and demolition waste aggregates in full-scale geogrid-reinforced embankments

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ABSTRACT

The use of recycled aggregates (RAs) derived from construction and demolition waste (C&DW) in geogrid-reinforced embankments was investigated through a near-real-scale experimental approach, bridging the gap between laboratory research and field application in sustainable geotechnical engineering. Embankments were constructed using different fill types: RAs with particle size classes 15 ÷ 30 mm and 0 ÷ 80 mm, and a mixture of RAs with excavation soil.

Material properties were characterised through laboratory testing, and full-scale pullout tests were carried out at low normal stress levels (10÷12 kPa), which are critical for shallow embankments, to evaluate RA-geogrid interaction.

The results demonstrated pullout peak forces ranging from 20 to 30 kN/m for soil–RA mixtures to 40÷50 kN/m for coarse granular RA, exhibiting mechanical behaviour comparable to that of natural aggregates. The full-scale setting and the heterogeneity of the RA materials provide valuable insight into the field performance of recycled materials in reinforced embankment applications.

The test campaign also provided procedural insights relevant for future field-scale testing and applications.

These findings support design practices involving RAs and offer practical evidence to advance circular-economy principles in geotechnical infrastructure.

Introduction

The construction industry is one of the largest consumers of natural resources globally and a significant contributor to waste generation. In the European Union, construction and demolition waste (C&DW) accounts for approximately 38 % of total waste [12]. This growing volume of waste presents environmental challenges and opportunities for promoting sustainability in civil engineering [2,28]. Recycled aggregates (RAs) derived from C&DW have emerged as viable alternatives to natural aggregates, with applications in geotechnical structures [3]such as highway embankments [14,32], levees, and rockfall barriers [37]. Incorporating RAs into construction projects reduces environmental impact and aligns with circular economy principles by minimizing resource extraction and landfill use.

Recent studies highlight the feasibility of using RAs in geosynthetic-reinforced structures [29], focusing on their mechanical performance and sustainability. Geosynthetics allow even more efficient use of waste materials and can be used as substitutes for soil and aggregates of lower quality [4]. Vieira et al. (2018) explored the use of fine RAs as backfill materials for geosynthetic-reinforced embankments. They found that their shear strength properties were comparable to those of natural aggregates. Similarly, Ok et al. [19] investigated geogrid-RA interactions through direct shear tests, highlighting the potential of geogrid reinforcement to enhance the structural behaviour of recycled materials. These studies were complemented by investigations on the influence of saturation conditions on the mechanical properties of embankments reinforced with geogrids, thereby providing further insights into their performance under various environmental conditions [27].

A series of large-scale direct shear tests were conducted in previous studies to investigate the interface shear strength of different types of RAs from C&DW, geomembranes, and geogrids. These investigations have provided critical insights into the interaction mechanisms between

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geosynthetics and various fill materials, allowing for a better prediction of field performance. Currently, several types of common and uncommon materials can be recovered for different uses, considering the fundamental features of technical performance and the absence of contaminant release due to fluent water contact [18].

Despite these advancements, most studies have been confined to laboratory-scale experiments, which are valuable; however, they may not fully account for the complexities of real-world applications. Full-scale field experiments, on geogrid-reinforced embankments constructed with RAs from mixed C&DW, remained limited [24]. Existing research has primarily focused on assessing the potential chemical and environmental degradation induced by RA on the geosynthetic tensile behaviour [30,31]. Addressing this gap is crucial for testing the mechanical performance of RA–geogrid systems in real conditions and providing empirical data that can underpin reliable, design-oriented guidelines. The implementation of recycled aggregates in geotechnical infrastructure must be supported by field evidence to gain acceptance in standard practice and ensure mechanical reliability and environmental sustainability.

This study aims to bridge that gap by evaluating the field-scale performance of geogrid-reinforced embankments constructed with RAs derived from C&DW under near-real loading and confinement conditions.

This full-scale experimental approach is inspired by foundational works in soil–geogrid interaction research, where field pullout tests were shown to reveal behaviors not observable in laboratory-scale studies due to scale effects, construction variability, and stress heterogeneity [1,25]. Similarly, our work aims to extend validated laboratory methodologies to real-world embankment applications using recycled C&DW materials, which remain underrepresented in field-scale investigations. As such, this study does not only introduce a new material context, but also delivers a methodological contribution by testing under realistic boundary conditions, operational challenges, and low-confinement settings. In particular, it applies a combined approach involving full-scale embankment construction and detailed RA material characterisation. This methodology enables the validation of laboratory findings under realistic boundary conditions and provides valuable insights into the performance of these materials in infrastructure applications. Ultimately, the research supports the development of cost-effective and environmentally responsible engineering solutions aligned with circular economy principles.

Materials and Methods

Three types of fill material were used in the experimental study (Fig. 1 and Table 1).

Although all RA types were processed in a single treatment facility using controlled selection, crushing, sieving, and mixing techniques, the raw demolition waste was collected from multiple construction and demolition sites, ensuring a representative material heterogeneity typical of urban recovery contexts.

The three different types of backfill reflect typical variability in recycled materials derived from demolition phases, which can include diverse constituents such as concrete, bricks, ceramics, and asphalt. This variability influences key geotechnical properties like particle size, shape, stiffness, and abrasiveness, which affect geogrid performance in terms of interface behaviour and long-term mechanical interaction.

Three experimental embankments (A, B, and C) were constructed using these fill materials [13]. Embankments A and B were designed with a base depth and width of 4 m, respectively, whereas Embankment

Fig. 1. Fill materials used for the experimental embankment. a) excavated soils; b) 15 ÷ 30 mm JC RA; c) mixture of excavated soil and 15 ÷ 30 mm JC RA; d) 0 ÷ 80 mm HM RA.

Table 1
Characteristics of the tested experimental embankments. The figure illustrates the key geometric and material properties of the embankments constructed for experimental analysis, providing insights into their structural configuration and composition. The geogrid used in the tests consisted of woven synthetic PET filaments coated with a protective polymeric layer. Mesh dimensions: 29 mm × 29 mm. Tensile strength in machine direction: > 110 kN/m.

Embankment	Fill Material	Number of Geogrid Strips	Geogrid Designation
A	RA 15 ÷ 30 mm JC	2	A1 A2
B	Mix 50 % RA 15 ÷ 30 mm JC and 50 % excavated Silty-Clayey Soil	2	B1 B2
C	RA 0 ÷ 80 mm HM	1	C1

Embankment A) Mixed Soil (50 % RA ÷ 50 % Excavated Silty-Clayey Soil): A blend of recycled aggregate from C&DW (15 ÷ 30 mm) and silty-clayey excavated soil in equal proportions by volume. The recycled aggregate (RA) was obtained by processing C&DW using a jaw crusher (JC), followed by sieving with a screen to isolate particles in the 15–30 mm size range (15 ÷ 30_JC).
Embankment B) RA from C&DW (15 ÷ 30 mm): The same recycled aggregate (15 ÷ 30_JC) described in A is used here without the addition of silty-clayey soil.
Embankment C) RA from C&DW (0–80 mm): This material was sourced from C&DW using a hammer mill crusher (HM) without further refinement (0–80_HM).

C had a width of 2,5 m (Fig. 2). Geogrid strips were installed after compacting the base layer, which measured 60 cm in height (Fig. 3). Each geogrid strip was 4 m long and 1 m wide, with 1 m spacing between strips. Two geogrid strips were installed on Embankments A and B, while Embankment C was reinforced with a single strip (Fig. 4). The embankments were completed with an upper compacted layer of 60 cm, resulting in a total height of 1.2 m.

The front faces of the embankments were supported using wooden panels stabilized with concrete blocks. Gaps were intentionally left between the panels to allow the geogrid layers to protrude, facilitating the pullout tests.

The particle size distribution curves of the fill materials used in this study were established according to European Standards [5] and [10], as shown in Fig. 5.

The recycled aggregates (RAs) were characterized through a series of laboratory tests in accordance with European standards. Geometrical properties such as shape and flakiness were determined [6,7], while the fine fraction was analyzed for Atterberg limits [11] to evaluate plasticity and workability.

Compaction-related behavior was evaluated through Proctor testing (EN 13286–2:2010). The RA–soil mixture (used in Embankment A) was tested using the standard Proctor method, resulting in a maximum dry density of 1.97 g/cm^3 and an optimum water content of 15.5 %, while the unsieved RA (used in Embankment C) required the modified method due to its coarse grain sizeresulting in a maximum dry density of 2.06 g/cm^3 and an optimum water content of 5.9 %. For Embankment B, no Proctor test was performed, as the RA particles exceeded the grain size limits specified by the standard.

For coarse RA fractions (4–63 mm), constituent components were classified according to [8], and mechanical resistance was assessed via the Los Angeles abrasion test [9]. Point-load strength tests were also conducted on selected mineral constituents to assess variability. A summary of all physical and mechanical properties is provided in Table 2.

Regarding field compaction, all embankments were constructed using a consistent method: backfill was placed in 30 cm thick layers and compacted using a Bomag BW 100 vibratory roller (1,500 kg, 1 m width), with three passes per layer. Although in-situ dry density was not measured during construction, the water content of the materials ranged from 9.1 % to 13.5 %, with an average laboratory-measured moisture content of 12.5 %. This approach ensured a repeatable and consistent compactive effort across all test sections.

While the absence of in-situ density data limits direct comparison with laboratory standards, the construction protocol applied was consistent and traceable. For future work, we recommend supplementing field protocols with direct verification methods, such as plate load or penetrometer tests, or alternatively the sand cone method (ASTM D1556-90) for more frequent, on-site assessment.

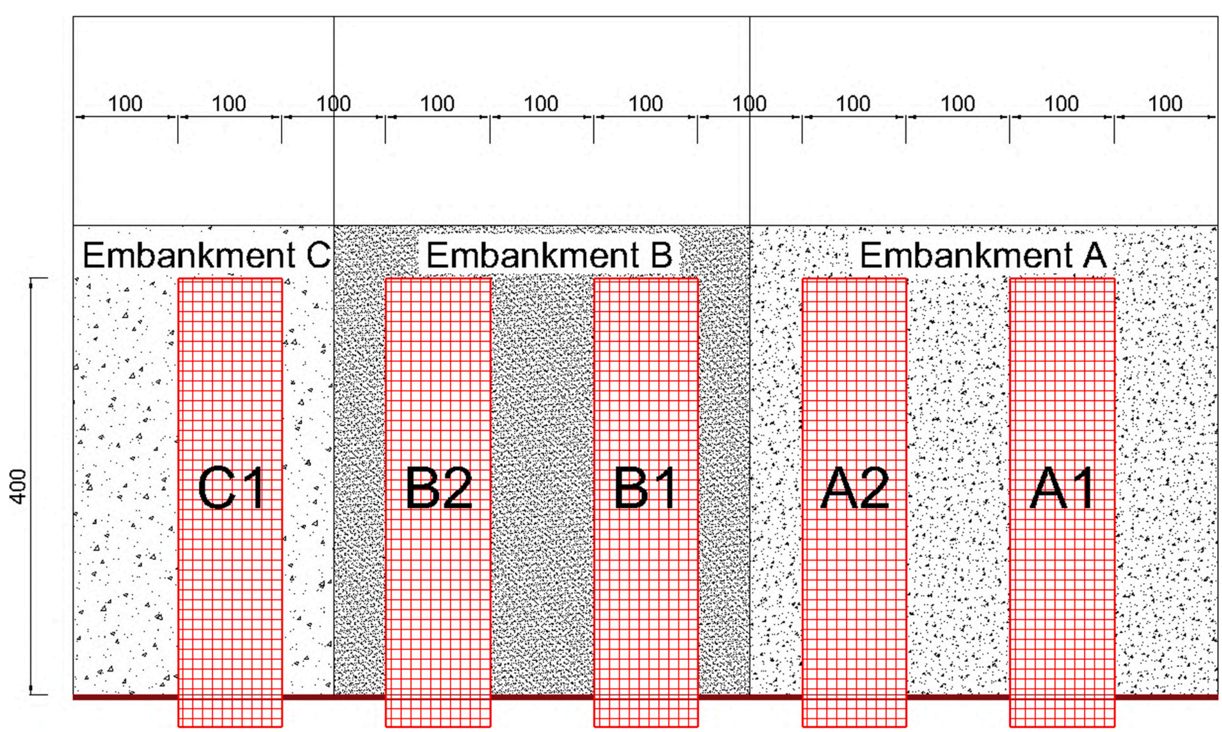

Fig. 2. Schematic plan view of the test embankments with geogrid layout. Measures in cm.

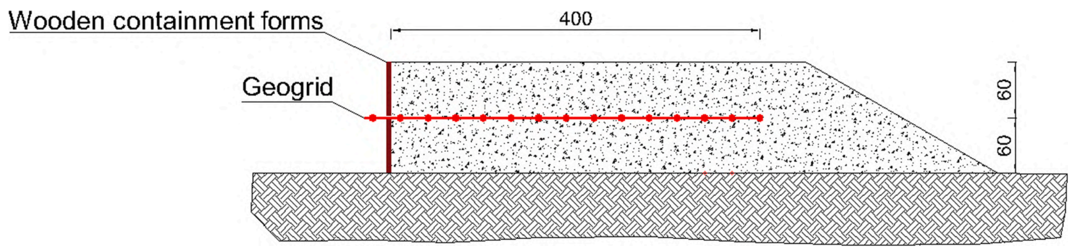

Fig. 3. Typical cross-section of the test embankments. Measures in cm.

Fig. 4. Testing embankments. a) Geogrids; b) and c) Placement of geogrid strips and wooden containment forms; d) and e) Construction phases of the experimental embankments; f) View of the first completed embankment.

A preliminary assessment of the shear resistance angle of the granular fill material was conducted by measuring the natural repose angle of the heap. The results indicated that for the 15 ÷ 30_JC and 0 ÷ 80_HM materials, the repose angles were 36° and 38°, respectively, as shown in Fig. 6.

Our findings aligned with those of Rahardjo et al. [21], who reported that finer RA exhibited higher shear strength than coarser RA under the same effective stress and matric suction conditions due to their greater density and lower void ratio. In an unsaturated state, the RA friction angle ranges from 36 to 47°, primarily depending on the particle size

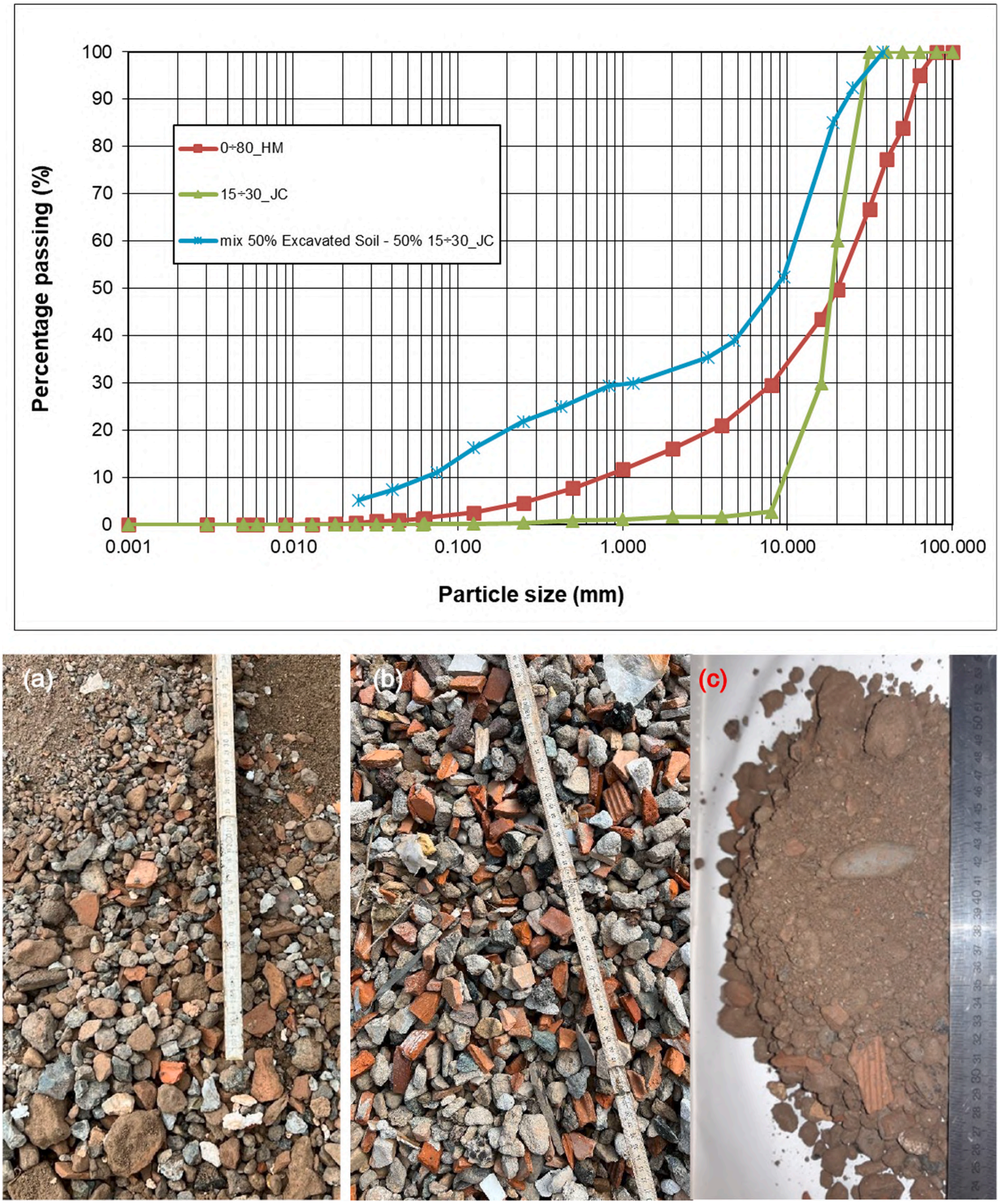

Fig. 5. Particle size distribution curves of the fill materials used in the experimental embankments, with detailed photographs of the aggregate mixtures: a) 0 ÷ 80 mm HM RA; b) 15 ÷ 30 mm JC RA; c) mix of excavated soils (50 %) and 15 ÷ 30 mm JC RA (50 %).

distribution of the aggregates, which is consistent with our observations.

The geogrid used in the tests (Table 1) is a uniaxial knitted product made from high-tenacity multifilament polyester yarns, coated with a protective polymeric layer (model: Xgrid PET C 110). It is specifically designed for reinforcement applications requiring high tensile capacity along the machine direction (MD).

As a knitted geogrid, the transverse filaments are not welded or bonded to the longitudinal ones, but serve only to maintain geometric regularity. Consequently, mechanical strength is provided almost exclusively in the MD, and CMD values are not structurally significant.

The main mechanical and geometrical properties are summarised below:

- Tensile strength (MD): > 110 kN/m
- Elongation at maximum load (MD): 10 ± 2.5 %
- Tensile strength (CMD): > 20 kN/m (not structurally relevant)
- Elongation at maximum load (CMD): 11 ± 2.5 %
- Mesh dimensions (MD × CMD × thickness): 29 × 29 × 3 mm

Table 2
Characteristics of RAs employed in the research.

Properties	0 ÷ 80_HM	15 ÷ 30_JC	Mix 50 % Soil – 50 % 15 ÷ 30_JC
Morphological			
Shape Index (SI)	45	51	a)
Flakiness Index (FI)	17	20	a)
Atterberg Limit			
Passing 0.425 mm sieve (%)	7.79	1.67	24.95
Liquid Limit (%)	28.9	*	26.0
Plastic Limit (%)	16.4	*	7.0
Plastic Index	12.5	*	19.0
Constituent components			
[Rc (%)]	60.81	39.41	a)
[Ru (%)]	15.63	32.89	a)
[Rb (%)]	17.91	24.75	a)
[Ra (%)]	3.42	1.96	a)
[Rg (%)]	0.10	0.00	a)
[X (%)]	2.13	0.99	a)
Mechanical			
Weight loss due to abrasion using the Los Angeles apparatus	37	*	*
Proctor Test ρ_d (g/cm^3)	2.06	*	1.97
Proctor Test w_{opt} (%)	5.90	*	15.50
Point Load Test			
$Is_{(50)}$ on Rc components (MPa)	1.46	2.16	a)
$Is_{(50)}$ on Ru components (MPa)	5.88	6.47	a)
$Is_{(50)}$ on Rb components (MPa)	1,23	1.28	a)
$Is_{(50)}$ on Ra components (MPa)	0.85	0.75	a)
$Is_{(50)}$ on Rg components (MPa)	*	*	*

Proctor compaction tests were performed in accordance with EN 13286–2:2010. For mixture A (50 % soil – 50 % RA 15–30 mm JC), the standard Proctor method was used, while for mixture C (RA 0–80 mm HM), the modified Proctor method was adopted due to the coarse grain size of the material.
* Technical properties not assessed.
a) These properties were not determined because they apply exclusively to granular fractions of > 4 mm in size. As shown in the particle size distribution curves in Fig. 5, adding excavated soil to the recycled aggregate (15–30 mm) did not increase the coarse fraction because it primarily consisted of fine-grained material, predominantly silty-clayey soil.
Rc = Concrete, concrete products, mortar, concrete masonry units;
Ru = Unbound aggregate, natural stone, hydraulically bound aggregate;
Rb = Clay masonry units (bricks and tiles), calcium silicate masonry units, aerated nonfloating concrete.
Ra = Bituminous materials;
g = Glass;
X = Other: cohesive (i.e. clay and soil), miscellaneous: metals (ferrous and nonferrous), non-floating wood, plastic and rubber, gypsum plaster.

These values were provided by the manufacturer and partly verified by internal laboratory tests on single filaments. The geogrid's design ensures durability and effective load transfer under demanding field conditions.

In order to validate the mechanical behaviour of the recycled aggregates in field conditions, a full-scale pullout testing campaign was then carried out to assess the interface response between the geogrid and the different RA-based fills.

The testing methodology is based on the preparation of a field site, where the selected geogrid interface with recycled fill were analysed through pullout tests conducted on three experimental embankments, each constructed with aggregates of different particle sizes. During the tests, the force applied to the front end of the geogrid and its displacement were continuously monitored. Fig. 7 illustrates the method used to apply a force to the front end of the geogrid. The connection method was modified between the tests to prevent immediate rupture of the transverse filaments of the geogrid. A section of the geogrid was intentionally left outside the embankment to enable proper clamping with the pullout system. All tests were conducted under normal stress of approximately 10–12 kPa, corresponding to the geostatic load exerted by the overlying material (approximately 60 cm in thickness). The applied force at the end connected to the steel bar gradually increased, leading to geogrid rupture by tearing in every test.

As with all geosynthetic products, it is important to consider potential damage to the geogrid structure that may occur during installation or as a result of excessive deformation in service. While crushed natural aggregates often exhibit angular edges that enhance interlocking and dilatancy, they may also compromise the mechanical integrity of reinforcements. Conversely, RAs could reduce the presence of sharp inclusions such as glass fragments, thereby limiting abrasion or tearing.

Previous direct tests [35] have shown that the effect of C&DW materials on the short-term tensile behaviour of geosynthetics varies depending on the material structure and polymer type, with greater strength loss observed in geocomposites. For geogrids, the loss of tensile strength observed in recovered specimens after pullout testing was comparable to the stiffness reduction measured at 2 % strain.

Accordingly, a comprehensive programme of geotechnical and geoenvironmental investigations, including tests relevant to pavement applications, was implemented to assess the suitability of C&D aggregates in various geotechnical contexts [26].

To measure and record the variables of interest during the pullout tests, a 200 kN load cell was used to measure the applied force, while a linear position transducer with a 200 cm stroke measured the displacement (Fig. 8). Data acquisition was performed using a data logger designed to measure force, weight, pressure, displacement, and temperature. Fig. 9 presents the instrumentation used in the tests and shows its arrangement and connection. This setup ensured accurate and reliable data collection throughout the experiments, enabling a detailed analysis of geogrid performance under varying conditions.

Force application was performed using the hydraulic arm of an excavator, with great care for motion control thanks to a specific valve for oil flow regulation. Acquiring a data logger made it possible to record the force applied to the geogrid and its displacement during various tests.

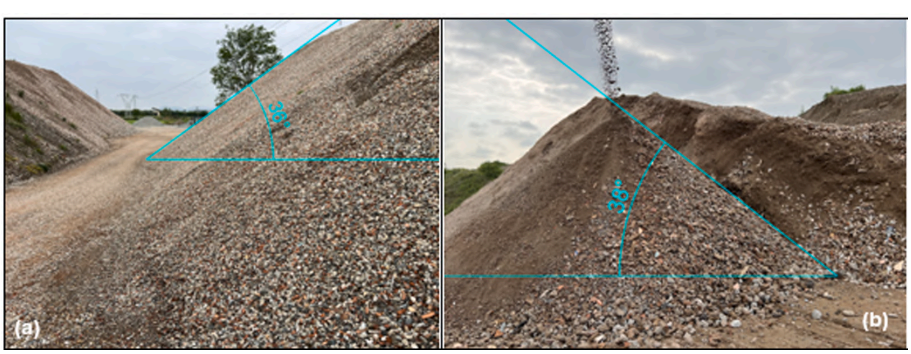

Fig. 6. Photographic representation of the granular material stockpiles used to evaluate the natural repose angle: (a) 15 ÷ 30_JC with a repose angle of 36°, (b) 0 ÷ 80_HM with a repose angle of 38°.

Fig. 7. Connection of the geogrid for force transmission: a) Initial method with stitching of the meshes one by one; b) Tying of the longitudinal filaments.

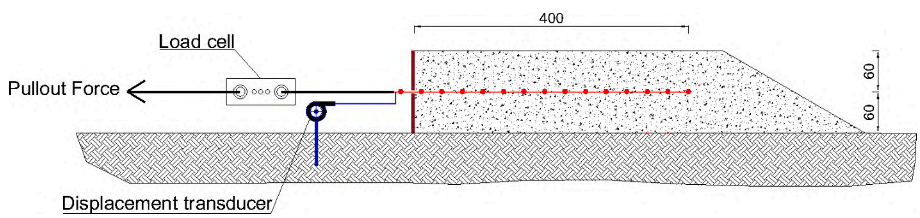

Fig. 8. Schematic representation of the pullout test setup, illustrating the main components and configuration used during the experimental procedure. Load cell and wire displacement transducers were connected to a data logger for acquisition. Measures in cm.

Fig. 9. Systems used to measure and record the variables of interest during pullout tests: a) 200 kN load cell; b) wire displacement transducer; c) data logger for data acquisition.

Results

The pullout tests were labelled with letters A, B, and C, corresponding to the tested embankment. For instance, A1 represents the test performed on the first geogrid installed on embankment A, A2 corresponds to the second test, and so on for all the embankments. In cases where the test must be repeated due to execution issues, subscripts (e.g. $A1_a$, $A1_b$, $A1_c$) are used to distinguish subsequent pullout trials. All tests were conducted under low confinement conditions, corresponding to the overburden weight of approximately 60 cm of fill material, and a normal stress of about 10–12 kPa. The tensile load was applied to geogrid panels 1 m wide, which provided a representative interface length considering both geogrid mesh spacing and maximum particle size in the aggregate. Fig. 10 presents the results obtained from the force–displacement diagrams, and Fig. 11 illustrates the sequential frames captured at successive time intervals during pull-out test C1.

The recorded force–displacement curves exhibited distinct behaviours across embankments. Tests A1 and A2, performed on the blended RA–soil mixture, recorded lower peak pullout forces (20–30 kN/m) and exhibited smooth, continuous force build-up followed by gradual failure. This ductile-like behaviour is consistent with reduced mechanical interlocking and the lubricating effect of the fine silty-clayey soil, which likely weakened the aggregate–geogrid interaction.

Tests B1, B2, and C1, conducted on granular RA fills, yielded higher peak pullout forces (40–50 kN/m). Among these, Test B2 was the most regular, displaying a smooth and symmetric load–displacement curve, whereas the remaining tests (B1 and C1) showed more stepped or irregular profiles. These differences are attributed to variations in grain packing and particle interlocking. The abrupt post-peak drops observed in B1 and C1 suggest semi-brittle failure modes, typical of angular coarse-grained fills under tension. Peak load events were clearly identifiable in all cases and were associated with macroscopic displacement of the front section of the geogrid, including visible detachment from the fill face. Although geogrid strain distribution was not instrumented, tensile rupture of the longitudinal filaments confirmed that failure occurred progressively under increasing load.

Consistent with prior studies [15], active interface shearing was localised within the initial portion of the embedded geogrid. Beyond approximately 30–40 cm from the clamping zone, the relative movement between geogrid and surrounding material appeared negligible.

Beyond the peak force values, the pullout tests revealed distinct mechanical behaviors depending on the backfill type. Coarser RA fills (B1, B2, C1) exhibited sharper post-peak drops in force, indicative of a semi-brittle response, whereas the RA–soil blend (A1, A2) showed more gradual failure, suggesting ductile behavior. These patterns reflect the role of particle interlocking, fines content, and packing effects on geogrid interaction.

Although the pullout curves exhibit behavior similar to typical soil–geogrid interactions, the present results provide valuable confirmation of such behavior under full-scale conditions and low confinement levels using recycled aggregates. This adds practical insight for field applications, where such conditions are often encountered.

Discussion

The results of this experimental investigation demonstrated that the pullout resistance of geogrid-reinforced embankments constructed with RAs from C&DW was comparable to the values obtained in previous laboratory-scale studies. Specifically, the peak shear strength values obtained in the full-scale tests were consistent with those reported by [33,34,36]. Fig. 12 compares the results obtained during the in-situ experimentation and those from pullout tests on geogrids with RA from C&DW conducted in the laboratory by Vieira et al. [36] at different normal stress values. In addition, Fig. 13 compares the particle size distributions of the RAs from the C&DW used in the in-situ experiments with those tested in the laboratory by Vieira et al. [36]. Fig. 14 shows a visual comparison of the various materials analysed. The experiments conducted in this study were performed at significantly lower normal stress values (10–12 kPa) corresponding to low-confinement conditions; however, the comparison remains significant in bridging the gap between laboratory-scale studies and conditions that are nearly representative of real-scale applications.

It is recognised that direct comparison between laboratory and field pullout tests is constrained by fundamental differences in geometry, confinement conditions, boundary control, and material homogeneity. Laboratory tests are typically conducted under higher and more uniform vertical pressures, with strictly controlled compaction and pulling rates, whereas field tests, such as those performed in this study, exhibit variable grain arrangements and limited confinement.

In this context, the presented comparison with literature data [36] should not be interpreted as a validation exercise, but rather as a behavioural assessment of interface mechanisms. Field observations

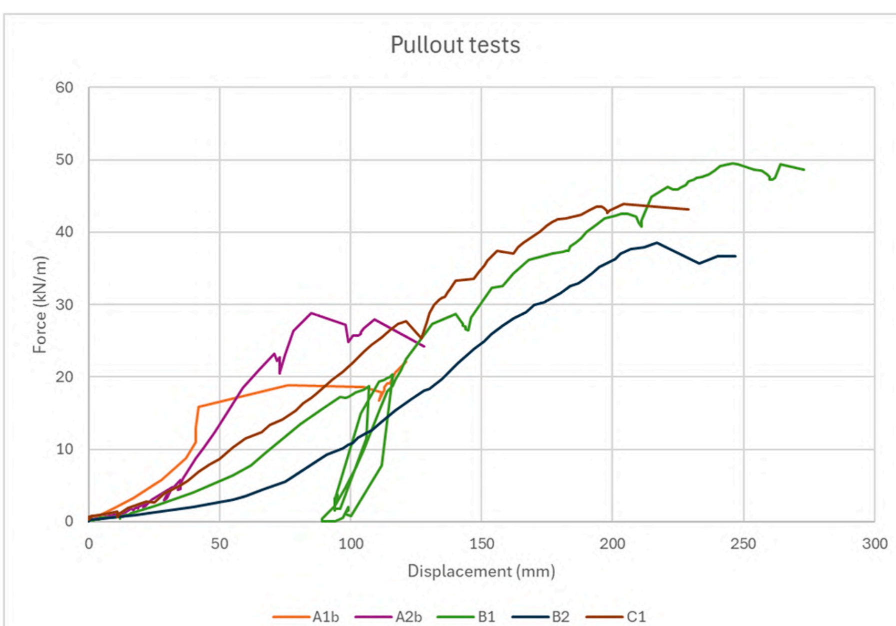

Fig. 10. Summary plot of pullout tests: displacement (X-axis) vs. tensile force applied to geogrids (Y-axis). Force has been applied on a grid width of 1 m. All tests were carried out under normal stress of approximately 10–12 kPa, corresponding to the geostatic load exerted by the overlying material (approximately 60 cm in thickness).

Fig. 11. Sequential frames captured at successive time intervals during the pull-out test C1. The graduated scale highlights the magnitude of the progressive displacement, providing a detailed visualisation of the phenomenon’s evolution. Notably, the progressive pull-out of the geogrid is accompanied by the ejection of some RA clasts. A short video of the pull-out test is provided in the supplementary materials.

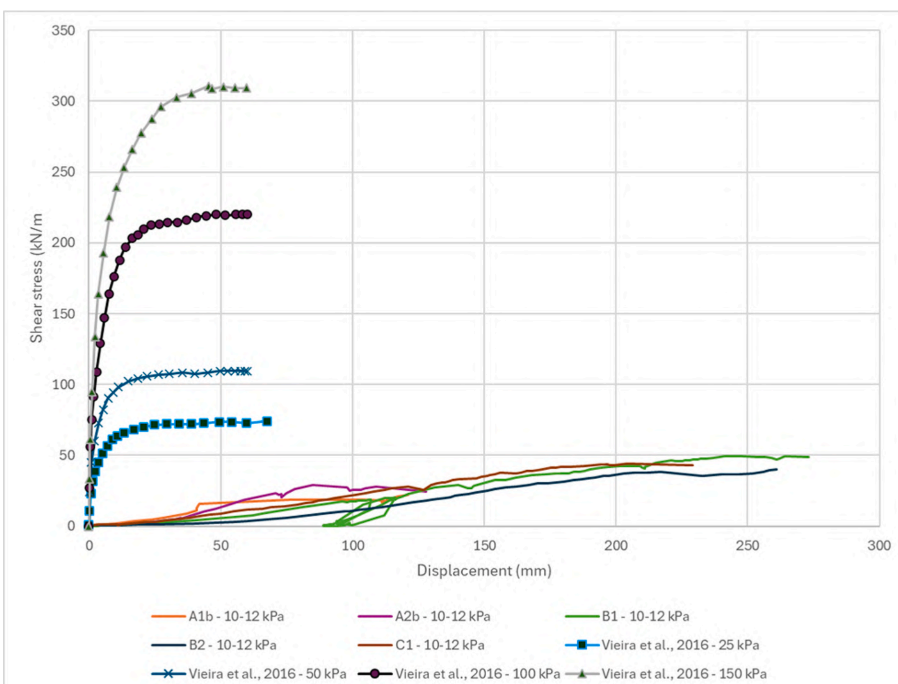

Fig. 12. Comparison of in-situ test results versus pullout tests on geogrids with RA from C&DW conducted in the laboratory by Vieira et al. [36] at different normal stress levels.

confirmed that geogrid–aggregate interaction under low confinement was governed by a combination of smooth sliding and mechanical interlocking or jamming, depending on local contact conditions between geogrid apertures and the size of particles.

In line with previous findings on scale-sensitive behaviour of geosynthetics (e.g. [15], the displacement response in field tests was characterised by early mobilisation due to grain rearrangement, while laboratory curves showed higher initial stiffness and delayed peak formation under higher confinement. These distinctions underline the importance of evaluating geogrid systems not only under idealised conditions, but also within representative boundary scenarios such as those addressed in this study.

Scale effects, installation, and operational features related to the final destination of the embankment are essential factors in assessing the performance of the reinforced structure, including the geogrid/aggregate interface and pull-out strength. Applications include subgrade and road support, void filling, surface regularization, reclamation areas, earth-retaining structures, rockfall protection systems, and others. Reinforcement with geogrids across various layers can increase the stiffness of both the structure and the subgrade — namely in deformable

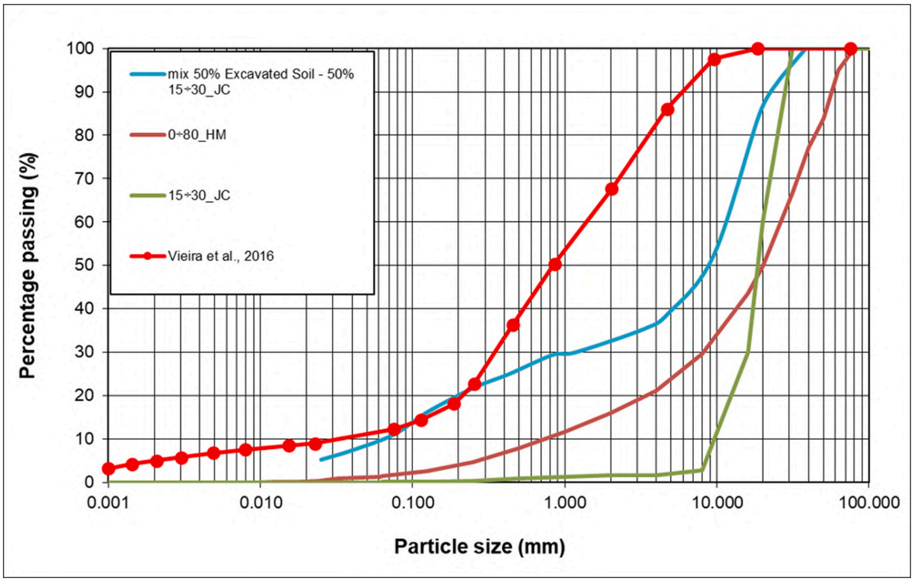

Fig. 13. Comparison of the particle size distribution of the RAs from C&DW used in the in-situ experiments and those tested in the laboratory by Vieira et al. [36.]

Fig. 14. Visual comparison of the different materials analysed in the study, highlighting the characteristics of the RAs used in both in-situ and laboratory tests. a). Mix 50 % Excavated Soils – 50 % 15 ÷ 30 mm RA obtained with JC. b). 15 ÷ 30 mm RA obtained with JC c). 0 ÷ 80 mm RA obtained with HM. d). RA tested by Vieira et al. [36].

soils, peat formations, or frozen ground—while also offering potential savings in construction costs. Traditional solutions, such as gravel columns, may be reconsidered in favour of horizontally reinforced mattresses.

Of particular interest is the graph shown in Fig. 15, where the peak shear load is plotted as a function of normal stress, comparing the values obtained from the in-situ experiments with those reported by Vieira et al. [36]. The in-situ test data show comparable magnitudes to the interpolated lab values, but due to differences in confinement and test setup, this should be interpreted as a similarity in mechanical trends rather than a direct validation. As previously mentioned in Section 2, the values from tests A1b and A2b should be considered less significant due to the deficiencies in the clamping system used for the geogrid pullout tests. The remaining data points fit well with the interpolation curve and even tend to exceed it slightly, reinforcing the reliability of the in-situ experimental results compared to those obtained under confined laboratory conditions.

While the measured pullout responses are consistent with values reported in previous laboratory studies, their reproduction under near-real-scale and low-stress conditions confirms the relevance of recycled aggregates in scenarios with limited confinement. This reinforces their applicability in practical engineering contexts, such as surface layers, transition zones, or temporary works.

The relevance of conducting field-scale pullout tests has been long acknowledged in the literature. Notably, Sayão et al. [25] and Abu-Farsakh et al. [1] demonstrated how full-scale tests exposed interface behaviors, anchorage effects, and post-peak responses not reproducible under laboratory conditions. These studies marked a turning point in the geotechnical understanding of geosynthetic–soil interactions. By applying a similar in situ testing methodology to recycled C&DW aggregates, still largely absent from large-scale datasets, our study extends this line of inquiry to sustainable materials, underlining both

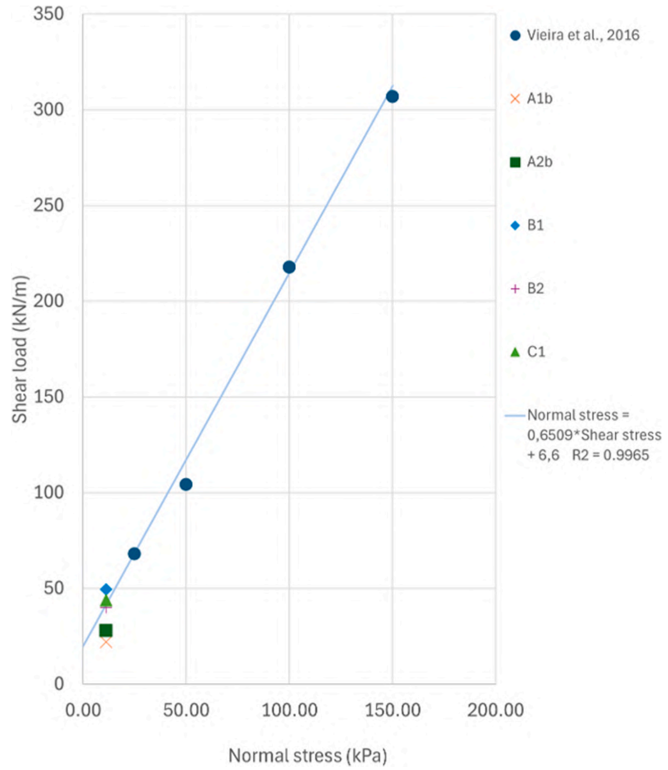

Fig. 15. Direct shear failure envelope, comparing in-situ test results versus laboratory tests by Vieira et al. [36].

performance and operational feasibility under realistic construction scenarios.

A key distinction and fundamental aspect of this study compared to previous research is the testing scale. Most studies on geogrid-reinforced embankments have been limited to laboratory conditions, where the material behaviour is analysed under small-scale controlled environments. While these studies provide valuable insights, they often do not account for the complex interactions occurring at full scale. This research is the first attempt to bridge this gap by employing near-real-scale testing, enabling a more accurate assessment of geogrid-aggregate interactions under actual field conditions. Fig. 8 illustrates that transitioning to real-scale applications, in addition to the low-confinement conditions used in testing, implies more significant displacements due to multiple factors, such as mechanical plays in the pulling system and the deformability of the pulling system itself.

However, the results obtained from the near-full-scale in-situ tests confirm the trends observed in the laboratory experiments, with peak shear stress values showing good consistency. It is essential to highlight that these full-scale tests were conducted under relatively low-normal stress conditions (10÷12 kPa). In contrast, laboratory tests are typically performed at significantly higher normal stress levels, such as 25, 50, 100, and 150 kPa. The normal stress values used in our near-full-scale tests more accurately represent the conditions of the uppermost layers of the reinforced soil embankments, where a low geostatic load leads to poorer confinement conditions and a higher risk of geogrid pullout. Moreover, low-stress levels are of particular interest in the outer zones of the reinforced embankment, where compaction difficulties and the lack of lateral confinement may lead to conditions characterized by reduced normal stresses and both stability and surface protection can be ameliorated with the use of geosynthetics, as they provide a kinematic restraint and calls for a dilatant behaviour of interlocking grains. Consequently, this experimental approach is particularly relevant and valuable for understanding the geogrid behaviour under these critical conditions.

It is particularly relevant to compare the results obtained from experiments with data available in the literature on geogrid interaction tests with natural aggregates [22,23].

This comparison is significant given that one of the main objectives of this research was to assess the feasibility of using RAs from C&DW as substitutes for natural aggregates. This aligns with sustainability goals, promotes circular economy principles, and reduces the consumption of natural resources.

For comparison, the laboratory test conducted by Liu et al. [15], there were various types of geogrids/geotextiles on four different natural soils. Those related to the geogrid that are most similar to those employed in our in-situ tests were selected. In particular, sand was tested at two different compaction levels, providing a more comprehensive evaluation of its interaction with the reinforcement materials.

Fig. 16 compares the particle size distribution of the RAs from the C&DW used in the in-situ tests and the natural aggregates tested by [15].

In Fig. 17, the peak shear load is plotted as a function of the normal stress, comparing in-situ experiments obtained with those reported in the literature for natural aggregates by Liu et al. [15]. The values obtained for the same aggregate type under different vertical-load conditions were interpolated using trend lines of the same colour. By extrapolating these trend lines towards lower normal stress levels, it became evident that the values obtained from the most significant in-situ experiments (tests B1, B2, and C1) were systematically higher than expected based on the interpolated trends.

These results indicate that the use of C&DW-derived RAs does not significantly alter the pullout resistance compared to traditional natural aggregates, reinforcing their potential application in sustainable construction. This provides an effective way to repurpose C&DW in high-value applications rather than their conventional use in low-end backfilling. The findings confirm the viability of using RAs in reinforced embankments without compromising the performance. More importantly, these results underscore the sustainability advantages of using RAs from C&DW because their application in geogrid-reinforced structures is technically viable, significantly reduces the extraction of natural resources, and minimises the landfill disposal of construction waste.

Future research could investigate whether the interpolation trend between the peak shear load values remains linear even at low normal stress levels or tends to follow a curvilinear pattern, as suggested by the results of our near-real-scale experiments.

In addition, this study expands on previous findings by demonstrating that geogrid-reinforced embankments constructed with C&DW-based RAs exhibit mechanical behaviours similar to those of embankments reinforced with natural aggregates. The pullout tests revealed that geogrid-reinforced C&DW-based fills achieved coefficients of interaction comparable to those reported in the literature for soil-geosynthetic interfaces [22,34]. This is particularly relevant when considering the sustainability and cost-effectiveness of RA-based embankments, as they offer a viable alternative to conventional materials while reducing waste disposal and resource extraction. Moreover, compared to traditional backfilling applications, using C&DW in geogrid-reinforced structures provides a more valuable and efficient utilisation of recycled materials, maximising their engineering potential and enhancing their role in sustainable infrastructure development.

Previous laboratory-scale investigations[22]have highlighted that increased moisture content tends to reduce the interface shear strength between the geogrid and fill material. This phenomenon is particularly evident in fine-grained soils, where water infiltration reduces suction force and a subsequent decrease in resistance. However, the moisture content primarily affects the sandy and fine fractions of soils, causing softening and reducing their consistency. Given the level of local compaction and the more significant heterogeneity of the mixed soils used in this study, significant effects related to variations in pore water pressure were unlikely. However, this remains an important topic for future studies. Further investigations should focus on assessing the influence of different moisture regimes on RA-geogrid interactions,

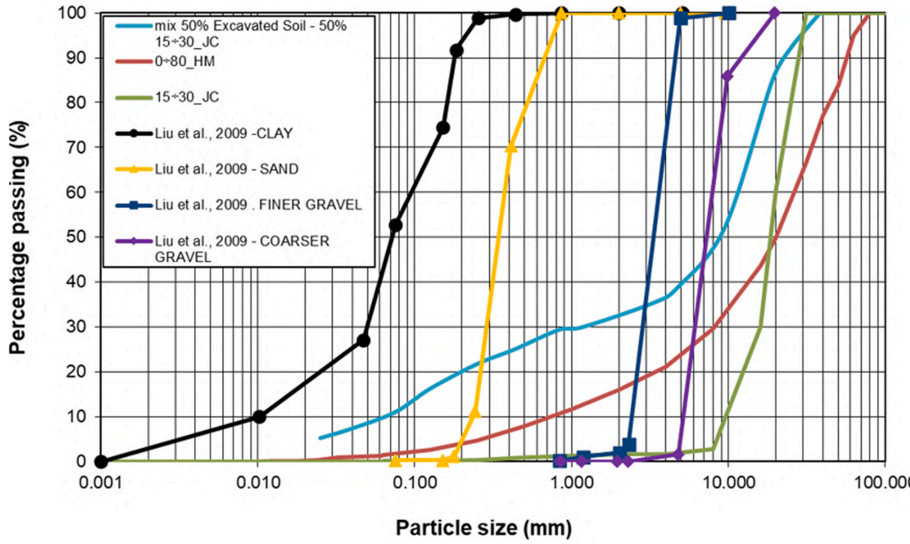

Fig. 16. Comparison of the particle size distribution of the RAs from C&DW used in the in-situ experiments and the natural aggregates tested in laboratory conditions by [15].

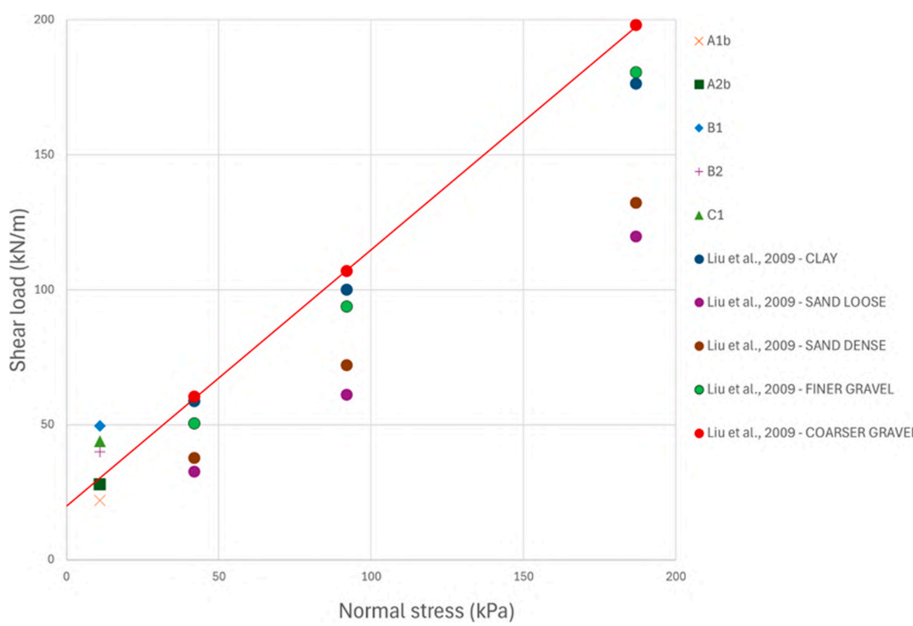

Fig. 17. Direct shear failure envelope, comparing in-situ test results versus laboratory tests on natural aggregates by [15]. The vertical axis exhibits different units because, in current testing, loading was measured, while the interested interface area during shearing may vary without precise control.

providing valuable insights into optimising drainage and performance under varying environmental conditions.

Previous laboratory studies highlighted the importance of grain interlocking within geogrid apertures. The impingement of aggregate particles against geogrid filaments contributes to the overall pullout resistance, and our results confirm that C&DW-based aggregates provide sufficient interlocking to maintain adequate reinforcement. This finding suggests that appropriate grading of C&DW materials can enhance performance, emphasising the need for further optimisation of aggregate processing techniques to ensure a consistent particle size distribution [16,38]. In addition, the type and size of the geogrid apertures used significantly influence the geogrid-recovered aggregate interaction, directly affecting the interlocking mechanism and the overall reinforcement efficiency [20].

Another observation in this study was the effect of the clamping mechanism used in the pullout tests. The initial failure of the transverse filaments prompted an adjustment to the clamping method, leading to an improved load transfer and more reliable results. This underscores the need for careful consideration of geogrid anchoring techniques in testing and field applications because improper clamping can lead to premature failure and misinterpretation of performance data.

During the initial tests (A1 and A2), the geogrid connection method adopted, based on manual stitching of the transverse filaments, resulted in premature rupture and ineffective load transfer. To address this issue, the connection system was modified in subsequent tests (B1, B2, and C1), by removing the transverse filaments and tying the longitudinal yarns directly to a steel bar. This adjustment significantly improved load distribution and allowed the geogrid to develop higher tensile resistance before failure.

Based on this experience, further improvements are proposed for future pullout testing. In particular, the use of a clamping system composed of dual steel plates with an interposed rubber layer is recommended. Such a configuration would ensure uniform gripping, minimise filament damage, and enhance the reproducibility and reliability of results under similar low-confinement conditions.

Conclusions

The findings of this study demonstrate that RAs derived from C&DW are viable alternatives to natural aggregates for constructing geogrid-reinforced embankments. Full-scale tests showed that RA-geosynthetic interfaces achieve shear strengths comparable to those of conventional aggregates, even under low. confinement conditions. These results validate the mechanical performances of RAs for reinforcement applications and highlight their suitability for large-scale use in infrastructure works. This study makes a significant contribution to sustainable geotechnical engineering by providing experimental evidence that enables a more efficient reuse of C&DW in technically demanding applications.

Practical applications should comply with technical standards to prevent issues such as compaction difficulties, differential settlement, anomalous water absorption, and swelling. These risks arise because some components of recycled aggregates — such as ceramics and bricks — may exhibit brittle or softening behavior, unlike natural raw materials. The adoption of recycled aggregates (or secondary aggregates derived from industrial, production, or extractive by-products) not only meets the requirements for construction-grade materials but also aligns with global sustainability goals. It supports the reduction of carbon footprints, encourages a sustainable approach, and contributes to the conservation of primary resources.

To ensure performance comparable to natural aggregates, appropriate selection and basic treatments of recycled aggregates are necessary. This includes removing components such as glass and ceramic fragments, which may otherwise cause damage during installation or compaction of the embankment layers.

From the preliminary tests conducted, biaxial geogrids appear to be more suitable than uniaxial ones, particularly due to their adaptability to varying grain size distributions. This advantage is especially relevant when dealing with significant percentages of fine particles in the aggregate mix, which can otherwise reduce shear strength along interfaces with uniaxial grids due to a lack of interlocking effect.

The incorporation of RAs not only reduces the environmental impact associated with the extraction and transportation of virgin aggregates but also promotes circular economy practices by valorising waste materials that would otherwise be discarded. The outcomes of this research offer a solid foundation for the practical implementation of RA-based embankments in engineering practice and inform future design approaches aiming to reduce the carbon footprint of infrastructure projects.

While this study focuses on short-term mechanical behavior, future research should prioritize the evaluation of long-term durability. Key degradation mechanisms, including strength loss from freeze-thaw cycles, swelling after water absorption, and chemical reactivity (e.g., with acid rain), must be investigated to compare RA performance with that of natural aggregates. These aspects are essential to ensure the reliability and service life of RA-based embankments under varying environmental conditions.

To further advance the field and optimise practical applications, the following research developments are proposed:

- Conduct additional in-situ pullout tests on full-scale embankments, incorporating diverse mixtures of soils and RAs, different types of geogrids (including variations in mesh apertures), a range of normal stresses, and varying compaction levels.
- Investigate the long-term stability of RA-based embankments by accessing the potential effects of moisture content, particularly on field performance and drainage design.
- Expand material characterisation testing, including direct shear tests, triaxial compression tests on aggregate mixes, and field compaction assessment (e.g. penetrometer tests and plate load tests) and compare these with the results from laboratory Proctor tests.
- Evaluate the durability and performance testing of RAs based on the intended application of the geogrid-reinforced embankment, including frost resistance, fragmentation behaviour during compaction, and other degradation mechanisms.
- Tests employing advanced equipment that allow for progressive, slow, and controlled pullout of geogrids to provide more detailed insights into material interactions.
- Improve geogrid clamping systems to enhance test reliability by minimizing artifacts caused by anchoring mechanisms.
- Conduct a comprehensive evaluation of the influence of varying normal stress levels on the pullout behaviour of geogrids, particularly to assess whether the fitting curve exhibits linearity at low-stress levels. This aspect is crucial, as[17]highlighted that most coarse-grained soils display non-linear characteristics at low net confining stress; however, transition to a linear behaviour at higher stress levels. This phenomenon is attributed to suppressing dilatancy and particle breakage at elevated net stresses. Grain size distribution of aggregate, acting normal pressure, and geogrid opening of meshes finally result as the primary influencing factors for performance assessment of the reinforcement.
- Consider environmental constraints related to potential leachate production and contaminant release, especially when RA originates from specific waste types (e.g., road paving, metallurgical slags, saw and wire stone-cutting, composite material for constructions). Ensuring source traceability and pre-treatment becomes critical to safeguard environmental compatibility.

These research developments would enhance understanding of the behaviour and performance of RAs and geogrids under diverse conditions, providing a robust foundation for designing and implementing more sustainable and resilient infrastructure. Ultimately, these advancements could contribute to developing reliable design guidelines, ensuring the practical and safe application of RA-based geogrid-reinforced embankments in engineering practice.

CRediT authorship contribution statement

Marco Casale: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giovanna Antonella Dino:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration. **Claudio Oggeri:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Investigation, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trgeo.2025.101638.

Data availability

Data will be made available on request.

References

[1] Abu-Farsakh MY, Almohd I, Farrag K. Comparison of field and laboratory pullout tests on geosynthetics in marginal soils. Transportation Research Record: Journal of the Transportation Research Board 2006;1975:124–36. https://doi.org/10.1177/0361198106197500114.

[2] Basu D, Misra A, Puppala AJ. Sustainability and geotechnical engineering: perspectives and review. Can. Geotech. J. 2015;52:96–113. https://doi.org/10.1139/cgj-2013-0120.

[3] Bordoloi S, Diran A, Ng CWW. Feasibility of construction demolition waste for unexplored geotechnical and geo-environmental applications-a review. Constr. Build. Mater. 2022;356:129230. https://doi.org/10.1016/j.conbuildmat.2022.129230.

[4] Dąbrowska J, Kiersnowska A, Zięba Z, Trach Y. Sustainability of Geosynthetics-based Solutions. Environments 2023;10:64. https://doi.org/10.3390/environments10040064.

[5] EN 933-1:2012 - Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method [WWW Document], n.d. . ITeh Stand. URL https://standards.iteh.ai/catalog/standards/cen/100b983f-85a4-4a80-934c-e93c584dbdb4/en-933-1-2012 (accessed 1.20.25).

[6] EN 933-3:2012 - Tests for geometrical properties of aggregates - Part 3: Determination of particle shape - Flakiness index [WWW Document], n.d. . ITeh Stand. URL https://standards.iteh.ai/catalog/standards/cen/0ccc19d3-9861-4d02-b943-5f166e7cf6d6/en-933-3-2012 (accessed 1.20.25).

[7] EN 933-4:2008 - Tests for geometrical properties of aggregates - Part 4: Determination of particle shape - Shape index [WWW Document], n.d. . ITeh Stand. URL https://standards.iteh.ai/catalog/standards/cen/86ed46c0-f6fe-4f0b-9381-f4309c159b0f/en-933-4-2008 (accessed 1.20.25).

[8] EN 933-11:2021 - Tests for geometrical properties of aggregates - Part 11: Classification test for the constituents of coarse recycled aggregate [WWW Document], n.d. . ITeh Stand. URL https://standards.iteh.ai/catalog/standards/sist/d27ac2b9-227d-425a-9e6d-3a9f3624229b/osist-pren-933-11-2021 (accessed 1.17.25).

[9] En 1097–2,. Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation [WWW Document]. n.d. . ITeh Stand. 2020. accessed 1.20.25.

[10] EN ISO 17892-4:2016 - Geotechnical investigation and testing - Laboratory testing of soil - Part 4: Determination of particle size distribution (ISO 17892-4:2016) [WWW Document], n.d. . ITeh Stand. URL https://standards.iteh.ai/catalog/standards/cen/eb256e27-684c-46f9-ac31-0d7c307ab226/en-iso-17892-4-2016 (accessed 1.20.25).

[11] EN ISO 17892-12:2018 - Geotechnical investigation and testing - Laboratory testing of soil - Part 12: Determination of liquid and plastic limits (ISO 17892-12: 2018) [WWW Document], n.d. . ITeh Stand. URL https://standards.iteh.ai/catalog/standards/cen/c3d39b6a-748d-43da-8a18-21a361d77e1e/en-iso-17892-12-2018 (accessed 1.20.25).

[12] European C. Waste statistics [WWW Document]. Explain: Stat; 2024. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics (accessed 1.17.25.

[13] Garau, E., 2024. Comportamento all'interfaccia tra geogriglie e materiali riciclati da costruzione e demolizione in rilevati rinforzati (Unpublished master's thesis). Politecnico di Torino.

[14] Gomes Correia A, Winter MG, Puppala AJ. A review of sustainable approaches in transport infrastructure geotechnics. Transp. Geotech. 2016;7:21–8. https://doi.org/10.1016/j.trgeo.2016.03.003.

[15] Liu C-N, Ho Y-H, Huang J-W. Large scale direct shear tests of soil/PET-yarn geogrid interfaces. Geotext. Geomembr. 2009;27:19–30. https://doi.org/10.1016/j.geotexmem.2008.03.002.

[16] Liu J, Pan J, Liu Q, Xu Y. Experimental study on the interface characteristics of geogrid-reinforced gravelly soil based on pull-out tests. Sci. Rep. 2024;14:8669. https://doi.org/10.1038/s41598-024-59297-9.

[17] Noor, M.J.M., Anderson, W.F., 2012. A Comprehensive Shear Strength Model for Saturated and Unsaturated Soils 1992–2003. Doi: 10.1061/40802(189)168.

[18] Oggeri, C., Vinai, R., 2020. Characterisation of geomaterials and non-conventional waste streams for their reuse as engineered materials, E3S Web of Conferences. Doi: 10.1051/e3sconf/202019506002.

[19] Ok B, Colakoglu H, Dagli U. Evaluation of the geogrid-various sustainable geomaterials interaction by direct shear tests. Geomech Eng 2023;34:173–86.

[20] Özer M. Determination of the relationship between geogrid aperture size and aggregate particle size. Arab. J. Geosci. 2021;14:3. https://doi.org/10.1007/s12517-020-06210-z.

[21] Rahardjo H, Santoso VA, Leong EC, Ng YS, Tam CPH, Satyanaga A. Use of recycled crushed concrete and Secudrain in capillary barriers for slope stabilization. Can. Geotech. J. 2013;50:662–73. https://doi.org/10.1139/cgj-2012-0035.

[22] Razeghi HR, Ensani A. Clayey Sand Soil Interactions with Geogrids and Geotextiles using Large-Scale Direct Shear Tests. Int J Geosynth Ground Eng 2023;9:24. https://doi.org/10.1007/s40891-023-00443-0.

[23] Sakleshpur VA, Prezzi M, Salgado R, Siddiki NZ, Choi YS. Large-scale direct shear testing of geogrid-reinforced aggregate base over weak subgrade. Int. J. Pavement Eng. 2019;20:649–58. https://doi.org/10.1080/10298436.2017.1321419.

[24] Santos ECG, Palmeira EM, Bathurst RJ. Behaviour of a geogrid reinforced wall built with recycled construction and demolition waste backfill on a collapsible foundation. Geotext. Geomembr. 2013;39:9–19. https://doi.org/10.1016/j.geotexmem.2013.07.002.

[25] Sayão ASFJ, Sieira ACCF, Castro DC, Gerscovich DMS. Field and laboratory pullout tests on geogrids. In: Delmas P, Gourc JP, Girard H, editors. Geosynthetics: 7th International Conference on Geosynthetics. Lisse: Swets & Zeitlinger; 2002. p. 1353–6.

[26] Sharma A, Shrivastava N, Lohar J. Assessment of geotechnical and geo-environmental behaviour of recycled concrete aggregates, recycled brick aggregates and their blends. Clean Mater 2023;7:100171. https://doi.org/10.1016/j.clema.2023.100171.

[27] Silvestre GR, Fleury MP, Lins da Silva J, Santos ECG. Use of Recycled Construction and Demolition Waste (RCDW) in Geosynthetic-Reinforced Roadways: Influence of Saturation Condition on Geogrid Mechanical Properties. Sustainability 2023;15:9663. https://doi.org/10.3390/su15129663.

[28] Soyinka OA, Wadu MJ, Lebunu Hewage UWA, Oladinrin TO. Scientometric review of construction demolition waste management: a global sustainability perspective. Environ. Dev. Sustain. 2023;25:10533–65. https://doi.org/10.1007/s10668-022-02537-7.

[29] Vibha S, Divya PV. Geosynthetic-Reinforced Soil Walls with Sustainable Backfills. Indian Geotech J 2021;51:1135–44. https://doi.org/10.1007/s40098-020-00450-2.

[30] Vieira CS. Valorization of Fine-Grain Construction and Demolition (C&D) waste in Geosynthetic Reinforced Structures. Waste Biomass Valorization 2020;11:1615–26. https://doi.org/10.1007/s12649-018-0480-x.

[31] Vieira CS, Ferreira FB, Pereira PM, de Lopes M, L., Gomes, A.T., Madeira, S., Cristelo, N.,. Valorisation of C&D waste as backfill material of geosynthetic reinforced structures – study of the long-term behaviour. Geosynthetics: Leading the Way to a Resilient Planet. CRC Press; 2023.

[32] Vieira CS, Ferreira FB, Pereira PM, Lopes ML. Pullout behaviour of geosynthetics in a recycled construction and demolition material – Effects of cyclic loading. Transp. Geotech. 2020;23:100346. https://doi.org/10.1016/j.trgeo.2020.100346.

[33] Vieira CS, Pereira P, Ferreira F, Lopes ML. Pullout Behaviour of Geogrids embedded in a Recycled Construction and Demolition Material. Effects of Specimen size and Displacement Rate. Sustainability 2020;12:3825. https://doi.org/10.3390/su12093825.

[34] Vieira CS, Pereira PM. Use of mixed Construction and Demolition Recycled Materials in Geosynthetic Reinforced Embankments. Indian Geotech J 2018;48:279–92. https://doi.org/10.1007/s40098-017-0254-6.

[35] Vieira CS, Pereira PM. Damage induced by recycled Construction and Demolition Wastes on the short-term tensile behaviour of two geosynthetics. Transp. Geotech. 2015;4:64–75. https://doi.org/10.1016/j.trgeo.2015.07.002.

[36] Vieira CS, Pereira PM, de Lopes M, L.,. Recycled Construction and Demolition Wastes as filling material for geosynthetic reinforced structures. Interface properties J Clean Prod 2016;124:299–311. https://doi.org/10.1016/j.jclepro.2016.02.115.

[37] Vinai, R., Ronco, C., Oggeri, C., 2021. Validation of numerical D.E.M. modelling of geogrid reinforced embankments for rockfall protection. GEAM, Geoing. ambient. min. LVIII, 36–45. Doi: 10.19199/2021.2-3.1121-9041.036.

[38] Zhao Y, Yang G, Wang Z, Yuan S. Research on the effect of Particle size on the Interface Friction between Geogrid Reinforcement and Soil. Sustainability 2022;14:15443. https://doi.org/10.3390/su142215443.

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