

Analysis of Damage in PP and HDPE Geocells Under Accelerated Pavement Testing (APT)

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Abstract. This study investigates the mechanical degradation of HDPE and polypropylene nonwoven (PP-NW) geocells subjected to accelerated pavement testing (APT). Geocells are widely used for reinforcement of granular layers; however, their post-loading mechanical behavior remains insufficiently understood. A large-scale experimental program was conducted using a wheel loading system to simulate traffic conditions on pavement sections reinforced with geocells of different materials and heights. After trafficking, specimens were extracted and subjected to tensile, adhesion, and shear tests to evaluate mechanical degradation. The results indicate that HDPE geocells exhibit stable mechanical behavior with high strength retention and low variability after loading. In contrast, PP-NW geocells show greater sensitivity to degradation, particularly in tensile and adhesion responses, associated with their fibrous structure. Shear response was less affected by loading in all cases. The findings highlight the importance of considering post-degradation behavior in geocell design and contribute to a better understanding of material-dependent damage mechanisms under repeated loading.

1 Introduction

The use of geocells in pavement engineering has been extensively investigated over the past decades as an effective solution for reinforcing granular layers and improving the structural performance of pavements, particularly those constructed over weak subgrades. The primary reinforcement mechanism of geocells is associated with the three-dimensional confinement of the infill material, which restricts lateral particle movement, reduces permanent deformation, and enhances vertical stress distribution [1–2]. Experimental studies under cyclic and repeated loading conditions consistently report significant reductions in rutting and substantial increases in pavement service life when compared with unreinforced systems.

Geocells used in roadway applications are predominantly manufactured from polymeric materials, mainly high-density polyethylene (HDPE), polypropylene (PP), and polymeric alloys. These materials exhibit distinct mechanical characteristics in terms of stiffness, ductility, tensile strength, and viscoelastic response, which directly influence geocell performance under repeated loading [1]. HDPE is generally characterized by higher flexibility and chemical resistance, whereas PP typically presents higher initial stiffness, potentially leading to different deformation patterns and damage evolution during service.

Several experimental studies have demonstrated the effectiveness of geocells in reducing permanent deformation and increasing the number of load cycles sustained up to critical rut depths, both in laboratory cyclic loading tests and in Accelerated Pavement Testing (APT) programs [1–2]. APT enables the simulation of near-field traffic conditions within a shortened timeframe by applying moving loads, shear stresses, and cumulative deformation effects, making it a valuable tool for assessing the structural behavior of geocell-reinforced pavements.

In current engineering practice, the long-term performance of geocells is typically addressed through empirical safety factors rather than through explicit durability-based design criteria. As a result, the potential effects of material degradation under traffic loading are not directly incorporated into pavement design methodologies. A more detailed understanding of degradation mechanisms may contribute to the development of more rational design approaches, including the use of reduction factors based on material behavior under repeated loading.

However, most available investigations focus on the global pavement response, such as surface deformation, stress distribution, and structural benefit factors. Studies directly addressing the physical and mechanical condition of geocells after repeated loading remain scarce, especially with respect to the identification of damage mechanisms, permanent deformation, cracking, and changes in mechanical properties of polymeric materials [1–5]. This gap limits the understanding of degradation mechanisms and hinders the incorporation of durability-based criteria into pavement design methods.

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Therefore, this study investigates the post-loading behavior of HDPE and PP nonwoven geocells subjected to accelerated pavement testing, with emphasis on their mechanical degradation and variability. The results aim to contribute to a better understanding of material-dependent damage mechanisms and to provide technical support for improving the design and durability assessment of geocell-reinforced pavement systems.

2 Methodology

This study was conducted using a wheel load testing program aimed at evaluating the structural performance of pavements reinforced with geocells of different heights. The pavement structure was designed to represent typical low-bearing-capacity conditions, consisting of a soft subgrade overlain by a base layer constructed with reclaimed asphalt pavement (RAP).

To enhance the mechanical response of the system and improve load distribution over the soft subgrade, geocell reinforcement was incorporated within the RAP base layer. Polymeric geocells manufactured from high-density polyethylene (HDPE) and polypropylene (PP) with different heights were evaluated. The geocells were installed at a predefined location within the base layer, forming a three-dimensional confinement system. The variation in geocell height allowed the assessment of the influence of geocell height on the structural behavior of the reinforced pavement.

The wheel load tests consisted of applying repeated loads at the pavement surface to simulate traffic-induced stresses. The tests were performed on pavement sections with different reinforcement configurations, while maintaining the RAP base material constant and varying exclusively the geocell height. This experimental approach enabled an isolated evaluation of the effect of geocell height on the mechanical response of the pavement structure.

The loading protocol was defined to induce cumulative deformation within the pavement system, allowing the evaluation of performance under repeated loading conditions. Throughout the experimental program, the structural response of the tested sections was monitored to assess the effectiveness of geocell reinforcement in increasing the load-bearing capacity of the RAP base and mitigating permanent deformation over the soft subgrade.

The adopted experimental configuration enabled direct comparison between pavement sections reinforced with geocells of different heights and polymer types, as well as with unreinforced reference sections, all subjected to equivalent loading conditions.

2.1 Materials and Methods

2.1.1 Geocells

The geocells used in this study were manufactured from high-density polyethylene (HDPE) and polypropylene nonwoven (PP-NW), cut to specific lengths, and joined to form the characteristic three-dimensional cellular

structure. The spacing between joints and cell heights were selected to match those of commercially available geocells, ensuring representative conditions for pavement applications.

Commercial geocells typically feature pocket dimensions ranging from approximately 230 to 320 mm in length and 190 to 290 mm in width. In this study, the HDPE geocell had nominal cell dimensions of 320 × 287 mm, while the PP-NW geocell was characterized by a nominal cell opening of 180 mm and a seam spacing of 380 mm (Tables 1 and 2).

Table 1. Geometric properties of HDPE geocells.

GEOMETRIC PARAMETER	HDPE 100 mm	HDPE 200 mm
Nominal strip thickness (mm)	1.25 (−10%)	1.25 (−10%)
Total thickness, including texture (mm)	1.50 (−5% / +10%)	1.50 (−5% / +10%)
Nominal diamond-shaped texturing (units/cm ²)	22 – 31	22 – 31
Nominal perforation diameter (mm)	10 (±10%)	10 (±10%)
Nominal cell height (mm)	100 (±2%)	200 (±2%)
Nominal cell dimensions (mm)	320 × 287 (±2%)	320 × 287 (±2%)
Nominal panel dimensions (m)	4.16 × 9.76 (±2%)	4.16 × 9.76 (±2%)

Table 2. Geometric properties of PP-NW geocells.

GEOMETRIC PARAMETER	PP - NW 100 mm	PP - NW 200 mm
Nominal strip thickness (mm)	2.0	2.0
Nominal cell height (mm)	100	200
Nominal cell opening (mm)	180	180
Nominal distance between seams (mm)	380	380
Number of cells per m ² (units/m ²)	25	25
Nominal panel area (m ²)	15.6	7.8
Nominal panel length (m)	6.0	3.0
Nominal panel width (m)	2.6	2.6

The HDPE geocell strips were joined by welding, providing structural continuity and adequate joint strength. In contrast, the PP geocell strips were stitched using polymer-compatible material, ensuring the integrity of the connections during installation and loading tests.

The geometric properties of the geocells are summarized in Tables 1 and 2. The HDPE and PP-NW geocells are illustrated in the corresponding figures.

2.1.2 RAP and subgrade materials

The base layer and the geocell infill were composed of reclaimed asphalt pavement (RAP). The RAP thickness was maintained at 200 mm for all configurations.

The RAP material was characterized in terms of its physical and compaction properties. The material presented a bitumen content of 3.86%, determined using a centrifugal extractor. The maximum dry density was 1.895 g/cm^3 , and the optimum moisture content was 4.6%. The particle size distribution curve is presented in Figure 1.

The subgrade was simulated using a closed-cell foam with a density of 45 kg/m^3 to provide a controlled and repeatable support condition.

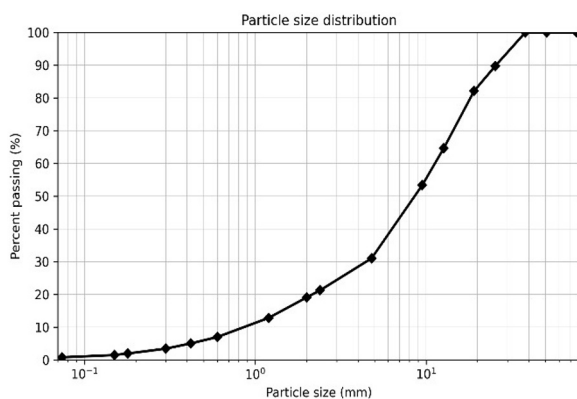
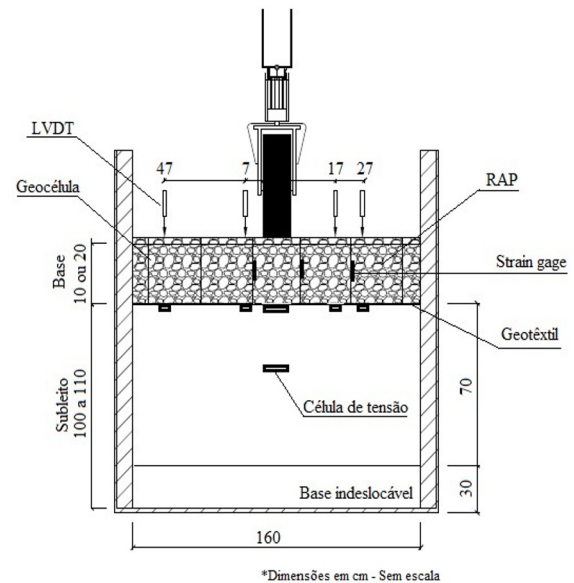


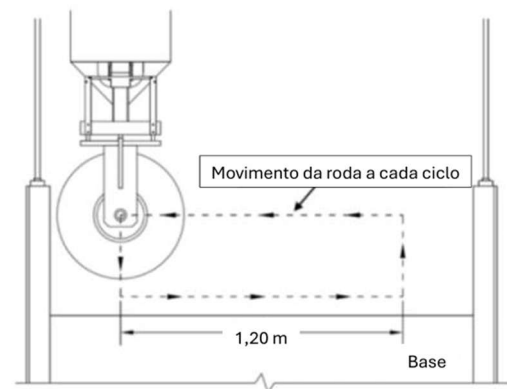
Fig. 1. Particle size distribution of the RAP material.

2.1.3 Experimental setup

This study employed a large-scale steel box with dimensions of $1,800 \times 1,600 \times 1,800 \text{ mm}$ for the experimental testing program. The accelerated pavement testing (APT) device was installed on the steel frame of the box. Figures 2 (a,b) and 3 present, respectively, the cross-sectional and photographic views of the experimental setup. The thicknesses of the subgrade layer and the RAP (Reclaimed Asphalt Pavement) base layer were set to 700 mm and 200 mm, respectively, with the RAP base layer placed directly over the soft subgrade.



(a) General schematic of the experiment



(b) Unidirectional wheel movement

Fig. 2. Cross-sectional view of the experimental setup.

The loading system consisted of a single-wheel configuration, fixed at the central axis of the box and fitted with a Trelleborg T-800 tire, with a diameter of 540 mm and a width of 154 mm. The wheel load was applied as a linearly increasing load, rising from 0 to a peak value of 16 kN within 0.1 s, resulting in a contact pressure of 700 kPa on the pavement surface. The load was then maintained constant along a 1.2 m wheel path. At the end of the travel, the load was reduced to zero, the wheel was lifted, and the system returned to the starting position in approximately 1.5 s [3].

This operational configuration was adjusted to perform 1,000 wheel passes every 1 h and 45 min, simulating repeated traffic loading conditions.

A load cycle period of 1.50 s was adopted, corresponding to a loading frequency of approximately 0.67 Hz.



Fig. 3. General view of the test setup.

2.1.4 Test Procedure

This study aimed to evaluate damage mechanisms in HDPE and PP-NW geocells subjected to repeated wheel loading. Two cell heights (100 mm and 200 mm) were investigated to assess the influence of geocell geometry on the mechanical response and damage development.

Filling geocells is recognized as a challenging procedure, as the cellular confinement restricts the free flow and redistribution of infill materials. In this experimental program, the geocell infilling process was carried out manually. Initially, adjacent cells were alternately filled to facilitate proper cell opening and alignment, ensuring uniform expansion of the geocell mattress. After achieving full deployment, all cells were filled with RAP material.

Compaction of the infill material was performed using a steel tamper weighing 10 kg, with base dimensions of 70×70 mm, applied uniformly across the geocell-reinforced layer. This procedure was adopted to ensure adequate densification of the RAP while minimizing localized damage to the geocell structure during construction. The compaction approach was kept consistent across all test sections to maintain comparability among the different configurations.

Within the present experimental program, the geocell-reinforced systems exhibited ultimate bearing capacities close to the standard applied pressure of 700 kPa, indicating that the selected loading level was appropriate for inducing damage while avoiding premature structural failure. This loading condition enabled a reliable assessment of geocell performance and damage evolution under repeated traffic-like loading.



Fig. 4. View of the geocells inside the test box.

2.1.5 Laboratory Testing

After completion of the accelerated pavement testing (APT) program, degraded specimens were extracted from the wheel path centerline, where the highest stress and strain levels occur. Virgin specimens were prepared from untrafficked geocell panels of the same products. For each geocell type, five specimens were tested in each condition (virgin and degraded).

The laboratory testing program included wide-width tensile tests, junction (adhesion) tests, and shear tests. Wide-width tensile tests were performed in accordance with ISO 10319 [8]. Junction (adhesion) and shear tests were conducted using the same universal testing machine and specimen preparation, following the laboratory procedures adopted at EESC/USP.

All laboratory testing was carried out at the Geosynthetics Laboratory of the São Carlos School of Engineering (EESC), University of São Paulo (USP), under controlled conditions and standardized procedures. Prior to mechanical testing, the geocell panels were carefully removed from the experimental setup and subjected to a detailed visual inspection to identify potential physical damage, such as cracking, permanent deformation, seam or weld failures, and localized ruptures. Subsequently, the extent of degradation was quantitatively assessed through mechanical testing, enabling the correlation between observed physical damage and the reduction in mechanical performance of the geocells following the APT program.

3 Results and discussion

3.1 Visual inspection

Visual inspection of the extracted specimens indicated no macroscopic damage (tearing, cracking, or

permanent geometric distortion) for either HDPE or PP-NW geocells after the APT program. Cell walls and connections remained intact, suggesting that the adopted trafficking conditions did not produce visually detectable degradation.

3.2 Mechanical testing results

Mechanical degradation was assessed through wide-width tensile tests (ISO 10319 [8]) and complementary junction (adhesion) and shear tests. Results are presented as mean strength (kN/m) with standard deviation (error bars) and as strength retention, calculated as $\text{Retention (\%)} = (S_{\text{degraded}} / S_{\text{virgin}}) \times 100$. Figures 5–8 present the mechanical response for each geocell type and height, while Figure 9 provides an integrated comparison across materials and heights.

Considering the effect of geocell height, HDPE geocells showed similar post-degradation behavior for 100 mm and 200 mm cells (Figures 5 and 6), with strength retention generally above 90% and limited

dispersion. For PP-NW geocells, the influence of height was more variable (Figures 7 and 8); the 200 mm configuration did not consistently improve strength retention and exhibited larger variability, particularly in shear.

Comparing materials under the same height, HDPE geocells tended to exhibit more uniform strength retention and smaller error bars than PP-NW systems, especially in tensile and junction (adhesion) tests (Figures 5–8). Across test modes, shear results generally showed smaller relative reductions than tensile and adhesion, suggesting a lower sensitivity of shear resistance to the applied trafficking conditions.

The use of strength retention as a comparative parameter allows the post-degradation mechanical response of geocells with different initial strength levels to be evaluated on a consistent basis. This approach is particularly relevant when comparing materials with distinct polymer structures and manufacturing processes, such as extruded HDPE and nonwoven PP systems. In addition to mean strength values, the consideration of result variability through standard

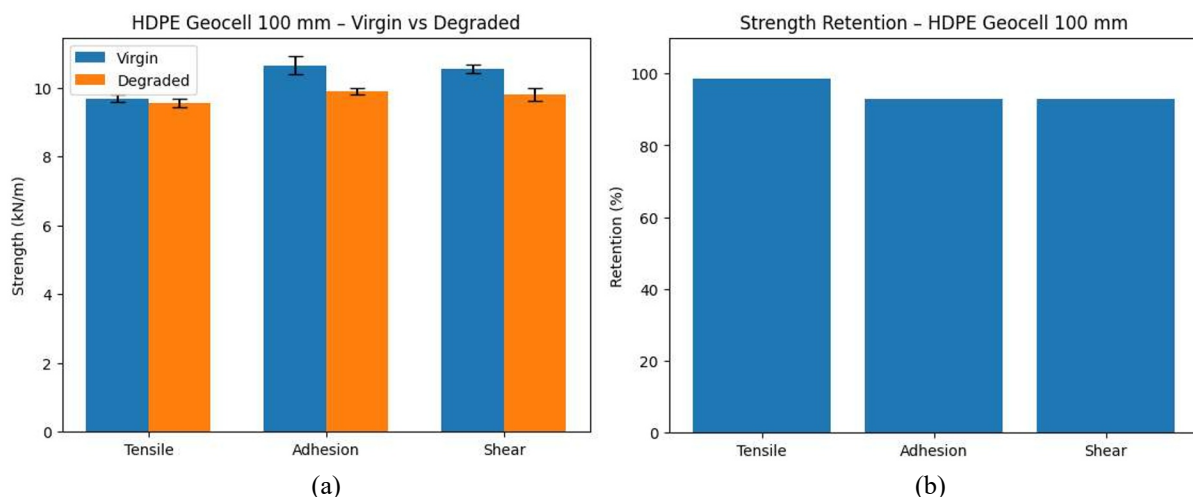


Fig. 5. Mechanical response of HDPE geocell (100 mm) before and after traffic-induced degradation under tensile, adhesion, and shear loading: (a) strength (kN/m) with error bars (b) strength retention (%).

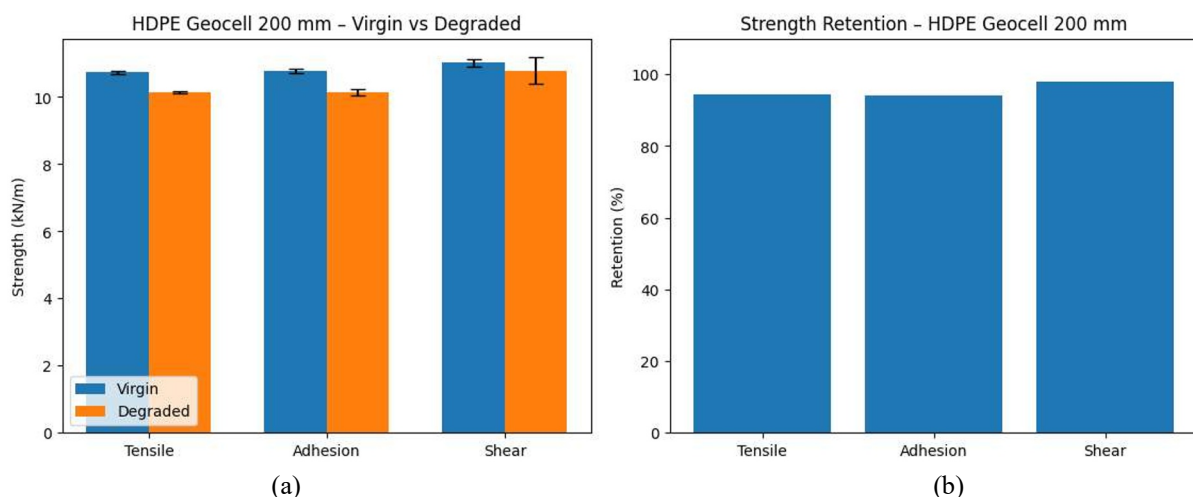


Fig. 6. Mechanical response of HDPE geocell (200 mm) before and after traffic-induced degradation under tensile, adhesion, and shear loading. (a) strength (kN/m) with error bars (b) strength retention (%).

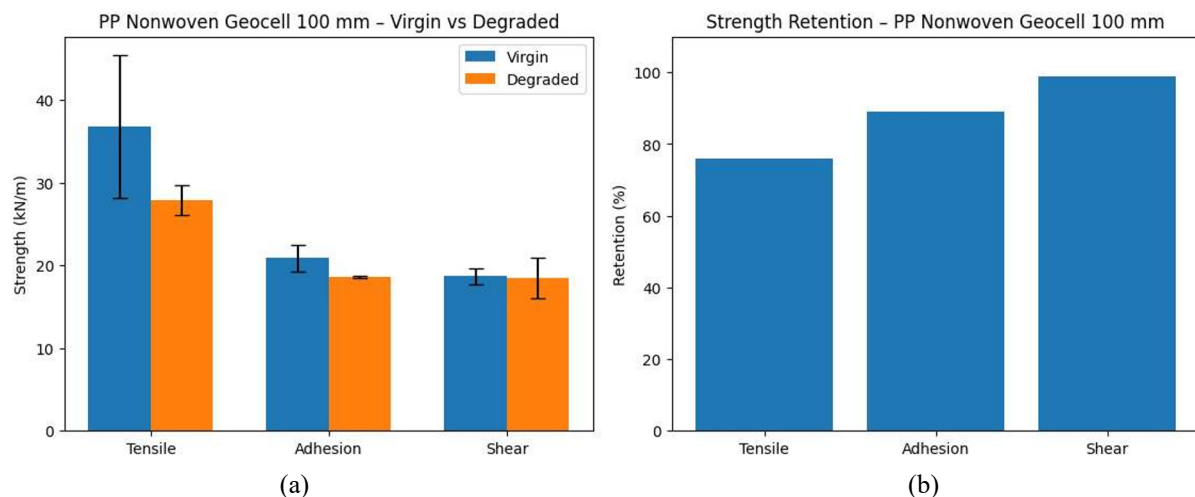


Fig. 7. Mechanical response of PP nonwoven geocell (100 mm) before and after traffic-induced degradation under tensile, adhesion, and shear loading. (a) strength (kN/m) with error bars (b) strength retention (%).

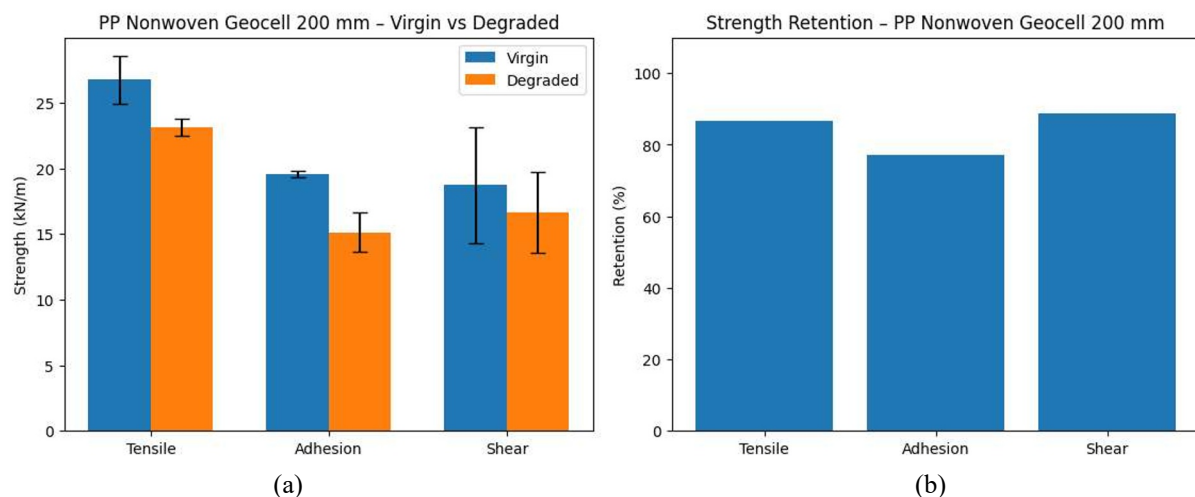


Fig. 8. Mechanical response of PP nonwoven geocell (200 mm) before and after traffic-induced degradation under tensile, adhesion, and shear loading. (a) strength (kN/m) with error bars (b) strength retention (%).

deviation provides insight into the uniformity and predictability of the mechanical response after traffic-induced degradation. This combined assessment enables a more comprehensive interpretation of damage effects than the analysis of absolute strength values alone. The observed differences in post-degradation mechanical performance are primarily associated with the material structure and manufacturing processes of the evaluated geocells. Extruded HDPE geocells, characterized by continuous polymer walls and welded joints, exhibited limited sensitivity to traffic-induced degradation, maintaining high strength retention and low variability. In contrast, PP nonwoven geocells showed greater variability and more pronounced reductions, particularly in tensile and adhesion responses. This behavior is attributed to their fibrous structure, which is more susceptible to microstructural changes under cyclic

loading. Particle-geocell interaction promotes fiber rearrangement, local rupture, and progressive loss of inter-fiber bonding, leading to heterogeneous damage. From a mechanistic perspective, these results indicate that degradation in PP-NW geocells is governed by fatigue-related processes, while HDPE geocells exhibit greater resistance to crack initiation and propagation due to their continuous structure. The influence of geocell height was found to be material-dependent. For HDPE geocells, height variation did not significantly affect post-degradation behavior. For PP-NW geocells, increased height did not consistently improve performance, indicating that geometric factors alone are insufficient to mitigate degradation in flexible systems. Across all configurations, shear response exhibited smaller relative reductions compared to tensile and adhesion responses, suggesting lower sensitivity to

localized material damage due to the predominance of distributed frictional mechanisms.

Figure 9 provides an integrated comparison of strength retention for all evaluated geocell systems, allowing the combined influence of material type, geocell height, and test mode (tensile, junction/adhesion, and shear) to be visualized under traffic-induced degradation. While differences between materials and heights are observable, the overall variations in retention remain relatively limited. The comparatively high shear retention across configurations may reflect the dominance of distributed frictional mechanisms along the cell walls, which are generally less affected by localized material damage than tensile or junction mechanisms.

The material-dependent degradation trends observed in this study are consistent with previous investigations on geocell- and geosynthetic-reinforced pavements subjected to cyclic and repeated loading. Accelerated pavement testing and large-scale studies generally report more stable post-loading responses for extruded

polymeric reinforcement systems compared to more flexible configurations, particularly under tensile- and junction-dominated loading modes [1–2]. However, most available studies focus on global pavement performance indicators, such as rutting and surface deformation, rather than on the direct mechanical condition of the reinforcement after traffic loading [1–5].

To further evaluate the significance of the observed differences, a statistical comparison between virgin and degraded specimens was performed using a t-test at a 95% confidence level. The results indicated that the reductions observed for HDPE geocells were not statistically significant, whereas PP-NW geocells exhibited statistically significant reductions in tensile and adhesion responses. This confirms the greater sensitivity of nonwoven systems to traffic-induced degradation.

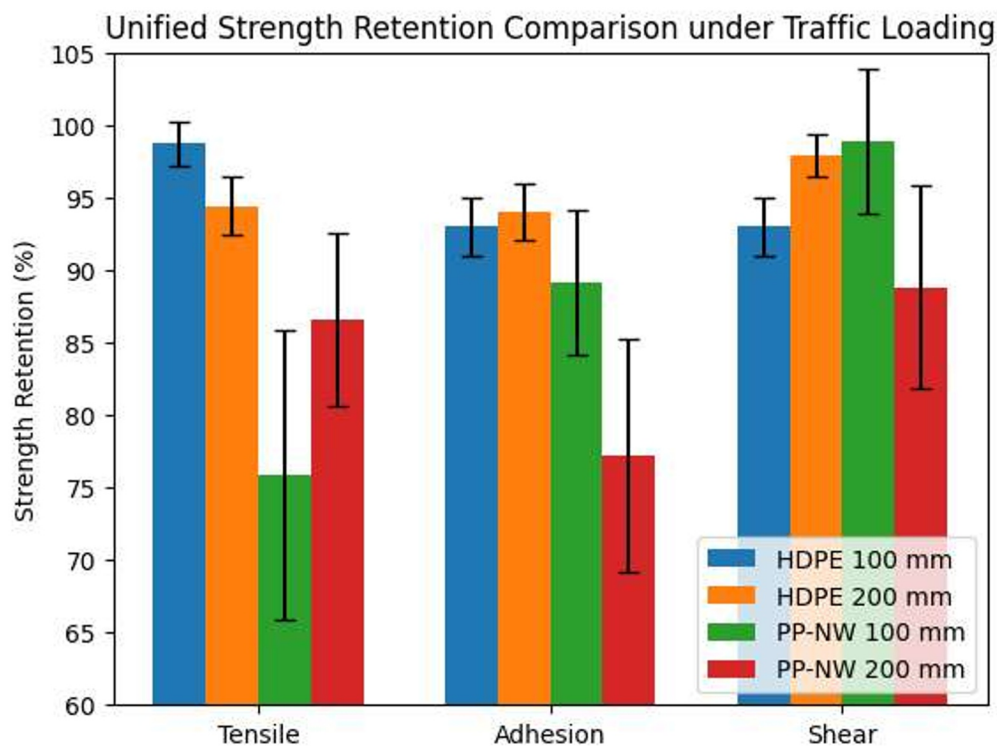


Fig. 9. Integrated comparison of strength retention for geocells with different materials and heights under traffic-induced degradation.

4 Conclusions

This study evaluated the effects of traffic loading on the mechanical performance of HDPE and PP nonwoven geocells under controlled accelerated pavement testing conditions.

The results indicate that traffic loading leads to measurable but relatively limited changes in mechanical

properties. HDPE geocells exhibited more stable post-degradation behavior, with high strength retention and low variability, whereas PP-NW geocells showed greater sensitivity to degradation.

The influence of geocell height was material-dependent and not a dominant factor in controlling post-degradation performance. Shear response was consistently less affected than tensile and adhesion mechanisms.

These findings demonstrate that degradation mechanisms are strongly influenced by material structure and should be considered in the evaluation of geocell performance.

This study was conducted under a single loading condition, using a specific RAP material and a controlled subgrade simulation. Therefore, the results should be interpreted within this experimental scope and may not be directly generalized to other material types or field conditions.

Acknowledgements

This research was funded in part (support granted to the first author) by the Brazilian Federal Agency for Support and Evaluation of Graduate Education (Coordenação de Aperfeiçoamento de Pessoal de Nível; CAPES)-Finance Code 001.

This work was financially supported by: Process 405594/2022-4. CNPq/FNDCT/MCTI 15/2022—Desempenho de pavimentos estabilizados com geossintéticos: uma abordagem experimental e numérica;

The UID/04708/2025 and <https://doi.org/10.54499/UID/04708/2025> of the CONSTRUCT – Instituto de I&D em Estruturas e Construções – funded by Fundação para a Ciência e a Tecnologia, I.P./ MECI, through the national funds. OBER and TDM for supplying the materials used in this study.

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