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A REVIEW OF STRUCTURAL PERFORMANCE OF GEOCELLULAR PLASTIC MODULE

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Abstract — The use of geocellular plastic modules, also known as stormwater modules, has begun to replace traditional drainage systems, which fail to sustain the unprecedented volume of stormwater runoff and convey floodwaters to the receiving watercourse in time. This subterranean module is a good and sustainable solution, because it can manage water sources through retention, infiltration, and attenuation. It is also suitable for the development of metropolitan areas with limited land. However, to date, the understanding of modules' real short-term or long-term structural behavior is limited. This work attempted to summarize the structural behavior of geocellular modules under various boundary conditions. The current codes of practice on traffic loads were reviewed, and the design of this geocellular plastic module was discussed. In Malaysia, the Public Works Department or *Jabatan Kerja Raya* (JKR) standard is used for national traffic load applications, while ASSTHO is applied internationally. Traffic loads are the primary contributors to vertical loading, whereas backfill soil and water pressure represent potential lateral loads that could impact the stormwater module system. For future application recommendations, it is suggested to consider the vertical and lateral loads that are applied to the system, which are not specified in the current code of practice. This review provides a higher confidence level when applied to the current construction industry.

Keywords: geocellular plastic module, modular infrastructure, structural performance, sustainable construction

1.0 INTRODUCTION

A geocellular plastic module is a modular subterranean retention unit with several applications, including rainwater infiltration, stormwater attenuation, and rainwater harvesting, that has been specifically created for rainwater management sustainability. It is utilised to manage an unprecedented amount of stormwater runoff and convert it into a reusable resource. Figure 1(a) depicts the geocellular plastic module with an infiltration design. It aids in stormwater management in place by temporarily retaining entering stormwater and gradually dissipating it back into the earth, assisting in the restoration of the natural water cycle. Geoplast S.p.A [1] found that their geocellular plastic module has a 300% higher effective storage volume than traditional piping systems. This allows for faster groundwater replenishment and eliminates the need for digging, excavation, and disposal of dig materials for piping system installation. An attenuation tank, as seen in Figure 1(b), will be constructed for places with low soil permeability, where water can barely permeate the soil. It will minimise stormwater peak flow rates, preventing sewage infrastructure and receiving watercourses from becoming overburdened, hence preventing significant flooding in cities. The particular drainpipe positioned in the lowest layer of the modules allows the stored rainwater to flow out gradually while adhering to the maximum discharge rate permitted by the planning authorities based on the kind of surrounding soil. Figure 1(c) depicts the plastic modules built for rainwater reuse, in which rainwater is routed through a sustainable pre-treatment stage before entering the storage tank and retrieved, as needed, by a specified outlet. This encourages the conservation of natural resources while cutting municipal wastewater expenses.

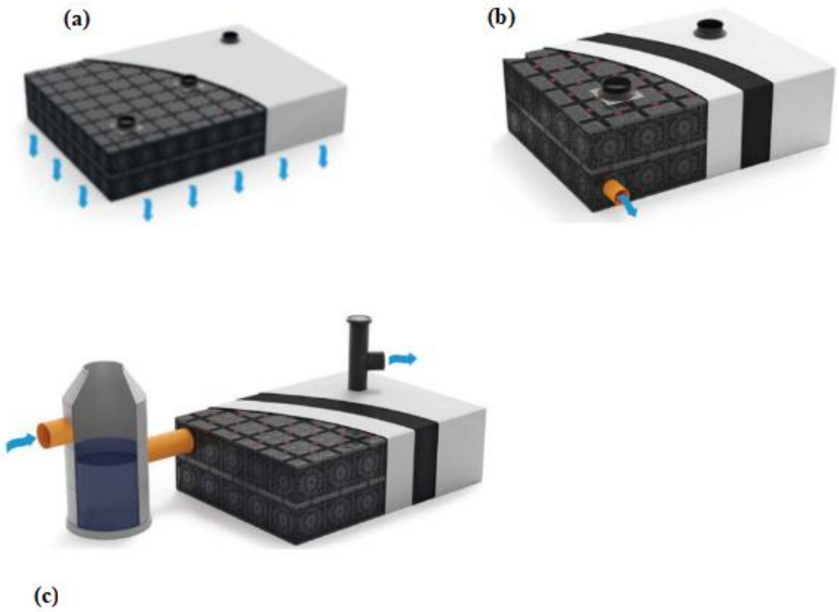


Figure 1 (a) Infiltration tank, (b) Attenuation tank, and (c) Rainwater harvesting tank

According to The World Bank Group's Natural Hazard Statistics [2], the average annual flooding occurrence in Malaysia between 1980 and 2020 was 57.61%, the highest percentage among other natural disasters, resulting in significant loss and tremendous impacts on the people and country. This is due to the increased growth in metropolitan areas that are vulnerable to flash floods caused by heavy rainfall. As a result, geocellular plastic modules, as a sustainable stormwater management solution, have a high potential for widespread implementation in this country to help alleviate flooding. The integrated modules are ideal for use as stormwater attenuation, infiltration, and drainage systems deployed underground as part of a sub-base formation. It can be used in residential areas, parking lots, sports fields, basements, pedestrian areas, roofs, industrial estates, and roads and highways.

The modular unit was initially used in Europe in the mid-1980s to store stormwater under road pavements [3]. However, as the demand for stormwater infiltration, attenuation, and harvesting has grown as a result of residential, commercial, and industrial expansions, the design of this structure has become increasingly complex and huge in scale. As a result, it is critical to investigate the structural behaviour of the geocellular plastic module in order to avoid failures that could cause significant damage. There is a lack of information when applying these modules under several loading conditions, where originally the system is applied under a non-bearing condition. This paper summarises the structural performance of geocellular plastic modules, compares traffic loads with current codes of practice, and discusses the system's design, which may provide the recommendations when it is applied to the industry.

2.0 STRUCTURAL BEHAVIOUR OF GEOCELLULAR PLASTIC MODULES

The modular components are often formed as cuboid plastic constructions consisting of regenerated polypropylene or recycled polyvinyl chloride (PVC). Rezania et al. [4] found that these materials have a high void ratio and porosity of over 90%, resulting in units with a light weight of 40 to 80 kg/m^3. Individual units are made up of layers of corrugated plastic sheets that have been bonded or welded together to form primarily hexagonal plastic columns. Lee et al. [5] suggest that the design of the stormwater module's column is crucial for its structural stability and ability to withstand loads. For example, the honeycomb design of the column depicted in Figure 2 allows for the distribution of applied vertical tension across the whole structure, preventing stress from becoming overly concentrated in specific locations. As a result, it improves the module's vertical performance while maintaining its lateral flexibility. According to Lee et al. [5], the hollow cone shape of a column with vertical stiffeners in Figure 3 improves the strength capacity of a traditional circular column. They are then formed into a suitable size tank, which is encircled by an impermeable geomembrane, a permeable geotextile, or a mix of the two.

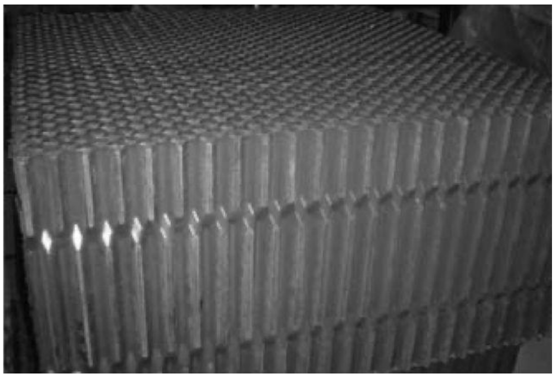


Figure 2 Honeycomb shape column [4]

Figure 3 Hollow cone shape column [5]

Figure 4 displays the various loads that must be considered during the testing and design process to guarantee the module installation is safe and serviceable. The geocellular structure's design must be strong enough to withstand any applied load resulting from both permanent and living actions expected during its service life. Polypipe's performance criteria requires geocellular modules to meet CIRIA Report C680 [6] for structural testing.

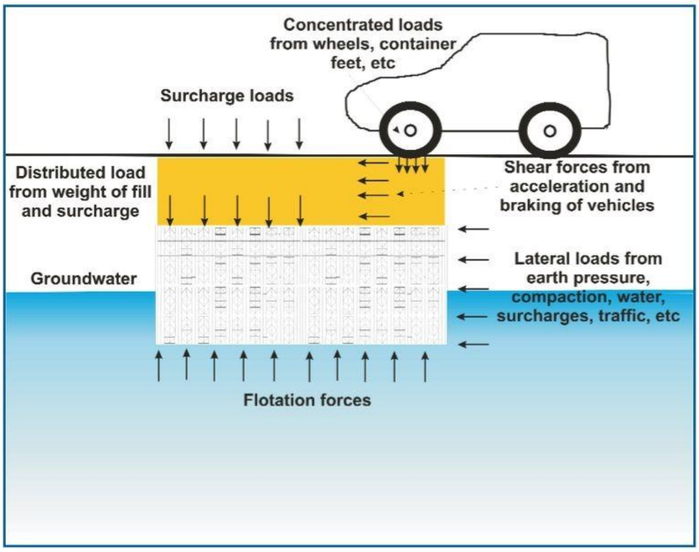


Figure 4 Loads on geocellular plastic module [7]

According to O'Brien et al. [8], CIRIA Report C737 (Structural and Geotechnical Design of Modular Geocellular Drainage Systems), which replaces CIRIA Report C680, suggests testing methods to ensure geocellular modules can support loads over their design life. A number of laboratory tests, including as short-term compressive strength, long-term (creep rupture), cyclic testing (fatigue), and plastic deterioration, can be performed to determine the module's structural performance. Wilson et al. [9] conducted compression tests on a single geocellular module to determine its properties, followed by cyclic testing on full-scale pavements to determine the system's deflection profile under loading.

According to CIRIA Report C609 on Sustainable Drainage Systems, the modular structure's worst-case load capacity should be determined through compression testing at several places [10]. To determine the structure's ultimate compressive strength and deflection performance, the report recommends using the method described in BS EN 124:1994 for determining the strength of manhole covers, in which the vertical load is applied via a 300mm plate replicating the vehicle tyre, as shown in Figure 5.

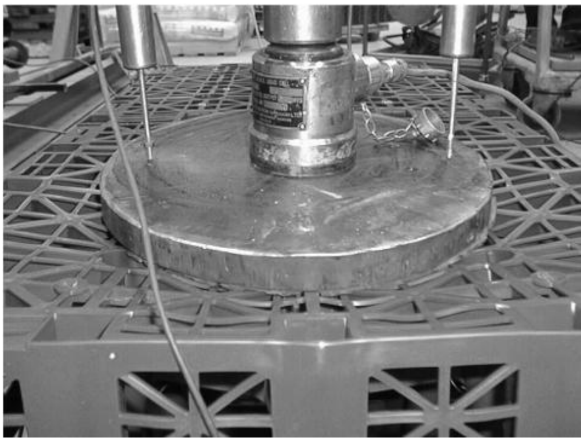


Figure 5 Compression test on geocellular plastic module [10]

2.1. Possibility of Applied Vertical Loads

Aung et al. [11] found that increasing the surcharge load incrementally leads to an increase in vertical stress (σ_v). Figure 6 shows that from 1m to 4m, both the width (B) and length (L) parameters of surcharge increase by 15% and 10% for the σ_v. Based on the findings, the width and length of the surcharge load are deemed negligible because they only make a small change in vertical stress. Furthermore, the surcharge load is primarily attributable to vehicular traffic driving around the subterranean modules. Ajagbe et al. [12] found that the surcharge load (kN/m^2) can be calculated by multiplying it by the coefficient of active earth pressure (k_a), which is calculated using the formula $tan^2\left(45-\frac{\emptyset}{2}\right)$ and an angle of internal friction. Figure 7 shows that the vertical tension, σ_v, is not significantly affected by soil internal friction.

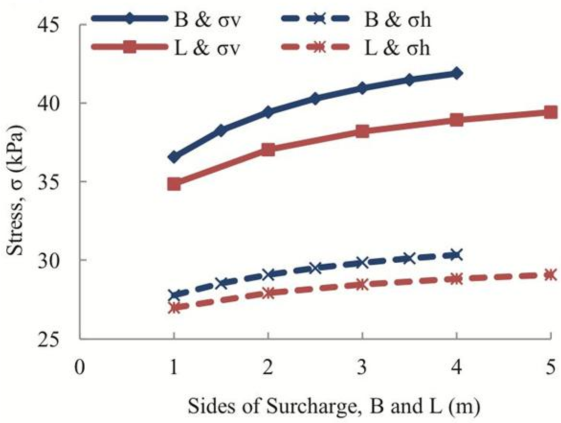


Figure 6 Effect of width and length of surcharge on vertical and lateral stress [11]

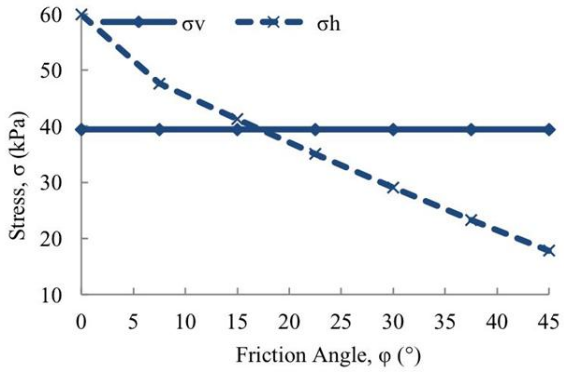


Figure 7 Effect of friction angle on vertical and lateral stress [11]

2.2. Possibility of Applied Lateral Loads

When the geocellular module is deployed underground, it is subjected to pressures caused by in situ horizontal earth materials, surcharge loads, water, and earthquakes. The geocellular module's design must be able to withstand all lateral forces in order to prevent unsatisfactory differential and total settlement over the module's service life. Given Malaysia's location in a low to moderate seismic region, distant from major fault lines, the impact of earthquake-induced pressure will be disregarded in this study [13].

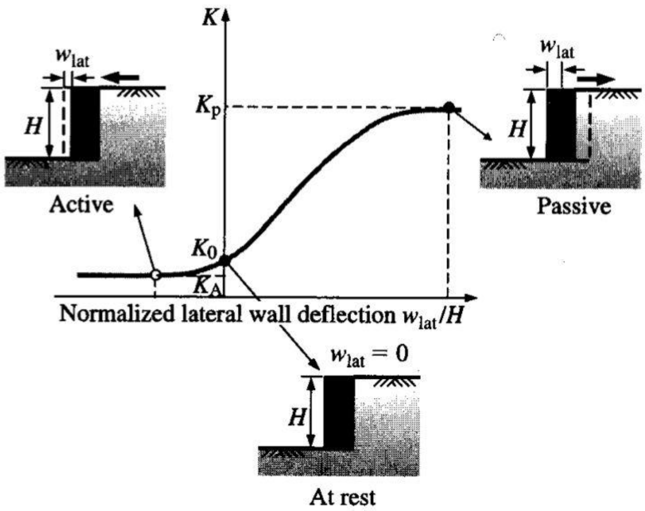


Figure 8 Coefficient of lateral earth pressure behind retaining wall versus lateral deflection [14]

The performance of this geocellular module is known to be influenced by the contact between the module and the backfill soil, which can cause relative displacement. The pressure exerted by the backfilling materials is determined by taking into account the soil quality and physical characteristics such as grain size, water content, void ratio, stress history, and boundaries. Soil backfill is typically granular material such as sand, sand with gravel, or silty sand, which is coarse-grained and non-cohesive in nature. This is because, according to an experiment conducted by [11], the cohesive type of soil is discouraged from being utilised as backfill soil since a modest increase in cohesiveness from 0 to 5 kPa results in 17% increased lateral earth pressure. [11] found that changing the friction angle of the soil (φ) by ±5% affects the lateral stress by ±16%. This highlights the need of considering the friction angle during testing. Figure 8 depicts the relationship between Earth pressure and horizontal displacement of Terzaghi's pseudo-retaining structure.

The hydrostatic pressure that accumulates behind the sides of the module's wall must also be considered because it increases the overall resulting force acting on the rear of the geocellular module's sidewall. According to Archimedes' principle, the water pressure exerted on the side wall increases with depth and distance from the ground level. As a result, the bottom of the geocellular module will bear a bigger weight [15]. To assess the soil's groundwater level, an on-site geotechnical soil investigation must be undertaken prior to module installation. It should be observed that as the water table behind the side wall rises, so does the lateral force pushing on it, causing the sides to become less stable. For a drained state without hydrostatic water pressure, the design calculation requires simply the total weight of soil γ behind the full height of the side wall [16].

2.3. Possibility of Failure Mode

The failure of this geocellular module is primarily due to the lack of understanding of the structural performance of the modules, such as where overloading may occur later; inadequate design by failing to account for the site ground conditions; and overestimation of the module's strength through inappropriate laboratory testing [7]. Furthermore, difficulties such as incorrect surface water flow management during construction excavation and failure to consider in-situ groundwater levels may result in poor performance of the placed geocellular modules. These challenges must be addressed properly in order to provide a safe, long-lasting, and effective stormwater management system in Malaysia. The breakdown of this geocellular module could result in catastrophic damage, particularly for those deployed beneath congested areas such as highways and roadways. Aside from the cost of rebuilding the tank, the cost of replacing the underlying structure and the cost of loss of usage may be considerably greater. Moreover, as this modular system is novel to Malaysia, a failure could erode industry confidence, potentially leading to its rejection as a viable option [8].

2.3.1. Under critical loading

As shown in Figure 9, creep rupture is a time-dependent phenomenon that occurs when a polymeric material is subjected to increased strain over time, causing it to fail abruptly after days, months, or years of service. Over time, creep may induce excessive deformation of the module and even fracture at high continuous stress, which is still lower than the short-term yield stress [3]. It is more likely to occur on a thick cover, which can withstand a higher permanent load even when the vehicle force exerted on it is reduced since it is distributed over a larger area. Figure 10 shows an example of creep rupture. When the plastic unit achieved the failure load during the short-term load test, it cracked and buckled, causing the units to fall immediately. According to Wong [3], the creep rupture that happens in a geocellular plastic module is significantly more complicated than that of a typical member under pure tension since the horizontal and vertical plates are under bending stress, and the vertical plates may also break due to buckling. Creep rupture is a typical failure condition in geosynthetic products that experience long-term loading. However, little study has been done on the topic of geocellular units.

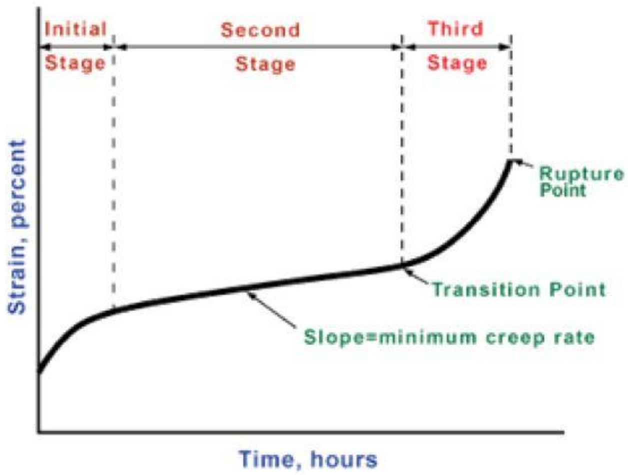


Figure 9 Typical creep behaviour [17]

Figure 10 Creep rupture of a geocellular module under short-term load test [3]

2.3.2. Under uneven settlement

The geocellular module's stability can be achieved by keeping settlement values within a reasonable range. Uneven settlement of the sub-base may cause additional compression load on the constructed plastic module, resulting in cracking and structural failure. Therefore, it is critical to determine the soil parameters of the intended location before building the module.Uneven settlement of a foundation is mostly caused by soil movement beneath it. Soil shifting is primarily caused by (i) soils with low bearing capacity, (ii) poorly compacted soil, (iii) soil moisture fluctuations, and (iv) soil consolidation.

Soil subgrade with low bearing capacity, such as soft and loose sand, cannot support the weight exerted by the structure. Furthermore, Malaysia has 2.5 million hectares of peatland region, making highway road construction unavoidable [18]. On highways or roads, traffic loads are transmitted to the subgrade, or lower layer of the road pavement. The subgrade serves as both the base of the road pavement structure and the shelter for the geocellular plastic module. Nonetheless, it must be of good quality so that it can handle the above-mentioned load without incurring shear failure, which may cause to excessive deformation [19]. If the subgrade consists of undisturbed ground soil, adjustments must be performed to adjust its bearing capability.

Insufficient compaction in the soil sublayer will result in air gaps, which can later be filled with water and dirt. This causes the plastic modules to swell, shrink, and be squeezed by the sublayer, resulting in structural damage. Compaction of soil may increase its strength to withstand any given force, resulting in no movement of the soil and geocellular module. Furthermore, variations in soil moisture content contribute to unanticipated soil settlement. This is because when there is an excess of moisture in the soil, it becomes saturated and loses its bearing capacity, making it more likely to settle. When moisture levels drop, the soil shrinks, resulting in a decrease in volume [20]. The same is true for soil consolidation, where pore pressure in soil dissipates with time as a result of the weight of plastic modules and the transferred traffic load [21]. By that point, the soil would have shifted and the sublayer would have settled.

2.3.3. Under lateral pressure of backfill soil

Active pressure occurs when the backfill materials exert force on the formed module, causing it to move away from the backfill. Because of the active lateral earth pressure, the buried module can move in a variety of ways, including rotation about the toe, rotation about the top, and translation as a rigid body, as shown in Figure 11. The module's movements may cause failure, such as cracking, splitting, and stressing or breaking of pipes attached to the module as a result of tilting and settling.

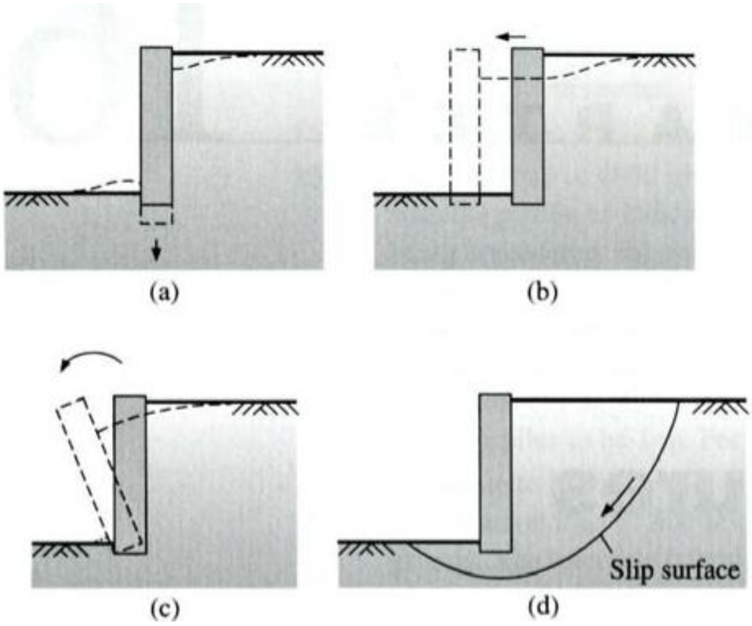


Figure 11 Rotational, transitional module active case [14]

2.4. Traffic Loads

Traffic loads are an important input parameter in the structural design of the geocellular plastic module. The load caused by the weight of cars that will be supported by the stormwater module over its design life must be determined. As a result, in this section, the loads provided by various types of commercial vehicles in accordance with the Malaysian JKR Standard ATJ 6/85 [22] and the AASHTO Standard Specifications for Highway Bridges [23] are addressed.

2.4.1. Malaysian JKR standard

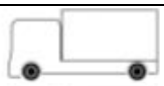
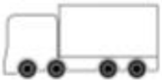
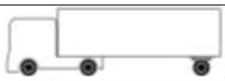
In 2013, the Malaysian Public Works Department, known as *Jabatan Kerja Raya Malaysia* (JKR), released an updated version of the design pavement guidelines titled ATJ 6/85 (Pindaan 2013): Manual for the Structural Design of Flexible Pavement. This guideline intends to establish a consistent process for designing pavements for all types of traffic for use by JKR and consultants involved in relevant pavement engineering projects in Malaysia. According to this document, the equivalent standard axle load (ESAL) in Malaysia is 80 kN, the same as the standard axle load used in the AASHTO pavement design procedure (Jabatan Kerja Raya Malaysia 2013).

JKR has published the Weight Restriction Orders 2017 (Amendment) to regulate the permissible weight limitations of commercial vehicles on Malaysia's federal roads. A motor vehicle's axle load can be calculated using the axle rating, axle arrangement, tyre rating, tyre number, and vehicle specification. In WRO 2017, there are two axle configurations: rigid and articulated. An articulated vehicle is one that has two or more independent frames connected by proper couplings, whereas a rigid vehicle has no separation elements, as illustrated in Figure 12. An axle limit load is the vehicle's maximum allowed gross weight load that can be supported by a single axle. Table 1 summarises the proposed vehicle weight limitations for federal roads in List 1 of the Second Schedule, WRO 2017 [24].

(a) (b)

Figure 12 (a) Rigid vehicle and (b) Articulated vehicle

Table 1 Vehicle Weight Limits for Federal Roads in List 1 of Second Schedule, WRO 2017 [24]

Type of vehicle	Number of axle	Axle configuration	Load limit (tonne) – WRO 2017
Rigid	2 axles		16 - 19
	3 axles		20 - 27
	4 axles		25 – 33
Articulated	3 axles		26 - 31
	4 axles		27 - 39
	5 axles		40
	5 axles		28 - 45
	6 axles		34 - 50
	7 axles		53

2.4.2. Other codes of practice

ATJ 6/85 was built on the Asphalt Institute and AASHTO design processes, which have also been revised multiple times [25]. This section will cover the 17th edition of the American Association of State Highway and Transportation Officials' (AASHTO) Standard Specifications for Highway Bridges. The standard requirements include two systems of highway live loadings: H loadings and HS loadings. The HS loading is significantly heavier than the corresponding H loads. The loadings are divided into four standard classes: H 20, H 15, HS 20, and HS 15. According to the standards, loading H 15 is 75% of loading H 20, as is loading HS [23].

The H loading refers to two-axle truck vehicles or lane loading, as seen in Figures 13 and 14. The suffix to the loading name reflects the normal truck's gross weight in tonnes. For example, H20 is a 20-ton, two-axle truck with a 14' spacing [23]. Moreover, HS loading is a tractor truck with a semi-trailer, or lane loading, as seen in Figures 14 and 15. The suffix to the loading name reflects the normal truck's gross weight in tonnes. The back axle spacing is set to vary between 14 and 30 feet to accommodate the tractor trailers currently in use. For example, the HS20 is a 20-ton tractor truck with front axle spacing of 14' and changeable rear axle spacing [23].

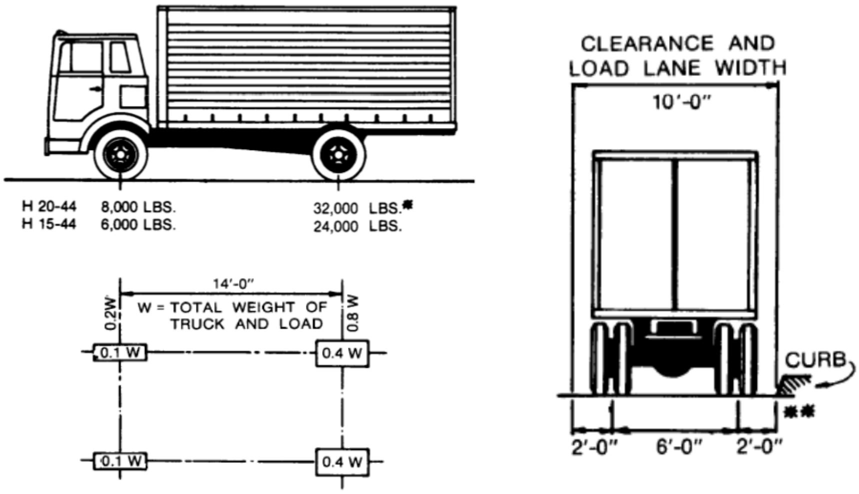


Figure 13 Standard H loading [23]

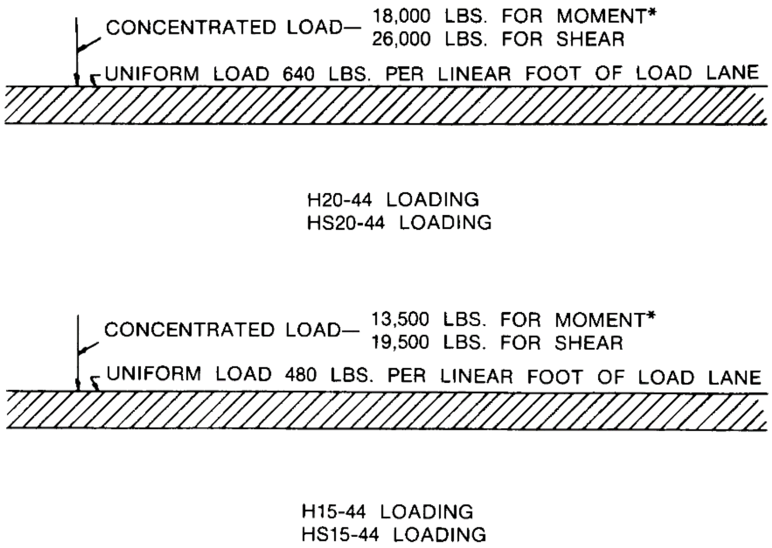


Figure 14 Lane loading [23]

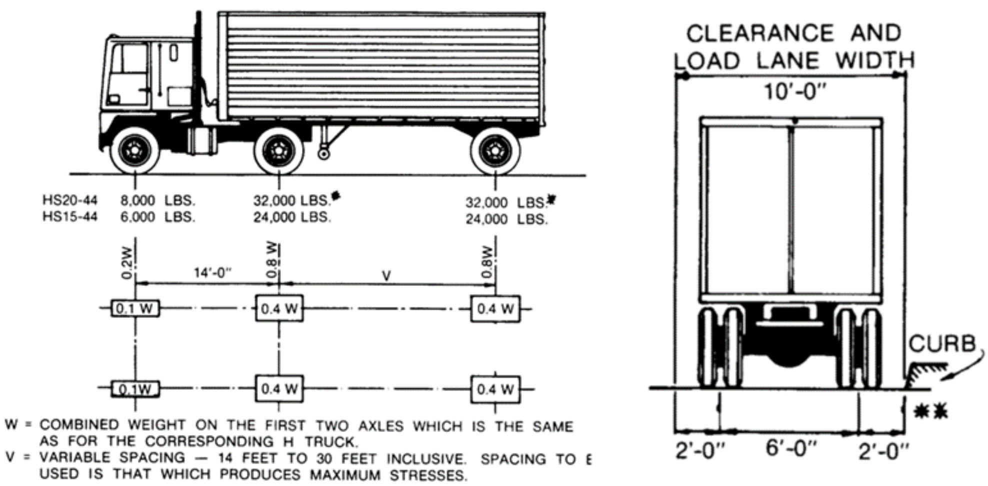


Figure 15 Standard HS loading [23]

3.0 PREVIOUS INVESTIGATION

3.1. Compression Test

The purpose of vertical compression testing is to determine the strength of the geocellular plastic module under dispersed load. Rezania et al. [4] conducted a few experiments to establish the module's structural behaviour under vertically distributed load. The first test was carried out using different densities of PVC sheets, with a sample with a higher density obtained by increasing the thickness and corrugation angles of the sample. According to the data given in Figure 16(a), units with 20% higher density have approximately 50% higher vertical strength and a little increase in strain at failure. Furthermore, the influence of curing time was examined utilising two samples built for two and 14 days to test under dispersed load. Figure 16(b) shows that the sample with a longer curing period has stronger vertical strength, resulting in less deformation. The sample with label Adv02 is less dense than the sample with label Adv04 [4].

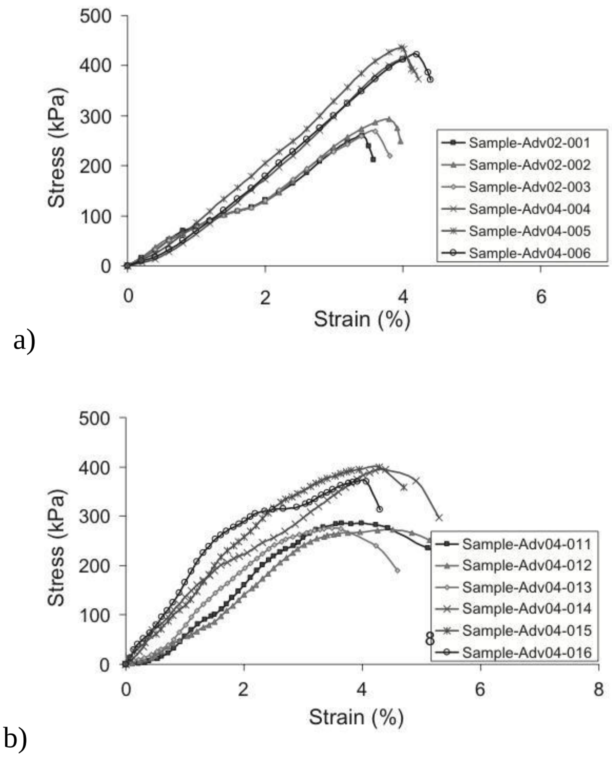


Figure 16 Stress-strain curves of modules with (a) Varying densities (b) Different curing time [4]

Wilson et al. [9] conducted a vertical compression test on one, two, and three layers of the geocellular plastic module. The results show that the rate of deflection increases as the number of layers increases. Figure 17, which depicts the graph generated by the transducers, shows that the units respond in a generally elastic fashion, with deflection steadily increasing until yield occurred, resulting in failure. The complicated behaviour of the modules caused certain structural elements to fail at the yield point. As a result, rather than taking the strength when ultimate failure or collapse occurs, the authors proposed recording the strength at the yield point as the short-term compressive strength for the tested sample.

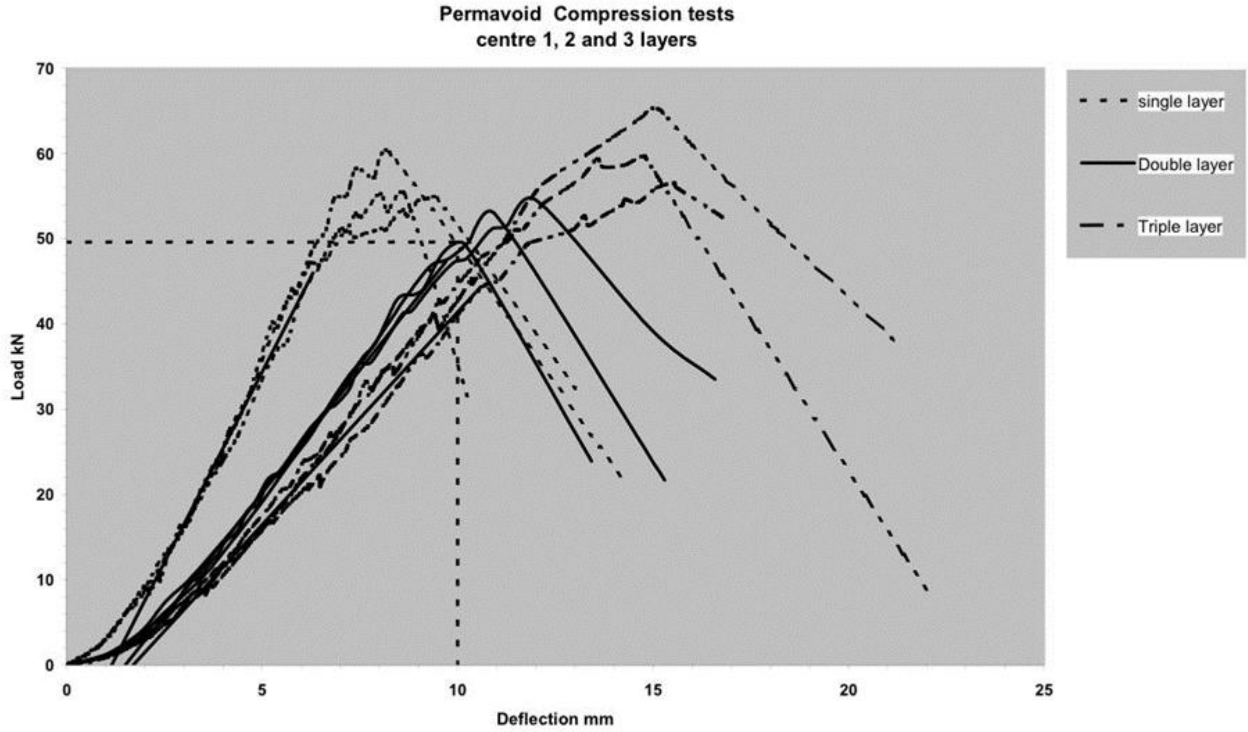


Figure 17 Compression test of 1, 2 and 3 layers of modules [9]

Lee et al. [5] examined the structural behaviour of a stormwater module under uniaxial load by testing four identical specimens vertically. The test procedures adhered to the specifications of ASTM D2412 and F2418 where applicable. Since there are no specific codes of practice for this type of product, these standards were adapted accordingly and the load rate was controlled at 1 mm per minute for the static load compressive tests.

According to [5], when the samples were evaluated under service load, they bent vertically by less than 4 mm, with no apparent deformations. At the conclusion of the trial, the specimens failed with an average ultimate load of 87.35kN and a deflection of 12.36mm. Two failure modes were identified: buckling of the side cover plate and buckling of the central or side column. It is determined that, within the plastic region, the central column helps to load stabilisation for load transmission, but buckling of the central column results in low load resistance of the module because the module can no longer withstand any load.

3.2. Lateral Load Test

The lateral load test is designed to assess the strength of the geocellular plastic module under in situ earth and hydrostatic forces. Rezania et al. [4] conducted a lateral load test on the module's side in two separate horizontal load directions: parallel and perpendicular to the surface of the PVC sheets that make up the modular tank. The results, as shown in Figure 18, revealed that the modules are stronger when lateral pressure is applied perpendicular to the surface of the PVC sheets. The sample module inserted parallel to the PVC sheet was designated LT1, while the one loaded perpendicularly was labelled LT2. Three samples with varying densities were examined for each load direction, marked from light to heavy weight (Avd02, Avd04, and Avd08). The sample's lateral strength increases with increasing density [4].

According to the results of the lateral load test provided by [5], the module had a lower load resistance in the lateral direction than the modules tested vertically. The module failed due to severe deflection, resulting in the fracturing of the side covers. Based on the findings, Lee et al. [5] recommend that the backfill adjacent to the modules to be no higher than three metres.

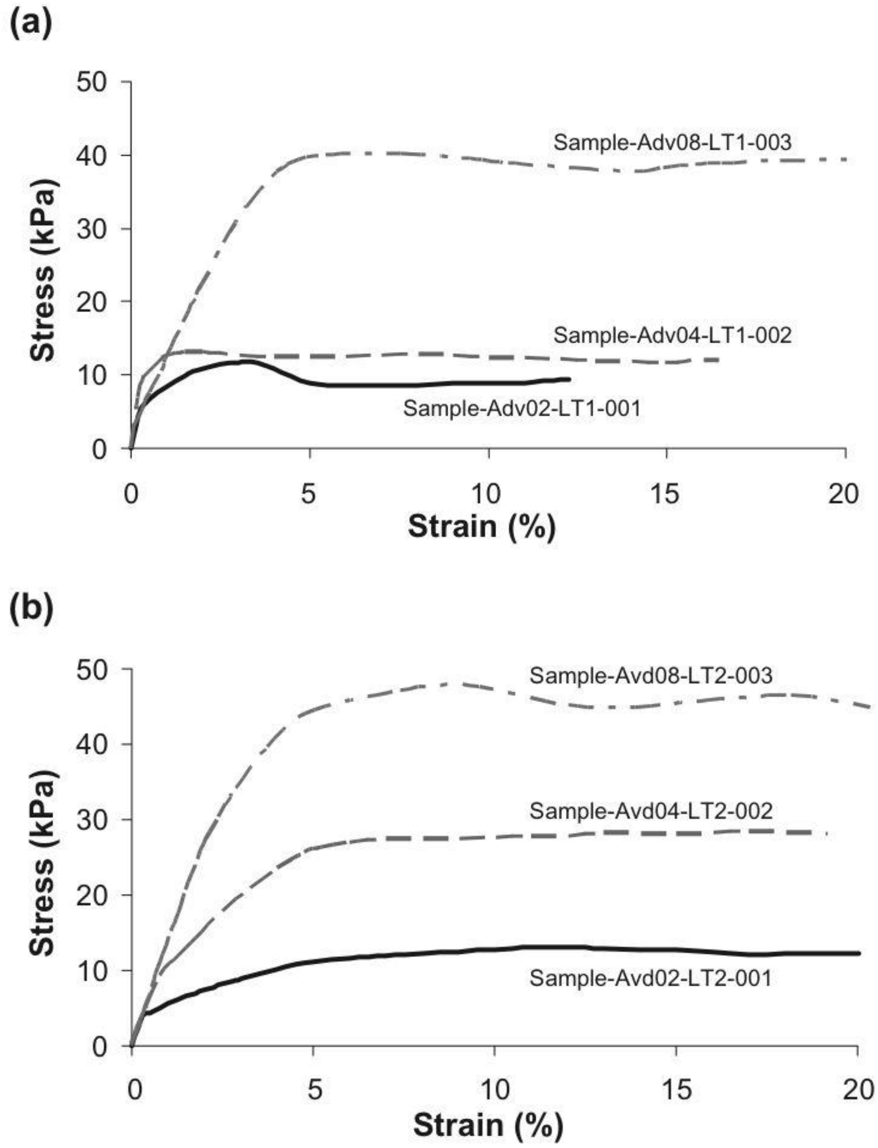


Figure 18 Stress-strain curves of modules under lateral load in (a) Perpendicular and (b) Parallel direction to the PVC sheets [4]

3.3. Numerical Modelling

Throughout the research process, it was discovered that there is relatively little research on the structural behaviour of the geocellular plastic module, particularly using the numerical modelling method. However, there are several computational assessments of the stormwater module's structural performance that have been developed thus far. The first is a parameter analysis conducted by [11] using MATLAB to discover the primary impacting parameters. The second will be a numerical model of the geocellular railway drainage system created using Abaqus software by Tasalloti et al. [26] to investigate the structure's hydraulic behaviour.

[11] used MATLAB to conduct a parametric research to determine the effective vertical and lateral earth pressure applied on modules in accordance with Australian Standards AS4678:2002 and AS5100.2:2004. The 2D-modelled stormwater module was tested under two separate real loads: traffic loads applied to the pavement layer and surcharge. The subgrade layers below the road surface are 0.15m of pavement, 0.5m of backfill, and 0.55m of sand. The normal operating point (NOP) and nominal range for each parameter were determined, as shown in Table 2. To investigate the effects of factors on the effective vertical and lateral loads acting on the modular tank, one parameter was modified within the nominal range specified in the composition table, while the others rigorously adhered to the NOP established. The results show that the friction angle of soil, φ, and wheel load, Q, have the largest influence on the major stresses. Other parameters with small impact, such as width and length of the loading parameters, depth and unit weight of the pavement, and soil cohesiveness, can be overlooked.

Table 2 Values of Influencing Parameters at NOP and Their Nominal Ranges [11]

Parameters		Value at NOP	Nominal Range
Soil Properties	Υ_{pav} (kN/m^3)	23	{19, 20, 21, 22, 23, 24, 25}
	Υ_{bf} (kN/m^3)	18	{16, 17, 18, 19, 20, 21, 22}
	Υ_s (kN/m^3)	20	{16, 17, 18, 19, 20, 21, 22}
	c (kPa)	0	{0, 2.5, 5, 7.5, 10, 12.5, 15}
	φ (°)	30	{0, 7.5, 15, 22.5, 30, 37.5, 45}
Geometric Parameters	D_{pav} (m)	0.15	{0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3}
	D_{bf} (m)	0.5	{0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6}
	D_s (m)	0.55	{0, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65}
	D_w (m)	3	{0, 0.5, 1, 1.5, 2, 2.5, 3}
Loading Parameters	B (m)	2	{1, 1.5, 2, 2.5, 3, 3.5, 4}
	L (m)	5	{1, 2, 3, 4, 5, 6, 7}
	q (kPa) Q (kN)	10 40	{5, 10, 15, 20, 25, 30, 35} {26.5, 40, 45, 67.5}

Tasalloti et al. [26] studied the hydraulic behaviour of the geocellular railway drainage system, as depicted in Figure 19, using both physical and numerical modelling techniques. Numerical modelling was used to assess the consequences of parameter modifications that cannot be considered in physical modelling. The calibrated model was tested against experimental data to determine that its properties were identical to those of the actual model. The study focused primarily on the effects of installing geocellular units across the track at the road's subgrade, without taking into account the units' mechanical response. The findings of this previous study will not be regarded because the current study does not take into account the influence of geocellular unit placement.

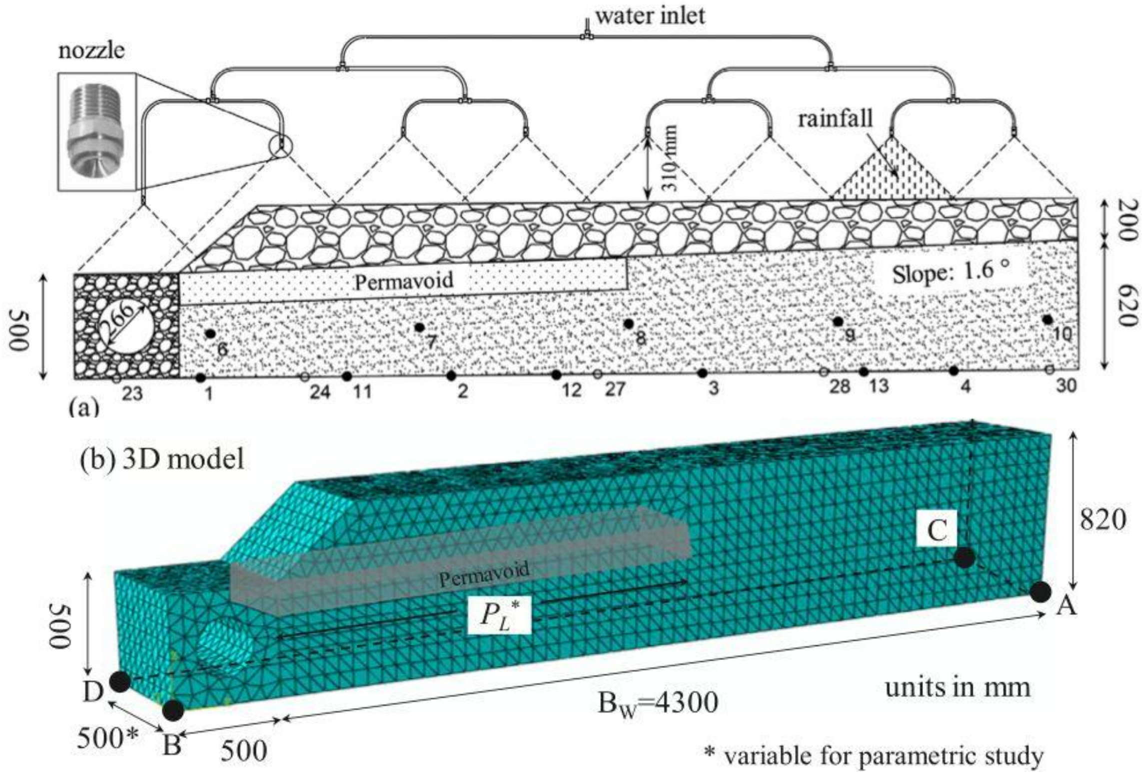


Figure 19 (a) Physical model and (b) FEM 3D model of the new geocellular railway drainage systems [26]

4.0 DESIGN OF GEOCELLULAR PLASTIC MODULES

Although the geocellular plastic module has been in use since the mid-1980s, there are few research being conducted on its structural behaviour [8]. In comparison to the numerical analysis, additional experimental experiments have been performed on this module to assess the structural behaviour of the geocellular units. However, it falls short of the requirements for data comparison and analysis. It was discovered that very few experiments have been done to evaluate the module's short-term and long-term compressive strengths, as well as probable deflections under particular loading conditions. There were just three vertical compression tests performed. Furthermore, of the three studies, only one was carried out to evaluate the structural behaviour of an integrated geocellular unit in several layers.

Lateral load tests are also useful for determining the strength of the stormwater module under in situ earth and water pressures. Nevertheless, only two lateral load experiments were done, one of them was to test the lateral load of modules with varying densities under different horizontal load orientations. In the other test, Lee et al. [5] evaluated the module's maximum resistance load and failure mode. A numerical research was conducted to model and simulate the structure in order to establish the most sensitive factors and the hydraulic behaviour of the stormwater module. However, there have been no numerical tests to determine the module's overall deflection limit under both vertical and lateral load.

Currently, there are no specific rules or suggestions for designing, installing, or building this stormwater module in Malaysia. The MSMA 2nd Edition [27] is a Malaysian urban stormwater management guidebook that gives design standards for controlling both the quantity and quality of stormwater runoff. However, it excludes the stormwater module's design criteria. This is because the module has not been widely employed in Malaysia to manage rainwater, and the country continues to rely on traditional trench drainage.

4.1. Enhancement in Structural Performance

After a standardized testing has been proposed, it is recommended to conduct detailed investigations on its structural performance in a single module setting and as a whole system. From previous study [5], columns in the modules are the vertical load bearing component to provide the structural stability of whole system. Therefore, it is essential to increase the columns number if it is to resist more design gravity load. There is another consideration of the efficiency of the stormwater control, where more than 90% was found in this module, and additional columns may reduce its efficiency. Hollow columns may serve an alternative to minimize the space usage. Moreover, within the module, the interlocking area is found to be structurally weaker than other parts. While commercially available products often prioritize prefabricated parts for rapid on-site assembly, this approach can compromise structural integrity due to potential deficiencies in load transfer paths.

As a whole system, generally, these modules are stacked or assembled without connections. All modules are placed to form a stormwater management system. This should be performed in structural analysis package. Constructing a reinforced concrete wall in a box shape surrounding the module is also another alternative to enhance the system structural performance, provided sufficient load bearing capacity for a single module.

5.0 CONCLUSION

Geocellular plastic modules are a sustainable solution for infrastructure construction. However, the structural performance of these modules renders them unsuitable for use in the building industry. The insufficient number of trials undertaken to assess the structural behavior of the module has limited its adoption in the stormwater management industry. Vertical and lateral loads should be checked, and their impact on these modules should be studied. Future development of this system should focus on the overall design when it is ready for use in the building industry.

Standardized testing procedures can serve as a foundation for further research on the structural performance of both individual modules and the entire system. Additionally, opportunities exist to enhance the structural capacity of the module to accommodate increased loads and expand its applications.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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