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STRUCTURAL PERFORMANCE OF STORMWATER MODULE UNDER UNIAXIAL LOAD

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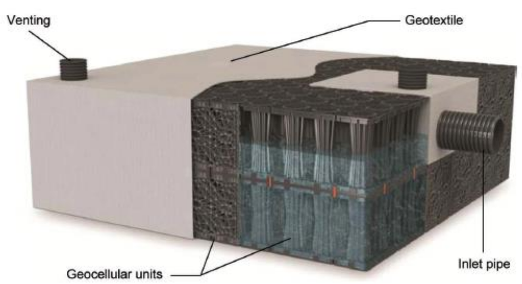
Abstract — Geocellular plastic units or stormwater modules are popular to replace conventional drainage systems due to land limitations of urbanization. Most research focuses on stormwater management rather than its mechanical properties. Several cases were discovered where the failure was not due to material or manufacturing quality. As there is a lack on information of structural behaviour, this paper presents an experimental study of performance for stormwater modules under uniaxial load. There are four specimens for vertical load test and one for lateral load test. The vertical and lateral loads are applied separately to the specimens and the deflections are measured. From the obtained results, it is found that the module is able to resist 87.3486 kN and exhibits 12.3551 mm in vertical load direction. The column buckling is the failure mode of these specimens, and it is within the design limit of ASSTHO HS20 unfactored traffic load design. For lateral load, it can go up to 19 kN resistance, which is equivalent to a 3-meter depth design for the worst scenario with wet clay. The specimen is found to have failed in the excessive deflection which leads to the facture of the side cover. Further consultation is required in the detailed design using these stormwater modules underneath roads, buildings or car parks in order to obtain a more reliable stormwater management system.

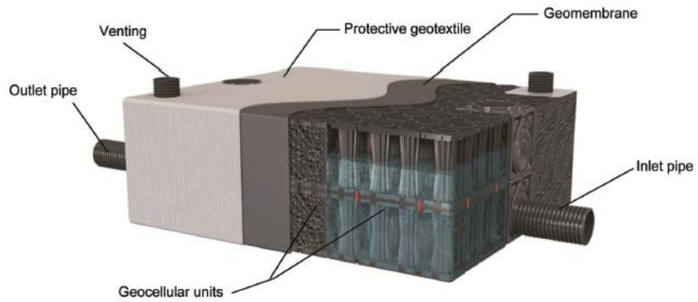
***Keywords*:** Stormwater module, compression test, structural performance, uniaxial load

1.0 INTRODUCTION

This stormwater module system is applied to regulate the stormwater flow [1]. They are designed to control the discharge rate of rainwater runoff by large storage space with an impermeable liner to prevent infiltration. The examples of the application can be found in Figure 1. These modules come across as an alternative to replace the stormwater drainage which is time and cost consuming. These ultralight modules provide efficiency for stormwater management. As the demand for stormwater modules system increases, the improved modules are ready to be applied as structural substructures for transferring loads from superstructures to foundations or soil.



(a) infiltration system



(b) attenuation system

Figure 1 Examples of stormwater module systems [2]

Despite their efficiency in storm water management, these modules should have high mechanical strength to withstand the loads especially traffic loads. Several failure cases have been lodged for the underground cellular tanks [3], also shown in Figure 2, and it is not related to its material properties or manufacturing quality [4]. Therefore, it is essential to know the modules' structural performance under several types of loading. There are three identified factors that may lead to the failure, namely ground condition which is not included in the design; overestimate modules performance; and wrongly interpreted the laboratory results or inappropriate experiments [4]. While all related issues have been addressed, this stormwater modules should contribute to a better stormwater control solution [5].

Figure 2 Failure of geocellular tanks after three years [2]

These stormwater modules are classified as geotechnical structures as they retain and support earthworks materials [2] and also transfer loads from superstructures. Previous studies are concentrated on monitoring system [6], flow efficiency and etc. Numerical models have been developed for further investigation [7]. As the system is built underground, they may transfer loading from ground surface to foundation according to the designed load path. Therefore, it is necessary to conduct static load test in order to know the product performance under these loadings. The higher possibility of this module is under compression loads. In line with this, this paper describes the experimental investigation on the modules behaviour under static compression load.

2.0 EXPERIMENTAL PROGRAM

As there is no related referred codes or standard of Eurocode and British Standard in determining the mechanical behavior of modular geocellular plastic units [5], the test procedures adapted other related codes like ASTM D2412 and F2418. There are two types of compression tests, laboratory and in-situ tests. Presenting here are the laboratory compression tests for these stormwater modules. The tests were conducted in Curtin Laboratory Malaysia. A total of four identical specimens were tested in vertical load and one specimen was tested for lateral load.

2.1 Compression machine

The calibrated Instron compression machine was used for compressing the specimens. The capacity of the Instron machine is 100 kN which is the same with the finite element prediction. Pre-test was carried out to determine the maximum strength of the product and it was found that this was within this machine capability. Figure 3 shows the Istron machine and the test setup.

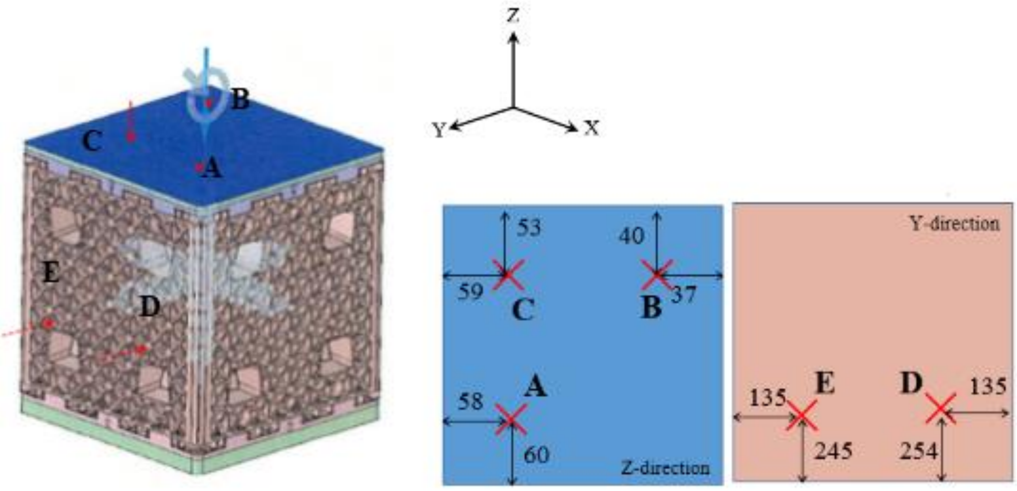
Figure 3 Instron compression machine with specimen

2.2 Loading and boundary conditions

The load was applied at the top centre of the specimen through a steel plate. At the bottom of the specimen is also a steel plate. These steel plates were to ensure the load is equally distributed on the specimen's surface. The steel plates dimensions are 0.6 × 0.6 × 0.02 m. Since it is an axially loaded condition, the specimen was positioned on the steel plate without fixed support. It is also to simulate the worst case scenario possible to occur underground without fixed at the base. However, in reality, this support is provided by the surrounding backfill and adjacent blocks which further improve the module bearing capacity. A constant rate of 1 mm/min load was applied to the specimens modified from ASTM D2412 in representing a quasi-static load.

2.3 Load transducers

There were six calibrated Linear Variable Differential Transducers (LVDTs) installed to record the specimen's deformation, where three LVDTs captured the vertical deflection and another three measured the lateral deformation. To be specific, three LVDTs were placed on the top measuring deflection of Z-direction (A, B & C), two for Y-direction deflection (D & E) and one for X-direction deformation at the centre of the side cover (F). The locations of LVDT were randomly assigned to accommodate the space availability for LVDT assembling. Figure 4 and 5 indicate the LVDTs' locations. These LVDTs are to measure the vertical deflections on the steel plates which should almost be the same and no additional stresses developed on top of the steel plate.



(a) 3D view (b) 2D view

Figure 4 Schematic drawing for the location of LVDTs

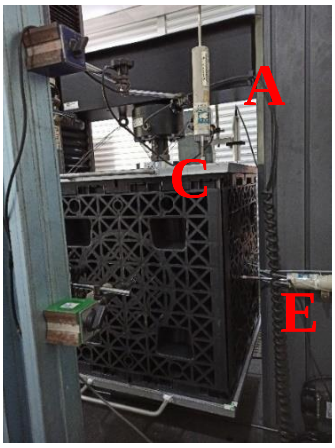


Figure 5 LVDT locations

2.4 Test procedures

There are four identical specimens that undergo the same procedures. The specimen will be conducted for stage 1 until 25 kN and released, after that, stage 2 is applied test until failure. As tested in preliminary stage, 25 kN was still in elastic region, where deformation may return to zero when the load is released. The test procedures are conformed to specifications of ASTM D2412 and F2418 wherever suitable. There is no specifications of this type of product in current code of practice and adapting these codes. In order to perform static load test, the load rate is controlled at 1 mm per minute.

In stage 1, it is to check the deflection at elastic region. The load is applied on the specimen and the deformations were measured until 25 kN, which is 20% of the ultimate load. Ultimate load is the maximum load when the structure is not able to take any more loading. The data will be analyzed for initial stiffness of the module. The load is then released and loaded again with the same rate until failure for stage 2 test. The test will be terminated when there is no load increment or gradual decrease in load pattern.

In order to ensure behaviour of other direction of loading, lateral load is applied to one specimen. The setup is the same, the specimen is turned to have inner column perpendicular to the applied load. The procedure and the load rate remained the same as the vertical load tests. The LVDTs location are also same and the results are recorded for further analysis.

2.5 Initial test

One specimen was used for initial test in order to determine the ultimate load and deflection to ensure all criteria are met. Figure 6 shows the failure mode of the specimen. The ultimate strength was 88.3432 kN with 13.7746 mm, failure occurred at buckling of side and centre columns. The specimen was not slip which can be further justified that the fixed support is not necessary in this test setup. Therefore, the setup is applied for the remaining tests.

(a) Cover deformation

(b) Column buckling

(c) Misplaced of the column interlocking

Figure 6 Failure mode of pretest specimen

3.0 RESULTS AND ANALYSIS

Generally, these stormwater modules failed due to column buckling in the event of axial compression load and there is no obvious deformation (< 4 mm, with average stiffness of 7.89 kN/mm) at service load of 25 kN. At average, this module fail at ultimate load of 87.35 kN with deflection of 12.36 mm. Table 1 shows the overall summary for the four specimens. The measurement and calculation of these parameters in Table 1 were taken from the loading point which is recorded from the Instron machine directly and no LVDT measurement is needed. Figure 7 shows the load-deflection curves for all measured deformation.

Table 1 Summary of the collected results for stormwater module load tests

Specimen	Initial stiffness, kN/mm	Max. strength, kN	Deflection at max. strength, mm	Observation at stage 1	Failure mode at stage 2
S1	8.1661	90.2094	13.5198	No obvious deformation observed	Buckling of side cover plate; one of the side column failed in buckling
S2	7.8121	88.3163	12.0934		Buckling of side cover plate; one of the side column failed in buckling
S3	7.6645	84.8486	12.6955		Buckling of side cover plate; one of the side column + central column failed in buckling
S4	7.8994	86.0190	11.1118		Buckling of side cover plate; one of the side column + central column failed in buckling
Mean	***7.8855***	***87.3483***	***12.3551***		

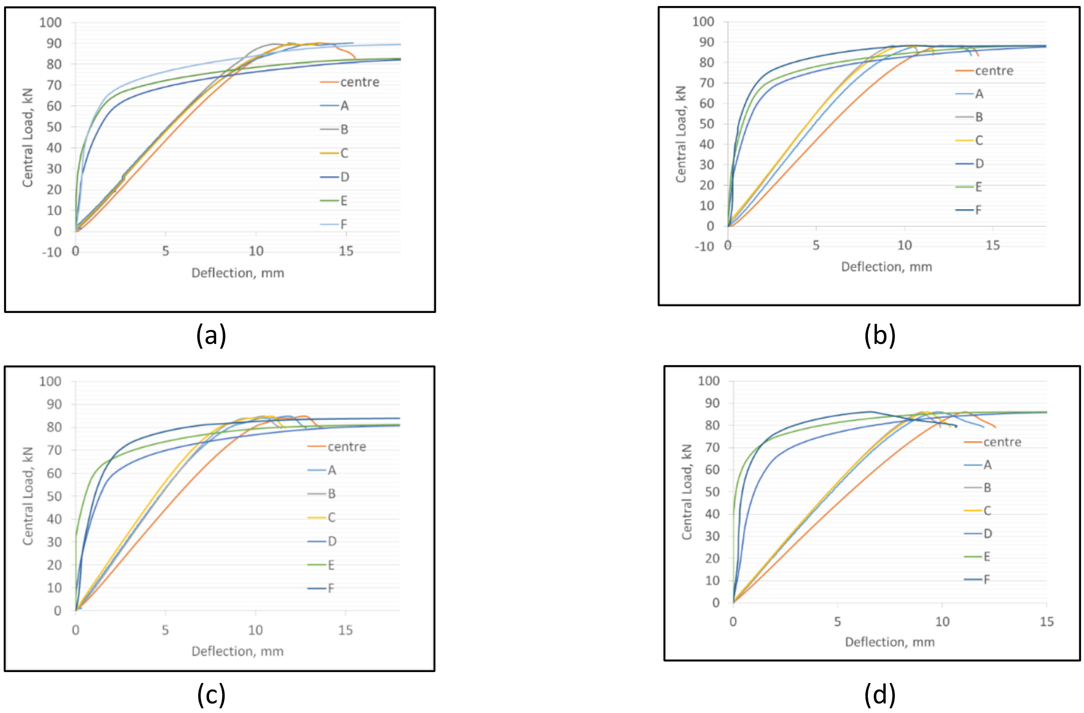


Figure 7 Load-deflection curve for (a) S1, (b) S2, (c) S3 and (d) S4

3.1 Test observation and failure mode

There is no obvious deformation found during the stage 1 tests. All specimens deformed less than 4 mm vertically (parallel to load direction) at the 25 kN load, 20% of the predicted compression load. There was neglectable deflection laterally (perpendicular to the load direction) in both X- and Y- directions during stage 1 observation. Figure 8 shows the typical deformation at 25 kN service load. As the lateral deformations were less than 1 mm, the interlocking of the side covers worked effectively to resist the compression load.

Figure 8 The observed deformation at 25 kN service load of stage 1 testing

Upon load release from stage 1, stage 2 took place until the failure of the modules. From test observation, there was a gradual increase in the vertical and lateral deformations which led to excessive deflection in the plastic region. The bending of the side covers were continued until failure and did not yet reach its material strength. Figure 9 indicates the side covers deformation which indicated the lateral deflections in X- and Y-directions. When dismantled from the test setup, all specimens were found to have the same failure mode, which is column buckling. Figure 10 shows the column buckling for all specimens.

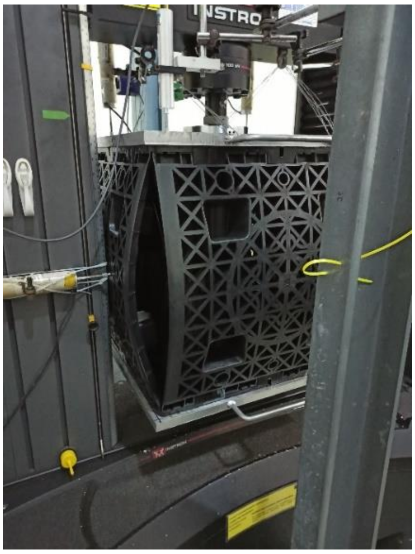


Figure 9 Side covers deformations

S1

S2

S3

S4

Figure 10 Column buckling of all specimens

3.2 Initial stiffness

Initial stiffness was in the range of 7.6645 and 8.1661 kN/mm and average value of 7.8855 kN/mm representing the elastic region of this module. From the obtained load-deflection curves (Figure 7), the central deformation and axial load behaviour revealed a brittle material performance, where there was no obvious plastic region being observed from the analysis. An approximate 0.8 ton will cause the module to have 1 mm centre vertical deflection and this relation can be maintained until 70 kN as illustrated from Figure 7.

For lateral stiffness contributed by the side covers, from load-deformation graphs, they showed having ductile material behaviour as compared to brittle behaviour of vertical deformation. The lateral initial stiffness may contribute from the side covers. Their yield points can be obtained at lower load capacity, which lateral initial stiffness is valid until 60 kN of the compression load.

3.3 Ultimate compression strength

The maximum compression strength obtained from the tests ranged 84.8486 to 90.2094 kN, almost 6% difference. As for the module in the plastic region, the column buckling may induce extra eccentricity moment and made the module fail at lower load. S3 and S4 have relatively lower load resistance as compared to S1 and S2, where central small column was suspect to fail first and induced moment to other columns. Central column did not fail in buckling for S1 and S2. Therefore, the central column is used to stabilize the load for load transfer in this module. As the column buckling have large deformation, the module is not able to withstand any load and will consider fail in analysis.

In the event of compression, this module is able to transfer 8.5 tons of loading average from the top surface to bottom foundation or to other structural members. This capability makes this module applicable in various structural application rather than non-structural system.

3.4 Deformation

The deformations of vertical and lateral directions obey the Hook's Law of elasticity till 70 kN and 60 kN respectively. As side cover behave like a ductile material, from graph observation, the deformation may yield in lower point and may fail in shear stress according to maximum shear stress theory and maximum distortion energy theory in structural analysis. The side covers deformation was in a large deformation due to its ductility. The side covers were still in ductile or plastic region when the tests were stopped due to overall failure. The side covers deflection was high with a small increment of load.

For the vertical deformation from the graph, it behaves like brittle material according to maximum normal stress theory. The vertical deformation exhibited a short period of plasticity and fail or fracture due to column buckling. The maximum centre vertical deflection was between 11.1118 and 13.5198 mm, giving an average value of 12.3551 mm.

3.5 Comparison with other available data

3.5.1 Stormwater module in current market

Table 2 shows the comparison with other online available data. In current market, stormwater modules have various dimensions. In this current study, the stormwater has the highest density of 80.64 kg/m^3 and it is considered relatively small as compared to water density of 1000 kg/m^3. For the compression strength, StormTank exhibited the highest pressure where it failed at 73 tons of load per m^2, followed by current study product, taking almost 35 tons before failure occurred. StormTank module has more column and smaller in size, as shown Figure 11. It has no weak joint in column (joint for extension), having constant cross section of column, and may in solid rather than hollow section, making it stronger. In this current study, the column also has been stiffened and it has higher strength than any other stormwater modules products in the market.

Table 2 Comparison of the available data with current study

Ref.	Specimen	Length, mm	Width, mm	Height, mm	Pressure, MPa	Weight, kg	Density, kg/m^3
-	Current study	500.0	500.0	500.0	0.349	10.08	80.64
[8]	StormTank	914.4	457.2	457.2	0.730	10.30	53.91
[9]	EnviroModule™	600.0	400.0	450.0	0.245	5.00	46.30
[10]	R-Tank	715.0	400.0	240.0	0.207	4.581	66.74
[11]	DYKA Rainbox 3S	1200	600.0	420.0	0.199	11.00	36.38

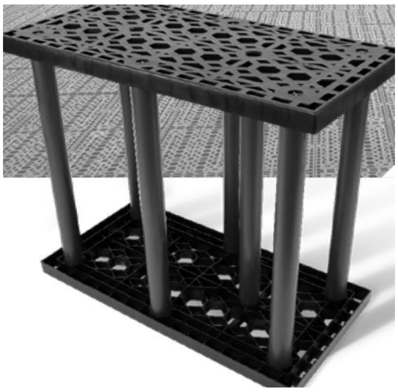


Figure 11 StormTank module [8]

3.5.2 Finite element models

Finite element analysis has been conducted [12] before experimental tests. Figure 12 shows the deformation from the finite element model. There is a difference between experimental data and finite element analysis. The failure mode is not the same where high stress was found on the top of the module (as shown in Figure 13) and experimental failure showed column buckling at the mid span of the inner column. Furthermore, the recorded vertical deflection is 12.3551 mm, where finite element model has 0.323 mm at the top column. It was suspected that the applied loading of the finite element analysis was not equally distributed on the top surface of the module, resulting a noticeable discrepancy between modelling and experimental data. Further modification or boundary condition should be added to the finite element model in order to represent the laboratory conditions.

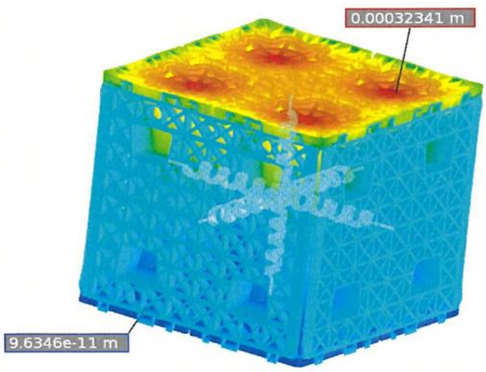


Figure 12: Deformation of finite element model [12]

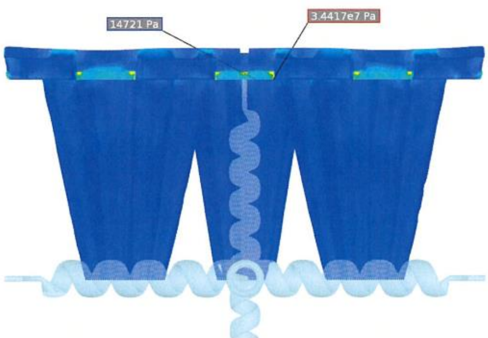


Figure 13: The developed stress within the module [12]

3.6 Behaviour under lateral load

As the water table or rainwater that undergo filtration may generate the lateral pressure to the module, it is essential to know the lateral load behaviour. The specimen failed at 19 kN with large deformation of 15 mm. It is expected that the module will resist lower load in lateral direction. There is no significant deflection observed until 2 kN, as shown in Figure 14. The specimen exhibited side cover curling near the top loading surface, as shown in Figure 15. Figure 16 showed the closed view from another plane where the curling also appeared immediate after the loading steel plate.

Figure 14 Stage 1 deformation for lateral load

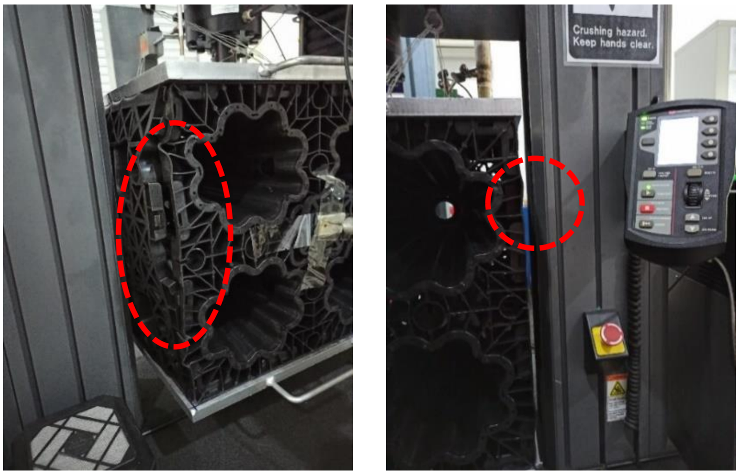


Figure 15 Stage 2 deformed shape for lateral load

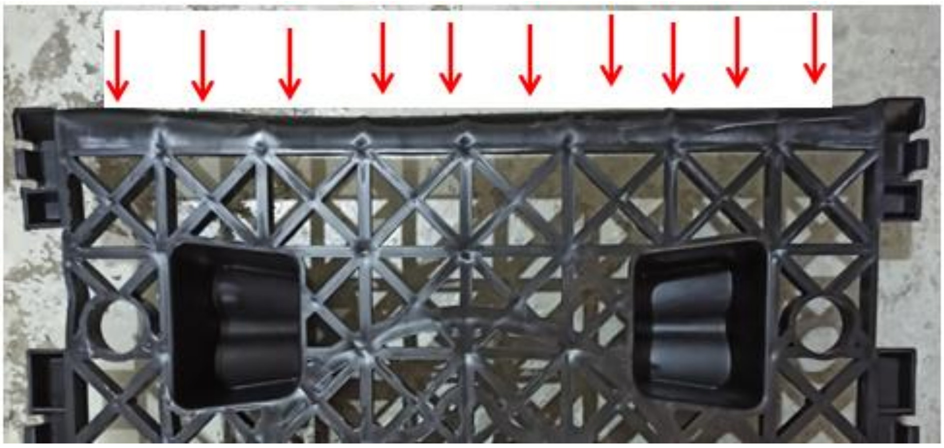


Figure 16 Closed observation of curling for loading top part of the side cover

4.0 STORMWATER MODULE STRUCTURAL DESIGN

4.1 Specimens and material properties

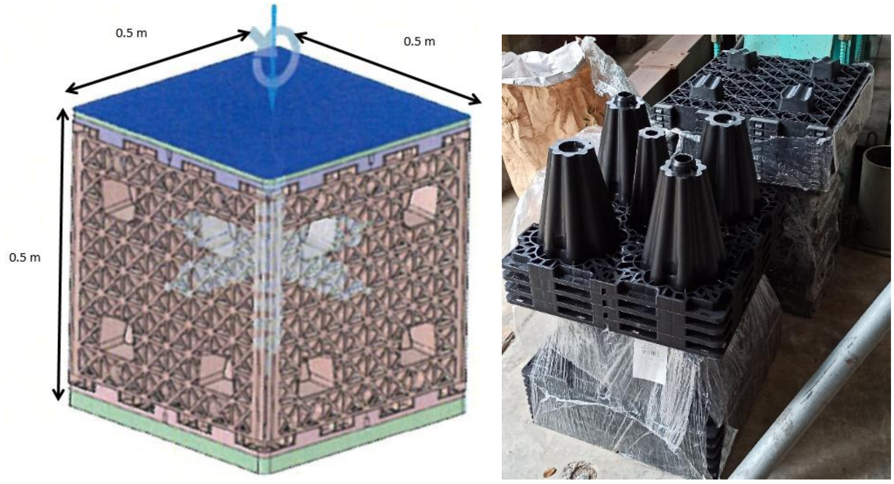
The specimens are the product from a local manufacturer, Wen Hong Plastic. Figure 17 shows the assembled stormwater module. This product is made of a material of EPC40R Titan Pro. It is a polypropylene impact copolymer, offering excellent heat stability and impact strength and stiffness. The material properties are shown in Table 3. The measured weight for this assembled stormwater module is 10.08 kg, with the dimensions of 0.5 × 0.5 × 0.5 m, as shown in Figure 18. This module consists of two column parts and four side covers. The module is easy to erect where it can shorten the installation time at site. The module has self-locking system at the side covers which makes the erected shape consistently in square. There are four same size cone-shape column and a smaller size central column in building its structural system inside the module.

(a) module with side covers (b) inner part of the module

Figure 17 Stormwater module from local manufacturer

Table 3 Material properties of EPC40R Titan Pro [13]

	Value	Test Standard
Physical properties		
Base resin density	0.900 g/cc	ASTM D1505
Water absorption	0.020%	ASTM D570
Base resin melt index	7.0 g / 10 min	ASTM D1238
Mechanical properties		
Hardness, Rockwell R	90	ASTM D785A
Tensile strength, yield	24.5 MPa	ASTM D638
Elongation at yield	4.0%	ASTM D638
Flexural modulus	1.18 GPa	ASTM D790B
Izod impact, notched	1.27 J/cm	ASTM D256A
Thermal properties		
Deflection temperature at 0.46 MPa	85°C	ASTM D648
Vicat softening point	150°C	ASTM D1525



(a) Drawing of the module (b) Parts of the module

Figure 18 Dimensions of the stormwater module

4.2 Structural behaviour

The stormwater module is initially designed for a capacity to take light loading like soil. However, nowadays, it has been designed to withstand some traffic loads for its extended use under pavement area due to land limitation. Therefore, the stormwater module should be able to withstand compression load from the vehicles load. There are two main elements to build up the module, namely column and side covers and their structural design are discussed.

4.2.1 Column design

The column of the stormwater module is the source of the resistance of compression load. The column design should be capable to withstand the applied load from the top surface. In this module, as shown in Figure 19, the column is made of two hollow cone shape. This is an innovative shape from conventional circular column. The stiffeners are provided in vertical direction which effectively increase the column capacity as compared to flat surface of a cone shape.

From the experimental results, the failure is concentrated on the column midspan, as shown in Figure 12. With the same thickness of the hollow section, at the mid length of the column, it has lower cross section area, resulted in high stress developed in this region. From Figure 20, it shows that the section area at mid-length of the column is much lower than the surface section area, with the same thickness of the hollow section. There are interlocking nibs in diagonal direction of the column, as shown in Figure 21, in order to prevent the column slip in X- and Y-directions which may further increase the load by eccentric moment.

Figure 19 Innovative column design of stormwater module

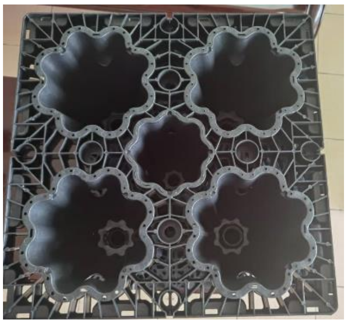


Figure 20 Cross section of hollow cone-shape column

Figure 21 Interlocking nibs

4.2.2. Locking system of side cover

The side covers are attached to the module with self-locking system at top and bottom, as shown in Figure 22. The vertical sides is not locked. The self-locking system is applied to make sure the rain water flow will not drift the plate out from the overall system and it may contribute to the module structural stability. This side cover also ensure the flow of the storm water. From the test results, there was no out of plane deformation (deflection due to torsional or distortional buckling) for the side covers.

Figure 22: Locking system of the side cover

4.2.3. Design recommendations

Generally, the stormwater modules are applied underground to regulate the rain water. There is a high possibility to be installed under a car park area or road. Therefore, vehicle loads is primarily considered in the design recommendation. From the experimental results, the ultimate compression strength 87.3483 kN which is an equivalent of ASSTHO HS20 traffic load design specification. It applied 16 tons axle load or 8 tons of wheel load where it is within the module limitation. However, it may exceed this limit if safety factor is applied on the design.

For lateral behavior, the results indicated 19 kN for 0.5 × 0.5 m area, equivalent to 0.076 MPa. Using the worst case, having backfill of wet clay, with density of 2300 kg/m^3. The height of the module should be 3.368 m in order to safely resist the lateral pressure exerted by the soil. Therefore, it is recommended to apply a depth not greater than 3 m when there is a backfill adjacent to the modules.

5.0 CONCLUSIONS

From the experimental investigation, it can be concluded:

- For vertical uniaxial load test, the average stormwater module is able to resist 87.3486 kN with deformation of 12.3551 mm. The specimens failed with column buckling.

- Recorded lateral load of 19 kN was found and the specimen failed due to excessive deflection and caused the fracture of the side covers.

- The vertical capacity can be related to unfactored traffic load design according ASSTHO HS20; while lateral capacity limited the module high to 3 m with wet clay as backfill.

Further detail design should be obtained from relevant parties such as road engineers and geotechnical engineers in order to produce more reliable and safe stormwater module system.

Conflicts of Interest

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

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