SILVA CELL 2 ENGINEERING REPORT AND TESTING CONCLUSIONS

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Table of Contents

Executive Summary

This document details compression testing and engineering assessment of Silva Cells. The assessment of ultimate loading capacity was performed utilizing common Canadian traffic loading standards. Using the results of these tests, engineers calculated allowable loads for standard pavement sections, including pavers, asphalt, concrete, and pavers with concrete.

Test Report

Introduction

This report documents product testing of DeepRoot's Silva Cell 2. This testing was performed to validate the crush strength predictions of 1X, 2X and 3X Silva Cell 2 systems. The testing was performed at TRI Environmental, an independent, third party testing and research firm in Austin, Texas in October 2015.

Test Configuration

The tests were performed using an Instron Model 5889 testing machine with a 15,876 kg (35,000 lbs) load cell and Blue Hill data acquisition software. A custom platen was used to apply load to the deck (top of the cell). This platen was contoured to conform to the shape of the deck. To provide a more uniform load transfer, a 1.27 cm (0.5 in) thick neoprene rubber pad was placed between the platen and the deck.

Load was applied under stroke control at a rate of 5 mm (0.2 in) per minute until the cell failed, either through a catastrophic fracture or an inability to carry further load. Three replications of each of the three configurations were tested.

Test Results

The results of the tests are shown in Table 1. All failures were due to buckling of the columns followed by fracture of the columns. No damage to the deck or base was observed in these tests. Failure loads for each test are shown in Table 1. Load-displacement curves and images of typical failures are shown in Figure 1 through Figure 6.

Protocol	Specimen	System	Max Load (kg)	Max Load (lbs)	Stroke (cm)	Stroke (in)	Mean (kg)	Mean (lbs)
1	1	2X	12,043	26,550	1.862	0.733	12,064	26,597
	2	2X	12,506	27,571	1.905	0.75		
	3	2X	11,644	25,671	1.839	0.724		
2	1	1X	11,092	24,454	1.659	0.653	11,023	24,302
	2	1X	10,873	23,971	1.605	0.632		
	3	1X	11,105	24,482	1.633	0.643		
3	1	3X	10,071	22,202	1.88	0.74	10,258	22,616
	2	3X	10,424	22,980	1.854	0.73		
	3	3X	10,281	22,665	1.872	0.737		

Table 1: Product Testing Summary

Load Displacement Results and Typical Failures

Figure 1: Typical Silva Cell 1X Failure

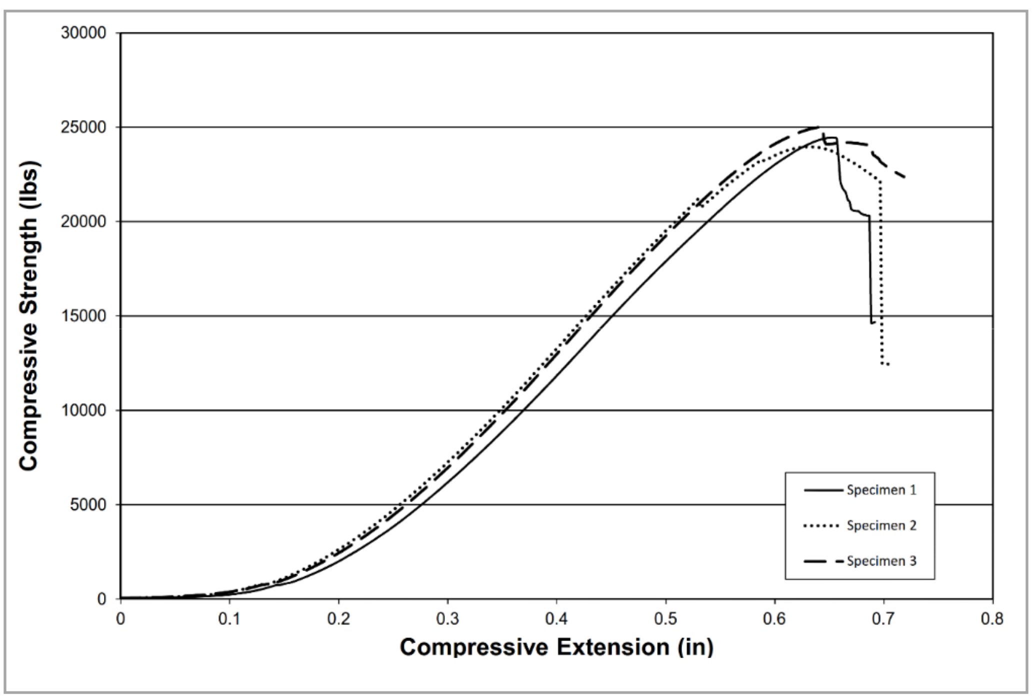


Figure 2: Silva Cell 1X Load-Displacement Results

Figure 3: Typical Silva Cell 2X Failure

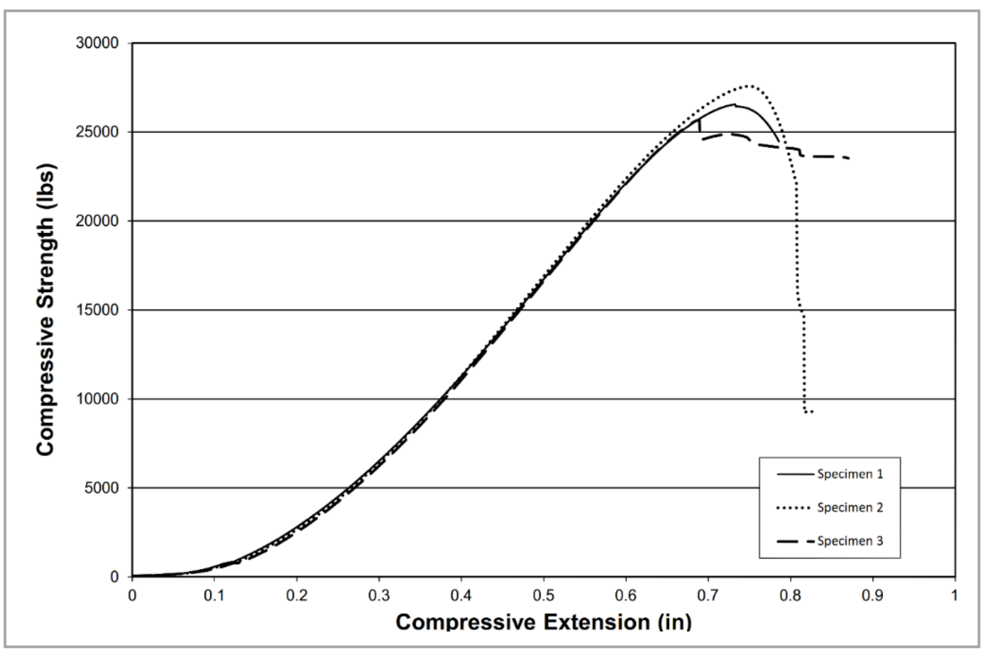


Figure 4: Silva Cell 2X Load-Displacement Results

Figure 5: Typical Silva Cell 3X Failure

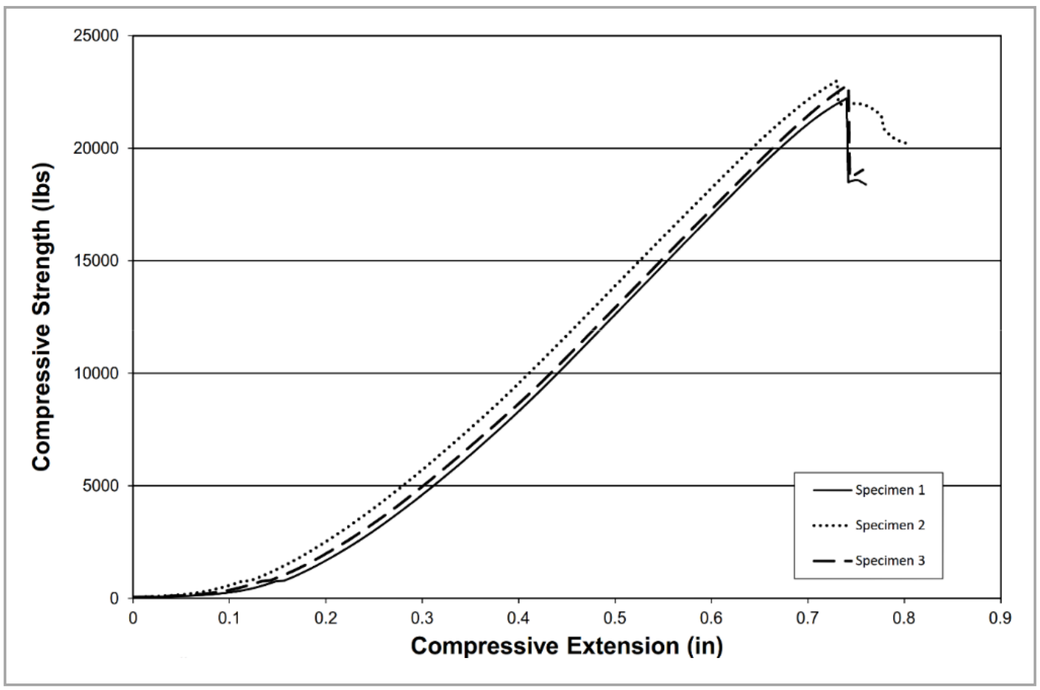


Figure 6: Silva Cell 3X Load-Displacement Results

Application to Pavement Sections

Based on the results of these tests, the following allowable loads were calculated for standard pavement sections using Silva Cell 2X system. These allowable loads assume that the pavers carry no load, that the pavement has sufficient strength to carry the load, and that the load is distributed over a circular contact patch of 406 cm^2 (160 in^2) (362 mm/14.25 in diameter).

Pavers: 148 kN (33,200 lbs)

- 8 cm (3.15˝) pavers
- 2.5 cm (1˝) sand base
- 30.5 cm (12˝) of aggregate

Asphalt: 228 kN (51,200 lbs)

- 10 cm (4˝) of asphalt concrete
- 30.5 cm (12˝) of aggregate

Note: While asphalt provides a relatively high ultimate load capacity once it has been installed, reduced size equipment may be required when installing asphalt over Silva Cells to prevent damage from occurring.

Concrete: 170 kN (38,300 lbs)

- 10 cm (4˝) of Portland Cement Concrete
- 10 cm (4˝) of aggregate

Pavers with Concrete: 188 kN (42,400 lbs)

- 6 cm (2.36˝) pavers
- 13 cm (5˝) of Portland Cement Concrete

Engineering Report

Assumptions

1. Pavement and underlayment are properly installed and compacted so that they form a structurally effective surface without failure under load.
2. For the purposes of this document, the effective area of the Silva Cells is calculated to be 61x122 cm (24”x48”).
3. Load on the Silva Cell is distributed uniformly by the underlayment above.
4. Pavers are assumed to carry no load.
5. The effects of soil in the empty void of the Silva Cells are not considered.

Methodology

Distributed load on the Silva Cell from a load on the pavement is calculated using Burmister’s method modified by Jones for multiple layers (Burmister, 1945; Jones, 1962). The following parameters are used:

- Portland Cement Concrete Modulus: 13,789,515 kPa (2,000,000 psi)
- Asphalt Cement Concrete Modulus: 6,894,757 kPa (1,000,000 psi)
- Aggregate Modulus: 137,895 kPa (20,000 psi)
- Silva Cell Modulus: 10,032 kPa (1,455 psi) from Silva Cell compression test
- Pavement and underlayment density: 68 kg/m^3 (150 lbs/ft^3)

The allowable load on Silva Cell 2X comes from the average of the failure load determined by compression testing with load applied to the deck of the cell by a very stiff platen (Barkey, 2016).

This value is 12,066 kg (26,600 lbs), which corresponds to a distributed load allowable of 12,066 kg/(61 cm x 122 cm) =1.62 kg/cm^2 or 26,600 lbs/ (24 in x 48 in) = 23.1 lbs/in^2.

The Silva Cell effective modulus was calculated from the linear region of the load-displacement test data as shown below. This excludes the initial part of the curve, which is dominated by compression of the rubber pad and contact between parts, and the later part of the curve, which is dominated by buckling.

This is calculated as follows:

$$E\ (modulus) = \frac{\sigma\ (stress)}{\varepsilon\ (strain)} = \frac{\Delta P/_{A}}{\Delta H/_{H}}$$

Where ΔP is an increment of load and ΔH is an increment of displacement from the load-displacement curve (see Figure 7); A is the area of the cell (61x122 cm or 24"x48"), and H is the height of the cell (78.1 cm or 30.75").

Data from the three test articles yields values of 10,073 kPa (1,461 psi), 9,860 kPa (1,430 psi), and 10,156 kPa (1,473 psi), with an average of 10,032 kPa (1,455 psi).

Calculations

Allowable loads are calculated as shown in Figure 8, and calculations for standard pavement sections follow in Table 2.

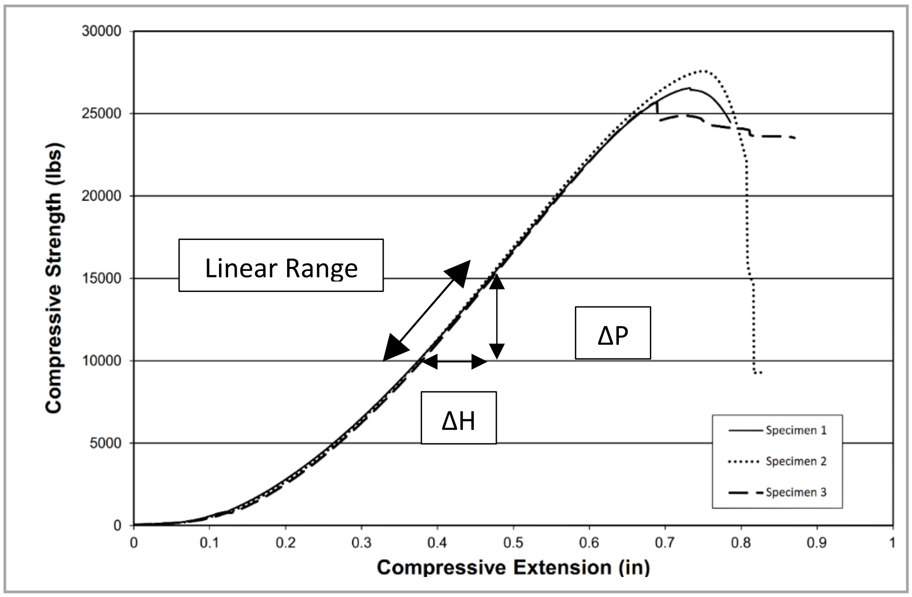


Figure 7: Load-Deflection Curves from Test

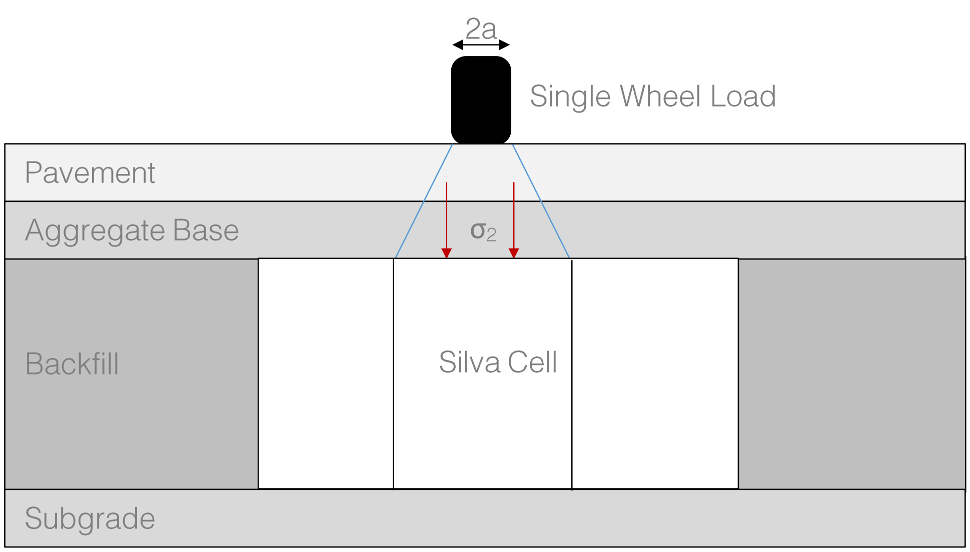


Figure 8: Configuration for Ultimate Load Calculation

Reference Tables

10 cm (4”) Portland Cement Concrete over 10 cm (4”) Aggregate Underlayment

Load Factor	Metric	Imperial
Tire Load	170 kN	38,300 lbs
Tire Pressure	1,650 kPa	239 psi
Contact Radius	181 mm	7.1 in
Distributed Load due to Tire Load	154 kPa	22.4 psi
Distributed Load due to Pavement Dead Load	5 kPa	0.7 psi
Total Distributed Load	159 kPa	23.1 psi

10 cm (4”) Asphalt Cement Concrete over 30 cm (12”) Aggregate Underlayment

Load Factor	Metric	Imperial
Tire Load	228 kN	51,200 lbs
Tire Pressure	2,200 kPa	320 psi
Contact Radius	181 mm	7.1 in
Distributed Load due to Tire Load	149 kPa	21.7 psi
Distributed Load due to Pavement Dead Load	9.5 kPa	1.4 psi
Total Distributed Load	159 kPa	23.1 psi

6 cm (2.36”) Pavers over 12.7 cm (5”) of Concrete

Load Factor	Metric	Imperial
Tire Load	188 kN	42,400 lbs
Tire Pressure	1,830 kPa	265 psi
Contact Radius	181 mm	7.1 in
Distributed Load due to Tire Load	155 kPa	22.5 psi
Distributed Load due to Pavement Dead Load	4.4 kPa	0.6 psi
Total Distributed Load	159 kPa	23.1 psi

8 cm (3.15”) Pavers over 30 cm (12”) Aggregate Underlayment

Load Factor	Metric	Imperial
Tire Load	148 kN	33,200 lbs
Tire Pressure	1,430 kPa	208 psi
Contact Radius	181 mm	7.1 in
Distributed Load due to Tire Load	150 kPa	21.8 psi
Distributed Load due to Pavement Dead Load	9.1 kPa	1.3 psi
Total Distributed Load	159 kPa	23.1 psi

Table 2: Allowable Loads by Standard Pavement Section

Silva Cell 2 Ultimate Load Capacity

Silva Cell 2 System Type	Pavers 8 cm pavers 2.5 cm sand base 30.5 cm of aggregate	Asphalt 10 cm of asphalt 30.5 cm of aggregate	Concrete 10 cm of concrete 10 cm of aggregate	Pavers with Concrete 6 cm pavers 12.7 cm concrete
1X	147 kN	225 kN	165 kN	184 kN
	33,100 lbs	50,500 lbs	37,000 lbs	41,400 lbs
2X	162 kN	247 kN	181 kN	202 kN
	36,400 lbs	55,500 lbs	40,700 lbs	45,500 lbs
3X	137 kN	210 kN	154 kN	172 kN
	30,900 lbs	47,200 lbs	34,600 lbs	38,700 lbs

Table 3: Summary of ultimate wheel load by standard pavement section and Silva Cell 2 system based on contact surface area 250 x 600 mm rectangle.

Lateral Loading

Pressure loads on the post were calculated using the Boussinesq equation with Terzaghi's experimental modifications for rigid walls in soil. For more detailed information, please see the full Lateral Load Analysis Report. The following allowable load curves were determined for loads adjacent to the Silva Cell system expressed as Allowable Load vs. Distance from Edge of Silva Cell. These curves assume the Cell is covered by the equivalent of 11.8" (300 mm) of aggregate which is a typical application using pavers or asphalt paving. In the case of typical applications using 4" (10cm) of concrete over 4" (10 cm) of aggregate this detail is considered to be the equivalent to 11.8" (300 mm) of aggregate. The effect of pavement is not included in the calculation of these loads, but can be expected to reduce the loads on the Cell.

Since these pressures are calculated for a rigid wall, the actual pressures on a flexible Silva Cell can be expected to be lower.

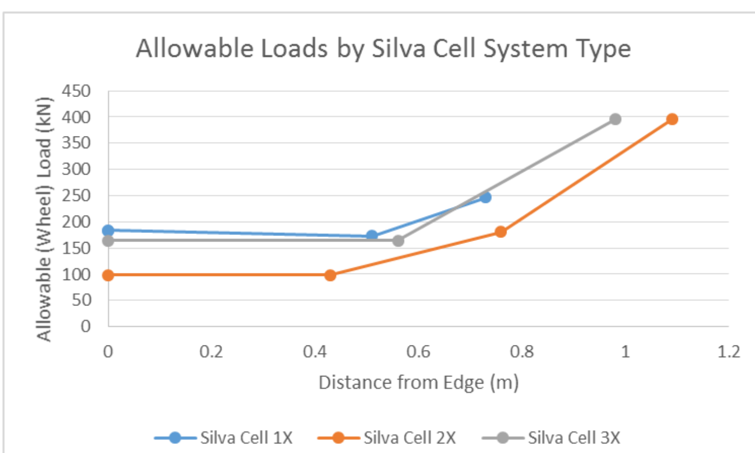


Table 6: Allowable load curves for loads adjacent to Silva Cells.

Sloped Surfaces

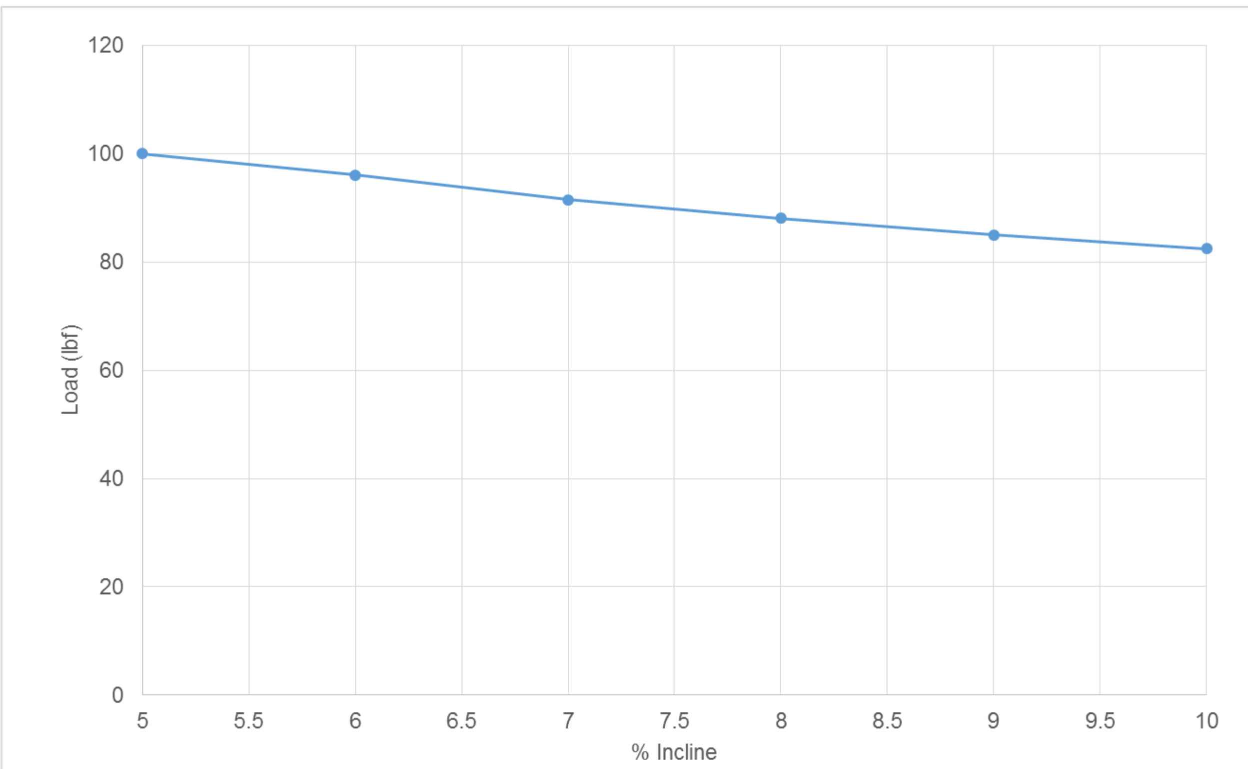
Inclined pavement surfaces are a reality of urban streetscapes, plazas, and parking areas.

The Silva Cell 2 is engineered with the unique ability to be installed at slopes of up to 5% with no reduction in load carrying capacity, and up to 10% with only a slightly reduced capacity. Other suspended paving systems rely on building in steps and/or adding extra depth aggregate above their systems in order to accommodate gradients.

With Silva Cells, the subgrade can be excavated to a uniform dimension below the finished paving grade.

The chart and table below detail the load capacity when installed on an incline. For more detailed information, please see our complete Silva Cell and Sloped Surfaces report.

Incline %	Load Capacity (%)
0-5	100
6	96
7	91.5
8	88
9	85
10	82.4



Conclusion

Independent lab testing and engineering analysis of Silva Cell 2 shows that Silva Cell 2X, when installed per manufacturer's specifications, has an ultimate allowable wheel load that in the standard paving sections analyzed in this report allows for vehicle loading and a safety factor that meets or exceeds most typical requirements for use. These loads can be adjusted based on section profile changes; the typical applications shown here are the most commonly used. For custom details and a review of your site specific loading requirements, please contact DeepRoot.

References

Barkey, D. (2016). "Silva Cell Generation II Strength Test Report". DeepRoot Green Infrastructure, LLC by Innova Engineering, 2 Park Plaza, Suite 510, Irvine, CA 92614.

Burmister, D. (1945). "The General Theory of Stresses and Displacements in Layered Soil Systems". Journal of Applied Physics 16.

Jones, A. (1962). "Tables of Stresses in Three-Layer Elastic Systems". Presented to the Highway Research Board.

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