SILVA CELL 2 ENGINEERING REPORT AND TESTING CONCLUSIONS

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Executive Summary

This document details compression testing and engineering assessment of Silva Cells. The assessment of ultimate loading capacity was performed utilizing common US, UK and 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, TX in October 2015.

Test Configuration

The tests were performed using an Instron Model 5889 testing machine with a 35,000 lbs (15,876 kg) 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 half-inch (1.27 cm) thick neoprene rubber pad was placed between the platen and the deck.

Load was applied under stroke control at a rate of 0.2 in (5mm) 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 (lbs)	Max Load (kg)	Stroke (in)	Stroke (cm)	Mean (lbs)	Mean (kg)
1	1	2X	26,550	12,043	0.733	1.862	26,597	12,064
	2	2X	27,571	12,506	0.75	1.905		
	3	2X	25,671	11,644	0.724	1.839		
2	1	1X	24,454	11,092	0.653	1.659	24,302	11,023
	2	1X	23,971	10,873	0.632	1.605		
	3	1X	24,482	11,105	0.643	1.633		
3	1	3X	22,202	10,071	0.74	1.88	22,616	10,258
	2	3X	22,980	10,424	0.73	1.854		
	3	3X	22,665	10,281	0.737	1.872		

Table 1: Product Testing Summary

Load Displacement Results and Typical Failures

Figure 1: Typical Silva Cell 1X Failure

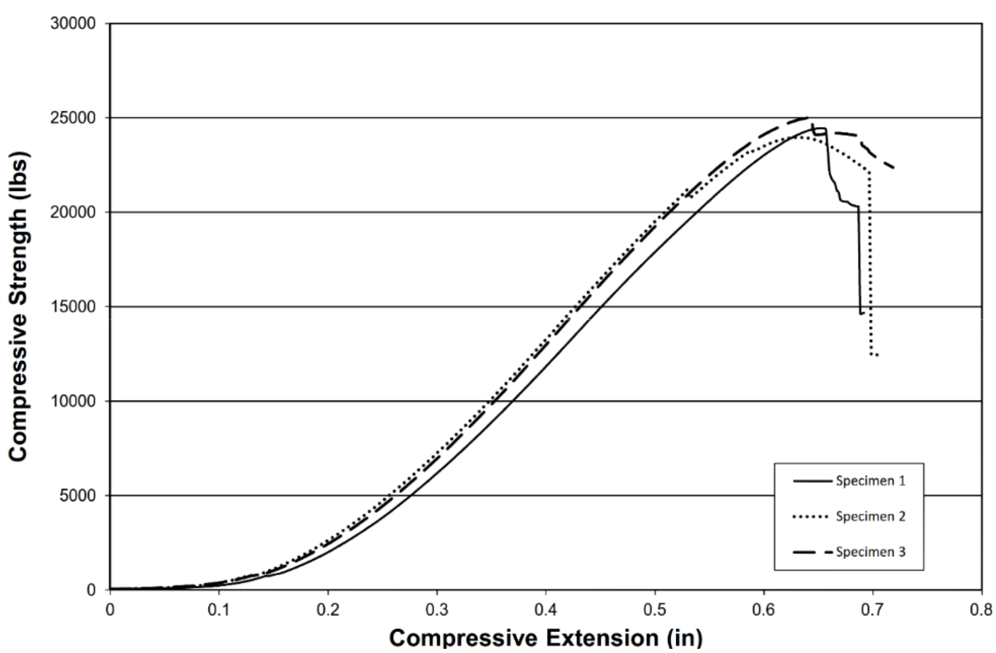


Figure 2: Silva Cell 1X Load-Displacement Results

Figure 3: Typical Silva Cell 2X Failure

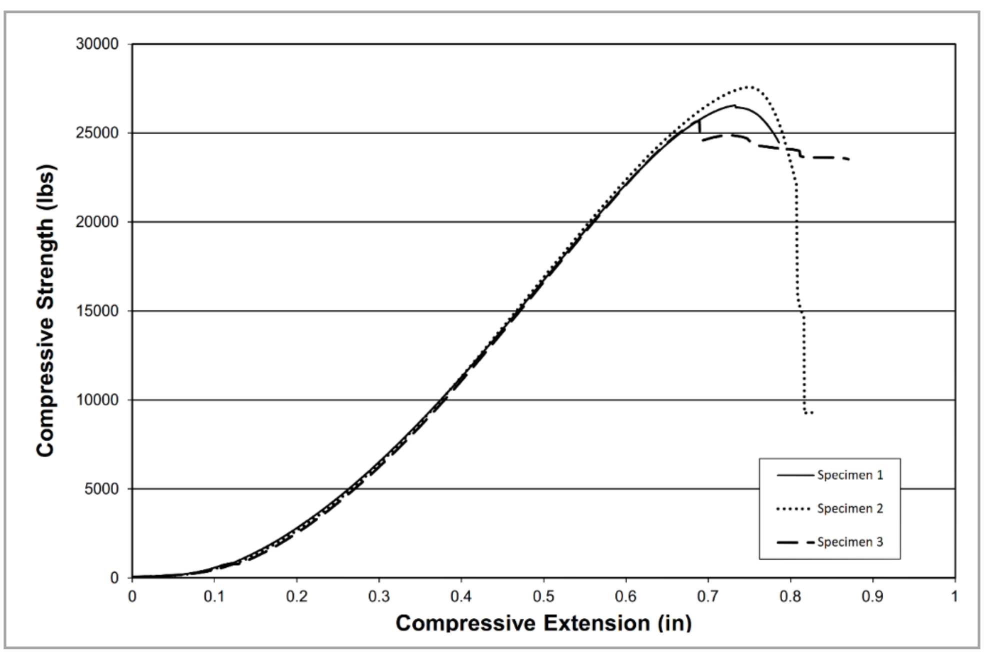


Figure 4: Silva Cell 2X Load-Displacement Results

Figure 5: Typical Silva Cell 3X Failure

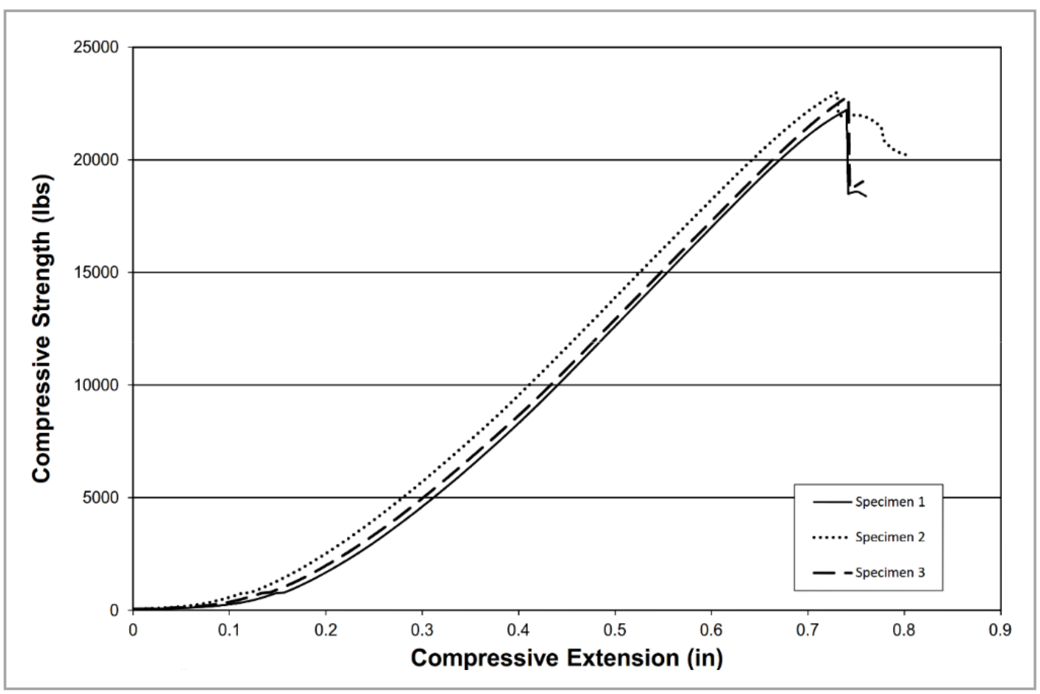


Figure 6: Silva Cell 3X Load-Displacement Results

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 160 in^2 (14.25 in/ 362 mm diameter).

Pavers: 33,200 lbs (148 kN)

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

Asphalt: 51,200 lbs (228 kN)

- 4˝(10 cm) of asphalt concrete
- 12˝(30.5 cm) 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: 38,300 lbs (170 kN)

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

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

- 2.36˝(6 cm) pavers
- 5˝(13 cm) 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 24"x48" (61x122 cm).
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: 2,000,000 psi (13,789,515 kPa)
- Asphalt Cement Concrete Modulus: 1,000,000 psi (6,894,757 kPa)
- Aggregate Modulus: 20,000 psi (137,895 kPa)
- Silva Cell Modulus: 1,455 psi (10,032 kPa) from Silva Cell compression test
- Pavement and underlayment density: 150 lbs/ft^3 (68 kg/m^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 26,600 lbs (12,066 kg), which corresponds to a distributed load allowable of 26,600 lbs/ (24 in x 48 in) = 23.1 lbs/in^2 or 12,066 kg/(61 cm x 122 cm) =10.5 kg/cm^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 (24"x48" or 61x122 cm), and H is the height of the cell (30.75" or 78.1 cm).

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

Calculations

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

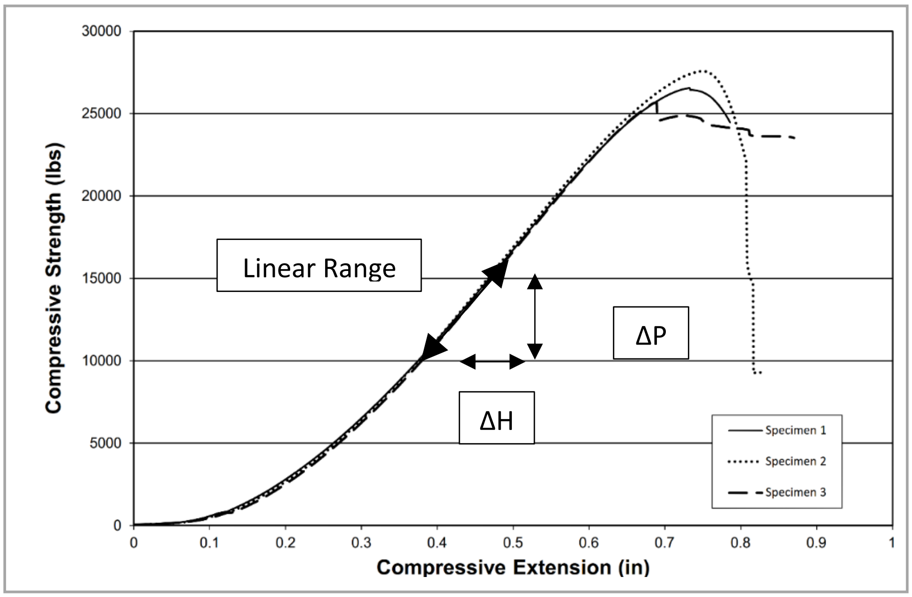


Figure 7: Load-Deflection Curves from Test

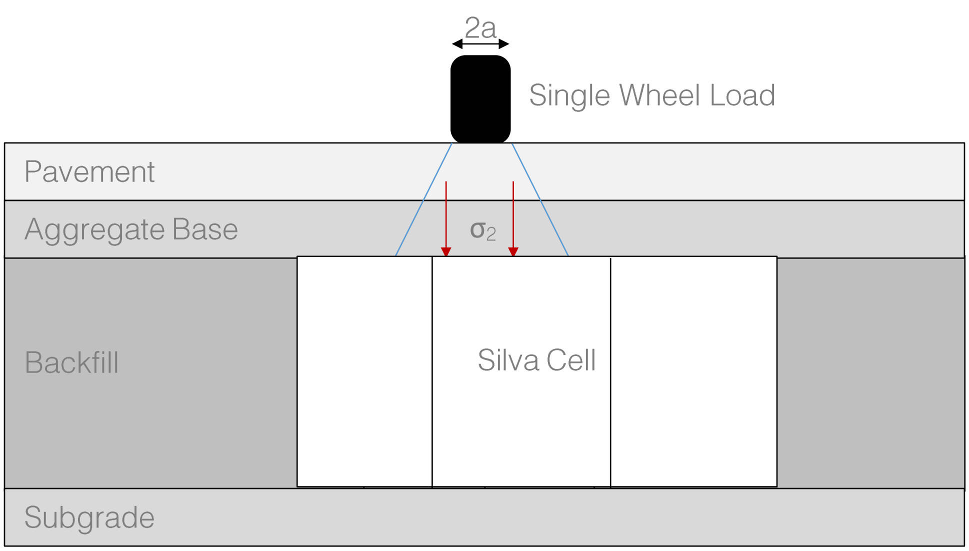


Figure 8: Configuration for Ultimate Load Calculation

Reference Tables

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

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

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

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

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

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

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

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

Table 2: Allowable Loads by Standard Pavement Section

Silva Cell 2 Ultimate Load Capacity (USA)

Silva Cell 2 System Type	Traffic Loading Standard	Pavers 3.15" pavers 1" sand base 12" of aggregate	Asphalt 4" of asphalt 12" of aggregate	Concrete 4" of concrete 4" of aggregate	Pavers with Concrete 2.36" pavers 5" concrete
1X	H-20	30,200 lbs	46,600 lbs	34,900 lbs	38,600 lbs
	HS-20	31,800 lbs	48,700 lbs	35,900 lbs	41,100 lbs
2X	H-20	33,200 lbs	51,200 lbs	38,300 lbs	42,400 lbs
	HS-20	34,900 lbs	53,500 lbs	39,500 lbs	45,200 lbs
3X	H-20	28,200 lbs	43,500 lbs	32,600 lbs	36,000 lbs
	HS-20	29,700 lbs	45,500 lbs	33,600 lbs	38,400 lbs

Table 3: Summary of ultimate wheel load by standard pavement section and Silva Cell 2 system based on AASHTO H-20 contact surface area 14.25" diameter circle and AASHTO HS-20 contact surface area 10"x20" rectangle.

Silva Cell 2 Ultimate Load Capacity (Canada)

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	
	Wheel	Axle	Wheel	Axle	Wheel	Axle	Wheel	Axle
1X	147 kN	294 kN	225 kN	450 kN	165 kN	330 kN	184 kN	368 kN
	33,100 lbs	66,200 lbs	50,500 lbs	101,000 lbs	37,000 lbs	74,000 lbs	41,400 lbs	82,800 lbs
2X	162 kN	324 kN	247 kN	494 kN	181 kN	362 kN	202 kN	404 kN
	36,400 lbs	72,800 lbs	55,500 lbs	111,000 lbs	40,700 lbs	81,400 lbs	45,500 lbs	91,000 lbs
3X	137 kN	274 kN	210 kN	420 kN	154 kN	308 kN	172 kN	344 kN
	30,900 lbs	61,800 lbs	47,200 lbs	94,400 lbs	34,600 lbs	69,200 lbs	38,700 lbs	77,400 lbs

Table 4: Summary of ultimate wheel load by standard pavement section and Silva Cell 2 system based on contact surface area 250 x 600 mm rectangle.

Silva Cell 2 Ultimate Load Capacity (UK)

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	
	Wheel	Axle	Wheel	Axle	Wheel	Axle	Wheel	Axle
1X	121 kN	242 kN	198 kN	396 kN	132 kN	264 kN	150 kN	300 kN
	12,338 kg	24,676 kg	20,190 kg	40,380 kg	13,460 kg	26,920 kg	15,296 kg	30,592 kg
2X	133 kN	266 kN	218 kN	436 kN	145 kN	290 kN	165 kN	330 kN
	13,562 kg	27,124 kg	22,229 kg	44,458 kg	14,786 kg	29,572 kg	16,825 kg	33,650 kg
3X	113 kN	226 kN	185 kN	370 kN	123 kN	246 kN	140 kN	280 kN
	11,523 kg	23,046 kg	18,864 kg	37,728 kg	12,542 kg	25,084 kg	14,276 kg	28,552 kg

Table 5: Summary of ultimate wheel load by standard pavement section and Silva Cell 2 system based on BS EN 1991-1-1:2002 including the UK annex, category G (<160 kN gross vehicle weight, on 2 axles) surface contact area 200 x 200 mm.

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.

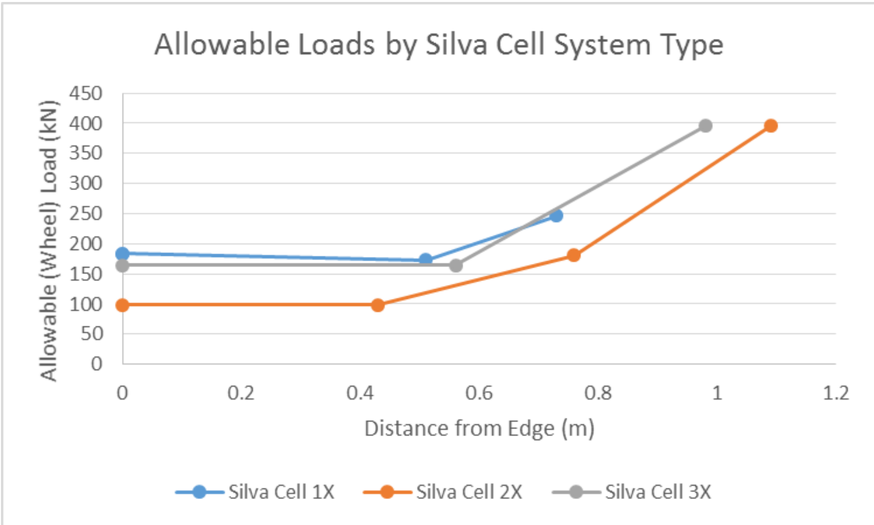


Table 6: Allowable load curves for loads adjacent to Silva Cells.

Sloped Surfaces

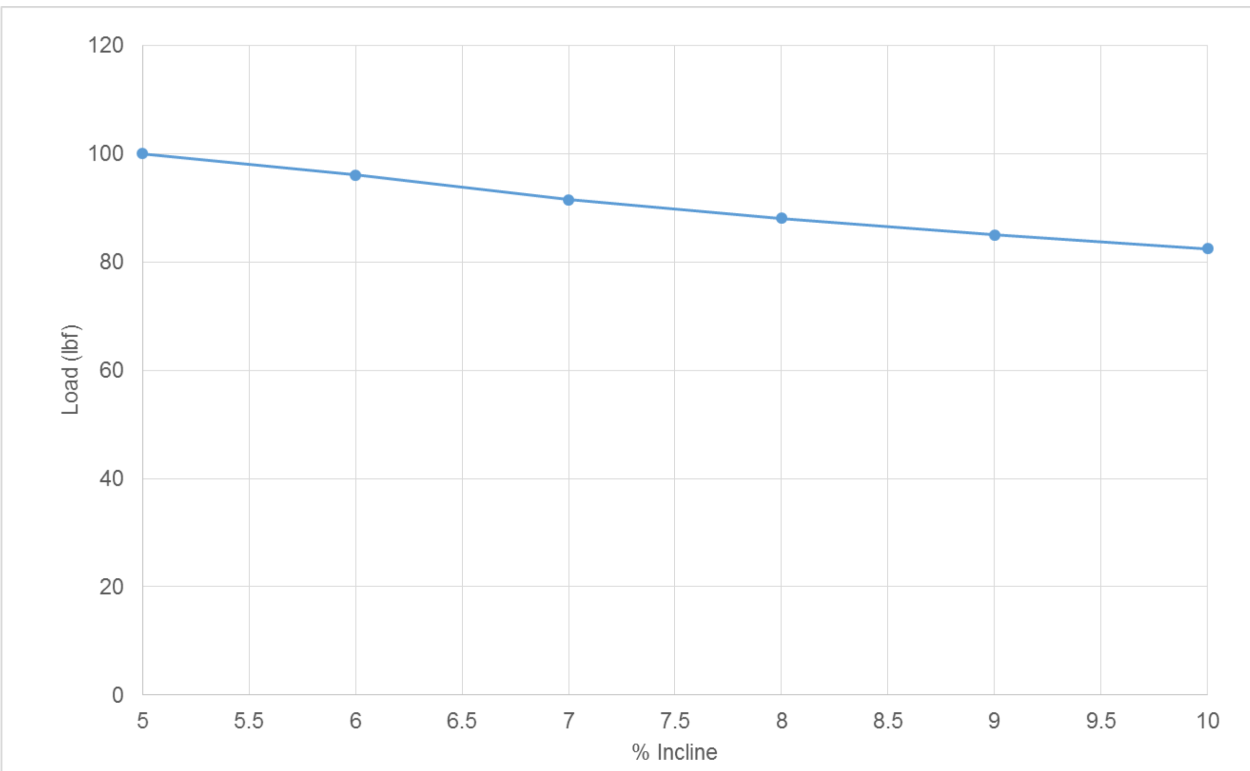
Inclined pavement surfaces are a reality of urban streetscapes, plazas, and parking areas.

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.

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