

## Passive Force-Deflection Curves for Controlled Low-Strength Material (CLSM) and Lightweight Cellular Concrete (LCC)

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### ABSTRACT

Contractors are increasingly requesting to use flowable fill (CLSM) or lightweight cellular concrete (LCC) to replace compacted granular backfill at bridge abutments because they can be placed more rapidly. In addition, LCC reduces the settlement of the underlying soils which is attractive to engineers. To evaluate the passive force-deflection curves for these materials, large-scale lab tests were performed with LCC and CLSM backfills in addition to a granular backfill for comparison. The response of the LCC was similar to that of the granular backfill with somewhat higher peak force developing at about 2.5% of the wall height. Although the stiffness was about twice as high as the granular backfill, the post-peak reduction was less than that for the granular fill. In contrast, the CLSM had a stiffness about 10 times higher than the granular fill and reached the peak value at a deflection equal to 1% of the wall height. The CLSM experienced a rapid decrease in strength of about 60% after the peak strength was reached. The ductility of the LCC makes it a more suitable material for seismic loading with higher displacement demands.

### INTRODUCTION

Increasingly, contractors are requesting to use controlled low-strength material (CLSM) or lightweight cellular concrete (LCC) to replace conventional granular backfill materials adjacent to bridge abutments. These materials can be more rapidly and easily placed than granular backfills and for LCC, the lightweight fill reduces the settlement of underlying soils and the active earth pressure on the abutment wall. These attributes are also particularly desirable when fills must pass over settlement sensitive utility lines. Despite these advantages, relatively little is known about the ultimate passive force or the passive force-deflection relationships for these materials, although these values are fairly well defined for granular backfill (e.g. Rollins and Cole, 2006). The performance of CLSM and LCC lies between conventional aggregate backfill and structural concrete in most of the measured engineering properties. The cement content gives it higher strengths than aggregate backfill, but for most mix designs, the cement content is much lower than that typically used for structural concrete and therefore yields lower strengths.

The low strength of these materials allows for them to be excavated with relative ease, either by hand or using machinery, after placement, unlike typical structural concrete mixtures. The compressive strength of these fill materials can be specified to be in the range of 140 to 8270 kPa (20 to 1200 psi), but the upper range is only used for applications where the fill is not likely to be removed. At strengths higher than approximately 2070 kPa (300 psi), excavation becomes akin



and LCC placed in a large box behind the wall. This paper describes the properties of the three backfill materials, summarizes the results of the passive force-deflection tests, and compares observed behavior.

## TEST LAYOUT

These tests were performed by pushing a 0.6 m tall by 1.22 m wide concrete wall into backfills consisting of compacted sand, CLSM, and LCC placed in a large box. The sand backfill tests provide reference values for comparison purposes. The backfill was 3 to 4 m long to completely contain the failure surface and was slightly wider than the wall 1.28 m to allow the wall to move into the backfill with minimal friction on the sidewall as shown in Figure 1. The backfill was 0.9 m thick and extended 0.3 m below the base of the wall to allow a potential failure surface to develop below the wall as might be expected for a log-spiral failure geometry. The sides of the boxed area were lined with plywood covered by two sheets of plastic with oil between the layers to create a low-friction interface to simulate a 2-D or plane strain geometry typical of a wide bridge abutment. The sides and ends of the box were restrained with braces to minimize lateral deflection. Roller bars were placed below the concrete wall to minimize base friction forces.

**Clean Sand Properties:** The sand backfill is clean poorly-graded sand classifying as SP according to the Unified Soil Classification System and A-1-b according to the AASHTO system. The particle size distribution curve falls within the gradation limits for washed concrete sand (ASTM C33) with  $C_u$  of 3.7 and  $C_c$  of 0.7. The clean sand backfill was compacted to  $17.4 \text{ kN/m}^3$  or about 98% of the modified Proctor maximum density ( $17.8 \text{ kN/m}^3$ ) at an optimum moisture content of about 8% using a jumping jack type compactor. Using a correlation developed by Lee and Singh (1971), the relative density ( $D_r$ ) for this level of compaction would be about 90%. Based on an in-situ direct shear test on the sand box, the drained friction angle ( $\phi'$ ) was found to be  $46^\circ$  with a cohesion of 7 kPa. Consolidation pressures covered the range of vertical stress in the box. Shear stress versus horizontal displacement curves typically showed a 35 to 40% reduction in shear strength from the peak to the critical state value with a friction angle of  $33^\circ$ . Interface friction tests were also performed between the sand and the concrete and a wall friction angle ( $\delta$ ) of  $33^\circ$  was measured. Therefore, the  $\delta/\phi$  is 0.72 which is in good agreement with results from other researchers (Potyondy, 1961, Cole and Rollins, 2006).

**Controlled Low Strength Material (CLSM) Properties:** The mix design for the CLSM backfill/flowable fill is provided in Table 1 and produced a water/cement ratio of 0.93 with a design unit weight of  $19.5 \text{ kN/m}^3$  ( $124 \text{ lbs/ft}^3$ ). The mix design produced a material that flowed into place and was essentially self-levelling. To ensure that this occurred, slump and viscosity tests were performed prior to placement. The average slump was 178 mm (7.0 in) and flow diameter was 184 mm (7.25 in).

A total of 24 test cylinders (203 mm tall by 102 mm diameter) were cast during CLSM fill placement. Of these, 12 cylinders were cured in a fog room environment and 12 cylinders were cured in the ambient laboratory environment. This was done to evaluate what strength difference could be expected for the cylinders cured in the fog room versus the cylinders cured in the ambient laboratory environment because the CLSM backfill that was used in the passive force-displacement tests was simply cured in the ambient laboratory conditions. Each time unconfined compressive strength (UCS) testing was performed, the moist unit weight was also calculated. The average dry unit weight was found to be  $19.1 \text{ kN/m}^3$  ( $121.5 \text{ lb/ft}^3$ ), which is about 15% lower than conventional concrete.

**Table 1 Mix design properties for CLSM**

Material Type	Description	Design Quantity	Specific Gravity, $G_s$	Volume (ft <sup>3</sup> )
Cement	Type II-V	40 lbs.	3.15	0.20
Fly Ash	Type F (ASTM C618)	200 lbs.	2.30	1.39
Coarse Aggregate	No.8 Pea Gravel (ASTM C33)	1442 lbs.	2.60	8.89
Fine Aggregate	Washed Sand (ASTM C33)	1442 lbs.	2.60	8.89
Water	Potable	223 lbs (26.8 gallons)	1.00	3.58
Air Content	-	15%	-	4.05
Yield	-	3347 lbs.	-	27.00

The unconfined compression test results for the CLSM tests performed on cylinders cured in the lab and in the fog room are summarized in Table 2. The strength of the cylinders cured in the laboratory peaked in strength after 14 to 21 days. In contrast, cylinders cured in the fog room continued to gain strength with time up to 28 days and the trend was still upward at that point. Furthermore, the strength of the laboratory cured cylinders was significantly less than the strength obtained by curing the same CLSM in the fog room. The measured UCS for the lab curing method is likely a better representation of the UCS of the backfill material. On the day of the passive force test (14 days after curing), the CLSM was found to be 311 kPa (45.2 psi), which was about half of the strength of the cylinders cured in the fog room. The UCS values for the laboratory-cured specimens at the time of the passive force test only achieved about 35% of the 28-day strength of the cylinders cured in the fog room.

**Table 2 Summary of unconfined compression strength (UCS) testing with time after placement for cylinders cured in the lab and in the fog room.**

Curing Time (days)	Curing Environment	
	Lab	Fog Room
	Avg. Unconfined Compressive Strength, kPa (psi)	
7	223 (32.4)	280 (40.6)
<b>14</b>	<b>312 (45.2)</b>	<b>538 (84.6)</b>
21	286 (41.5)	790 (114.6)
28	252 (36.5)	942 (136.6)

**Lightweight Cellular Concrete (LCC) Properties:** In contrast to flowable fill or conventional concrete, LCC is only composed of water, cement and a foaming agent. LCC can also be considered a CLSM but is typically specified using ACI 523. The foaming agent produces a synthetic foam which generates air bubbles that replace the coarse aggregate. The foam is a blend of protein-stabilized surfactants. The mix design for the LCC is summarized in Table 3. LCC does not have the high strength of a typical concrete, it may be used as an alternative to compacted fill. Strength generally varies as a function of unit weight.

Caltrans has defined six classes of LCC based on cast density and unconfined compressive strength as shown in Table 4. Class type II is most common in practice followed by class type IV. For this study, the mix was designed to be Class Type II with a cast density of about 30

lbs/ft<sup>3</sup>. According to Caltrans specifications, the maximum height of a lift of LCC should not exceed 0.9 m (3 feet). The backfill in this test was exactly 0.9 m (3 ft) in height, therefore only one lift of LCC was necessary. The foaming agent was mixed with the cement slurry and pumped directly into the test box. Four to eight test cylinders of the LCC were taken from every cubic meter throughout the pumping process to determine the variation of unconfined compressive strength with time. Test cylinders were poured into Styrofoam molds which were then carefully cut away from the test specimen. Conventional testing procedures for concrete would cause too much disturbance to the cellular concrete. After six days of curing, the UCS of the LCC cylinders had reached 480 kPa (70 psi) and the passive force test was performed to have a UCS close to that for the companion CLSM test. The 28-day unconfined compressive strength of the cellular concrete was 814 kPa (118 psi), which exceeds the minimum value required by the Caltrans Cellular Concrete Class II.

**Table 3 Mix design properties for lightweight cellular concrete (LCC)**

Material Type	Description	Design Quantity	Specific Gravity, G <sub>s</sub>	Volume (ft <sup>3</sup> )
Cement	Type II-V	40 lbs.	3.15	0.20
Foaming Agent	JLE (ASTM C 869)	70.4 lbs.	1.128	1.00
Water	Potable	236 lbs (28.3 gallons)	1.00	3.78
Air Content	-	80%	-	4.05
Yield	-	346.4 lbs.	-	27.00

**Table 4 Caltrans Lightweight Cellular Concrete Classes**

Cellular Concrete Class	Cast Density kN/m <sup>3</sup> (lb/ft <sup>3</sup> )	Minimum 28-day Compressive Strength kPa (psi)
I	3.8-4.6 (24-29)	69 (10)
II	4.7-5.5 (30-35)	276 (40)
III	5.7-6.4 (36-41)	550 (80)
IV	6.6-7.7 (42-49)	830(120)
V	7.9-12.4 (50-79)	1100 (160)
VI	(12.6-14.1) 80-90	2070 (300)

## TEST PROCEDURES AND INSTRUMENTATION

Tests were performed by pushing the wall longitudinally into the backfill sand using a 490 kN hydraulic actuator which was bolted to the wall. Load was applied at a rate of 0.25 mm/min. Vertical and horizontal load cells were mounted between the reaction frame and the actuator so that the loads necessary to hold the wall in position could be measured. Nevertheless, because of the flexibility of the actuator piston, there was still a small amount of movement of the backwall at the soil-wall interface.

**Instrumentation:** Load was measured by a pressure transducer in the actuator. To measure the movement of the backwall, four longitudinal string pots were positioned at the corners of the

wall and two transverse string pots were positioned at the top and bottom of one side. In addition, a final string pot was used to monitor the vertical movement. Longitudinal string pots were also attached to steel rods inserted into the backfill surface at distances of 0.3 to 0.6 m spacing behind the backwall to determine average compressive strain within the backfill. All string potentiometers were connected to an independent reference frame. A surface grid was painted on the top of the backfill material so that heave could be measured using conventional surveying techniques before and after the load test.

## PASSIVE FORCE-DEFLECTION CURVES

The passive force versus longitudinal deflection curves obtained from the tests on the three backfill materials are plotted together in Figure 4. The passive force was computed from the applied actuator force while the wall deflection was the average of the four longitudinal strain potentiometers attached to the concrete backwall.

**Curve for Sand Backfill:** Prior to reaching the peak resistance, the passive force-deflection curve appears to exhibit a typical hyperbolic curve. The peak passive force for the sand was about 200 kN (45 kips) and typically developed at a normalized deflection of 2.5% to 3.5% of the wall height ( $H$ ) which is in the range typical of large-scale passive force test results (Rollins & Cole, 2005). The initial stiffness was about 23 kN/mm or 130 kips/inch. Beyond the peak resistance, the test typically showed a reduction in the passive force to a residual value at a normalized displacement of 0.04 $H$  to 0.06 $H$ . This post-peak reduction in passive force to a residual value is consistent with the stress-strain behavior expected from dense compacted sand and the results of the direct shear tests. The dense sand dilated during shearing and the resulting lower density led to a reduced strength. The post-peak strength was about 75% of the peak value and may be important for large displacement applications such as seismic loading situations. This post-peak strength reduction is much greater for this densely compacted sand than for other passive force-deflection tests on sand reported by Rollins and Cole (2006) or Marsh et al (2015). This difference in behavior is likely due to the fact that this sand was compacted to 98% relative compaction ( $D_r = 90\%$ ) while the sand in other tests was compacted to 95% relative compaction ( $D_r = 70\%$ ). Small increases in relative compaction can have significant impact on relative density and lead to post-peak dilation with strength reduction.

**Curve for CLSM Backfill:** Prior to reaching the peak resistance, the passive force-deflection curve for CLSM is very linear compared to the conventional granular backfill. The stiffness was about 228 kN/mm (1300 kips/in) which is about 10 times the stiffness of the granular backfill. Peak passive force was developed at a normalized displacement of about 1% of the wall height, which is about half of that for the granular fill, and then remained relatively constant to a normalized displacement of about 2%. The peak passive force for the CLSM was 267 kN which was 33% higher than the peak strength of the granular backfill. At displacements beyond the peak, (3 to 4% of the wall height) the passive force rapidly decreased with displacement, reaching a low of about 100 kN which is only 37% of the peak passive force. This post-peak strength is considerably lower than the post-peak strength observed for the granular backfill and represents a comparative weakness for seismic loading situations where ductility is particularly valuable. As the resistance decreased, a distinct failure surface developed in the backfill and daylighted at a distance of about three times the wall height or 1.8 m (6 ft) behind the wall face.

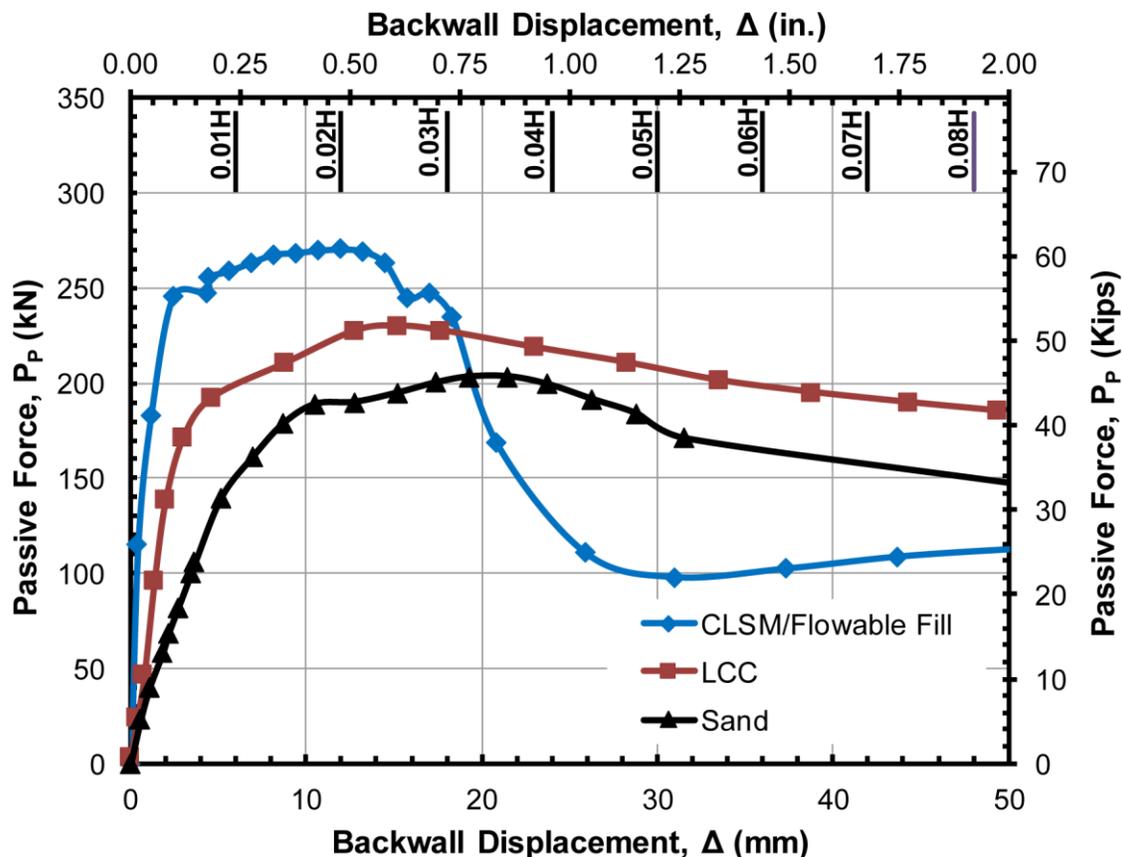


Fig. 2. Passive force-deflection curves for backfills consisting of sand, lightweight cellular concrete (LCC) and Controlled Low Strength Material (CLSM) or flowable fill.

**Curve for LCC Backfill:** Similar to the CLSM backfill, the passive force-deflection curve for LLC is very linear compared to the conventional granular backfill until just prior to reaching the peak. The stiffness was about 43 kN/mm (246 kips/in) which is about twice the stiffness of the granular backfill. Peak passive force was developed at a normalized displacement of about 2.5% of the wall height, which is about the same as that for the granular fill. The peak passive force for the CLSM was about 230 kN which was 13% higher than the peak strength of the granular backfill. At displacements beyond the peak, the passive force gradually decreased with displacement, reaching a low of 185 kN or about 80% of the peak passive force even at a displacement of about 9% of the wall height. This post-peak strength is somewhat higher than the granular backfill but considerably higher than the post-peak strength observed for the CLSM backfill. Again, this behavior represents a comparative advantage for seismic loading situations where ductility is valuable.

## CONCLUSION

The clean, poorly graded sand backfill, compacted to 98% of the modified Proctor maximum density, had a friction angle of 46°. The passive force-deflection curve reached a peak value of about 200 kN at a normalized deflection of about 3% of the wall height. After the peak, the passive resistance of the very dense sand decreased to a post-peak value equal to about 75% of the peak value as the dense sand dilated.

Both the CLSM/flowable fill and the LCC backfills produced passive force values (270 and

230 kN, respectively) which were similar to, but somewhat higher than, that obtained from the dense compacted sand backfill. In addition, both backfills were considerably stiffer than the compacted sand. However, the CLSM was nearly 10 times higher than the granular backfill while the LCC was only about two times higher than the granular backfill. The LCC reached its peak passive force at a deflection equal to about 2.5% of the wall height which is quite similar to that for the granular backfill. In contrast, the much stiffer CLSM reached its peak value at a displacement of only 1% of the wall height.

Perhaps the biggest difference in behavior for the LCC and CLSM backfills was with respect to post-peak strength reduction. The CLSM experienced a reduction in strength of about 60% over a deflection range equal to 3 to 4% of the wall height followed by development of a distinct failure surface. In contrast, the passive force of the LCC only decreased by about 20% after reaching the peak which is somewhat less than the granular backfill and considerably less than the CLSM. In addition, this reduction in strength occurred over a large displacement range equal to 2.5 to 8% of the wall height. This increased ductility of the LCC is particularly beneficial for seismic events where large displacement demands must be accommodated. The ductility of the LCC is similar to that obtained with the granular backfill.

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