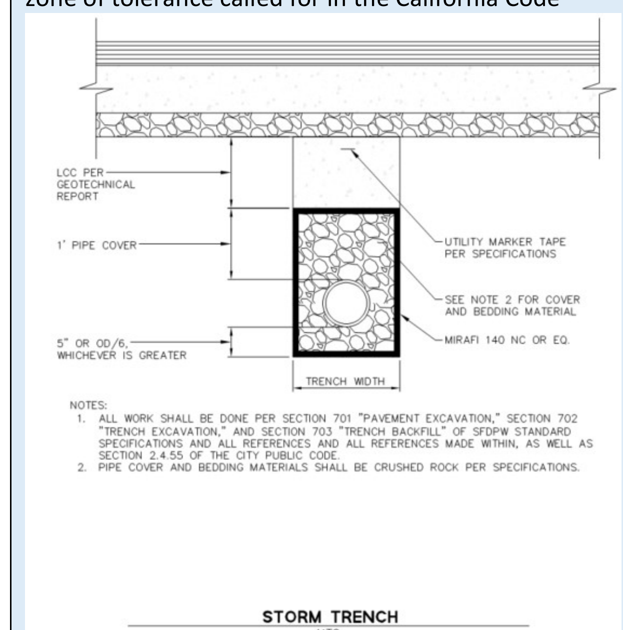
Responses to DPW Comments 28, 32, and 34 on Excavatability

Preparation for Meeting with Port, MRP, TAP and City Thursday, 15 April 2020 RE: Excavatability (Removability) of LCC

(rev.01 expanded response regarding pipe trench details and excavatability/removability)

Responses to questions 28, 32 and 34 from Public Works

Comment No.	Document Reviewed	Page	Text or figure	Comment/Issue	Proposed Revision or Solution	Response
28	Mission Rock Lightweight Cellular Concrete Technical Advisory Panel, Technical Review Report, dated March 12, 2020	Appendix A Page 6	LCC Excavatability	Memorandum states: "...LCC with a maximum compressive strength of 300 psi is likely the upper limit for which LCC can still be excavated. The specification for the LCC specifies a maximum 28-day compressive strength of 200 psi. Because strength can continue to increase beyond 28 days, it is appropriate to specify 200 psi so that the LCC strength does not ultimately exceed 300 psi overtime and is still excavatable." However ACI 229R-13 states for Consolidated Low Strength Materials: "Long-term strengths (90 to 180 days) should be targeted to be less than 100 psi (0.7 MPa) for excavation with hand tools" and "5.3.7 Excavatability — The ability to excavate CLSM is an important consideration on many projects. In general, CLSM with a compressive strength of 100 psi (0.7 MPa) or less can be excavated manually." Further, National Ready Mixed Concrete Association Guide Specification for Controlled Low Strength Materials (CLSM) states: "R3.3 Excavatability - The excavatability of hardened CLSM can generally be divided into two categories: 1) Unconfined compressive strength < 150 psi is considered to be EXCAVATABLE by hand tools and conventional machinery such as backhoes. 2) Unconfined compressive strength > 150 psi is considered to be NON-EXCAVATABLE." The City requires the LCC to be safely excavatable by hand tools. Industry standards indicate MRP's proposed LCC specifications would not satisfy the excavatability requirement.	MRP to provide justification and rationale for its request to exceed industry norms, including demonstration of hand digging to utility. TAP to review and make recommendation regarding MRP's proposal.	See write up by Stan Peters sent 14 April 2020. Additionally, MRP would like to point out that all wet and dry utilities, except the private owned and maintained DES pipes, have at least 12" of sand or pea gravel pipe cover between the top of pipe and bottom of LCC or bottom of pavement section above the pipe as well as warning tape above the pipe cover. There is also 12-16" of side cover between the pipe and LCC at the side of the trench—see separate Typical Trench Section Exhibit and thumbnails below The pipe cover material is very easy to excavate and within the zone of tolerance called for in the California Code 

Comment No.	Document Reviewed	Page	Text or figure	Comment/Issue	Proposed Revision or Solution	Response
32	Mission Rock Lightweight Cellular Concrete Technical Advisory Panel, Technical Review Report, dated March 12, 2020	Appendix C Page C.2		The crushing resistance and “excavatability” criteria (20 psi to 300 psi) are significantly different than proposed specifications which call for 50 psi to 200 psi LCC. However ACI 229R-13 states for Consolidated Low Strength Materials: "... Long-term strengths (90 to 180 days) should be targeted to be less than 100 psi (0.7 MPa) for excavation with hand tools." and "5.3.7 Excavatability — The ability to excavate CLSM is an important consideration on many projects. In general, CLSM with a compressive strength of 100 psi (0.7 MPa) or less can be excavated manually." Further, ACI 301 states: "4.3.7 Excavatability - The ability to excavate CLSM is an important consideration on many projects. In general, CLSM with a compressive strength of 0.3 MPa (50 psi) or less can be excavated manually. Mechanical equipment, such as backhoes, are used for compressive strengths of 0.7 to 1.4 MPa (100 to 200 psi) ..." Finally, National Ready Mixed Concrete Association Guide Specification for Controlled Low Strength Materials (CLSM) states: "R3.3 Excavatability - The excavatability of hardened CLSM can generally be divided into two categories: 1) Unconfined compressive strength < 150 psi is considered to be EXCAVATABLE by hand tools and conventional machinery such as backhoes. 2) Unconfined compressive strength > 150 psi is considered to be NON-EXCAVATABLE. The City requires the LCC to be excavatable by hand tools.	TAP to review and to make a recommendation regarding MRP's proposal. MRP to provide justification to support proposed exceedance of industry norms, including hand digging to utility. Additionally, worker safety must be evaluated.	See response to 28 above
34	Mission Rock Lightweight Cellular Concrete Technical Advisory Panel, Technical Review Report, dated March 12, 2020	Appendix C Page C.2	Section 3	This comment is related to Comment Nos. 27 and 31. Maximum compressive strength performance criteria is 300 psi, which is measured against 10 years of time elapsing after construction. Is that reasonable to excavate using hand tools as required under California law?	TAP to review and recommend. MRP to provide justification for request to exceed industry norms.	See response to 28 above

TAP Report Volume1 - Section 1.12 - Excavatability

Introduction

The Developer proposes LCC to be used in the place of native soil materials within the entire public right-of-way. In a letter dated April 3, 2020, Public Works requests the Developer (MRP) to demonstrate that LCC with a compressive strength of 300 psi can be excavated using hand tools (as required under California law) and after 28-days, the compressive strength does not increase by more than 50% for the life of the project. The demonstration shall include:

- excavation solely with hand tools,
- to the full depth of utilities,
- in LCC representative of long-term strength

In addition, Public Works transmitted a comment / issues matrix dated April 3, 2020. Item #42 from that matrix requests the TAP to:

- Review and make recommendations regarding the hand-diggability of the LCC,
- The potential safety issues for those performing hand-digging, and
- The likelihood (given the relative ease or difficulty of the hand digging) that a crew would comply with State requirements to hand dig

Background on State requirements. California Government Code Sections 4215 - 4216, Protection of Underground Infrastructure, regulates the safe excavation of "subsurface installations" or underground pipelines, conduits, and ducts. Furthermore, City construction contracts as well as permits issued by both Public Works and Port (reference Article 2.4 of the Public Works Code) requiring cross-reference compliance with these state code sections for excavators performing construction in the public right-of-way.

Prior to excavation, utility operators must locate, and field mark their facilities with identifiable delineation, usually paint markings on the pavement surface. A "tolerance zone", based on these paint markings, is 24" each side of that paint marking. Excavations within this tolerance zone is limited to the use of hand tools (defined as using human power and is not powered by any motor, engine, hydraulic, or pneumatic device).

For work below Public Works and Port rights-of-way, sawcutting and powered equipment may only be used on the upper pavement section, usually about 12" thick and consisting of an Asphalt Concrete Wearing Surface (ACWS) layer over a concrete pavement base.

If an excavation is required within the tolerance zone of a subsurface installation and below the pavement section, the excavator shall determine the exact location of the subsurface installations in conflict with the excavation using hand tools before using any power-driven excavation or boring equipment within the tolerance zone of the subsurface installations. This code is intended for the safety and welfare of construction workers and protection of utility operator s' facilities.

LCC Excavatibility

Flowable fills are self-compacting low-strength materials, typically consisting of a combination of cement and/or fly ash, sand and/or rock. They are typically called Controlled Low Strength Materials, (CLSM) with various strength limits suggested, depending upon whether the material will require re-excavation or not and, more specifically, based on whether hand-excavation or normal backhoes will be utilized. ACI 229-13 suggests that CLSMs with compressive strengths of less than 100psi are readily excavatable by hand tools. NRMCA indicates that CLSMs with compressive strengths less than 150psi can readily be re-excavated by hand tools AND conventional machinery, such as backhoes.

The TAP recognizes the City's concern to comply with California's state law that materials over utilities must be excavatable with hand tools.

The ACI 229-13 report includes several items that are relevant to determining if the LCC materials within the project's ROWs should be deemed excavatable by hand tools, even at the maximum specified limits of design (200psi) and for "failure" criteria (300psi). First, Table 5.2.2 lists examples of CLSM mixture proportions. Secondly, Equation 5.3.7 for Removability Modulus, RE (under the Section 5.3.7 "Excavatability") shows a relationship that utilizes unit weight and compressive strength at 28days to predict excavatibility of various materials. A material with RE of less than 1.0 is removable with hand tools. Finally, ACI 229-13's Chapter 9 addresses Low Density CLSMs using PreFormed foams, called LD-CLSMs, which are the same materials that are referred to as LCC on the Mission Rock project. This chapter mentions that "Because of its low density, LD-CLSM is preferred when reduction of dead load is a critical requirement." The report also states that "In addition, LD-CLSM is easily excavated, which is a requirement in some applications", such as required by California law.

Using the mixture proportions of various CLSMs in Table 5.2.2, unit weights were calculated. The equation for RE in the ACI report is in metric units of kg/M3 and kPa. Performing a units conversion, into Imperial units of lb/CF and psi shows that this equation with 0.619 yields the same RE values as using 104 with psi & pcf, as previously reported. Thus, the various examples of CLSMs were analyzed in the attached table with their resulting RE values, as well as other CLSM mixtures.

Please note that in these examples, at or less that 100psi, the mixes with rock exceeded an RE of 1.0 for hand excavatability, and the mixes with sand only come reasonably close. Only the mixes with no aggregate fillers are below the 1.0 recommendation.

For those that were not in attendance for the September kick-off meeting, this analogy/explanation for Removability Modulus was given for various CLSM mixtures with 100psi at 28days. A traditional flowfill made at a concrete batch plant with sand and gravel would likely have a density of 145pcf, and would be difficult to dig with a shovel, due to the rock. A sand only flowfill would have a lower density without the rock, and also be easier to dig without the coarse aggregate. ACI 229-13 mentions that "Mixtures with high coarse aggregate quantities can be difficult to remove by hand, even at low strengths"; the RE equation values reflect this trend. A "slurry" CLSM would have a lower density without sand, and would be even easier to hand-excavate. Table 5.2.2 mixtures S-2 through S-43 show a lower density and RE values much less than 1.0; the mixtures are easier to dig with a shovel without the penetration resistance offered by the sand. When we use pre-formed foam to create large amounts of air, instead of sand and/or gravel the trend continues to make the CLSM easier to excavate.

Reference to various Removability Moduli in Colorado; explanation

To further demonstrate this trend with air, several commercial CLSM mixtures (approved in Colorado, subject to an RE of 1.5 or less) are also listed in the attached table. One producer uses custom "powder-only" volumetric on-site mixing trucks with pre-formed foam to produce cellular material that is significantly less than ACI's recommendation of less than 1.0 for excavation with hand tools. The three mixes with sand and gravels are significantly over the 1.0 recommendation. The high-strength flashfill mixture was developed for Denver Water, who wanted a fast-setting mix (100psi minimum in 4 hours) to resist water hammer, yet still subject to an RE of 1.5 or less. Before the normal flashfill was approved for use in Colorado Springs, the city required a "pot-hole" test of material that was in-place for over a year; the backhoe did not "stand off its pads" nor did the operator "feel" any resistance with his hydraulic controls. Chunks of material were readily broken up by hand, as samples of LCC brought to the kick-off meeting in September were.

Comparison of Removability Modulus at Mission Rock Pilot Project with other projects

The last group of mixes and RE calculations in the below table show the strength and unit weights of the 27pcf and 30pcf LCC tested in the Pilot project. The calculated RE values are significantly less than the 1.0 recommended limit, even at the maximum "design" strength limit of 200psi or 300psi "failure" limit. TAP understands that the Developer will be scheduling another excavation demonstration for city officials that were not able to attend the first one during Pilot Project testing; we would encourage those still concerned with excavatability to attend. Additional long-term coring (over 90 days) will also occur to evaluate actual strength gain, compared to cores obtained during the Pilot project.

Removability Modulus Values for Excavatability

CLSM Examples from ACI229-13 Table 5.2.2

Mix Identification	PCF	PSI	RE
CO DOT, includes rock	145	60	1.41
FL DOT, sand only	130	50	1.09
FL DOT, sand only	130	50	1.09
SC DOT, sand only	135	80	1.46
Mix AF, rock only	143	65	1.43

Mix D, Rock only	136	65	1.33
Non-Air CLSM, includes rock	145	100	1.82
Mix S-2, no aggregate	94	40	**0.60**
Mix S-3, no aggregate	86	60	**0.64**
Mix S-4, no aggregate	91	50	**0.64**

Hypothetical at 100psi & 150psi

Sand only CLSM	130	100	1.54
Sand only CLSM	130	150	1.89
Sand & Gravel CLSM	145	100	1.82
Sand & Gravel CLSM	145	150	2.22

CRC's Colorado Client CLSM Mixes

Client 1, Normal Flashfill,fly ash & foam	55	210	**0.61**
Client 1, Hi-Strength, fly ash & foam	72	490	1.41
Client 1, Cement & Foam,	41	270	**0.45**
Client2, CDOT mix sand & #9 rock	134	70	1.35
Client2, CDOT mix, sand & #9 rock	133	80	1.43
Client3, CDOT mix, sand & rock	138	72	1.43

Mission Rock LCC Data & Forecasts

Pilot project, 27pcf - average	27.6	111	**0.16**
Pilot project, 27pcf - high	28.5	130	**0.18**
Pilot project, 30pcf - average	30	147	**0.21**
Pilot project, 30pcf - high	30	160	**0.22**
Projected 26pcf at 200psi	26	200	**0.19**
Projected 26pcf at 300psi	26	300	**0.24**
Projected 30pcf at 200psi	30	200	**0.24**
Projected 30pcf at 300psi	30	300	**0.30**

Note1 : Colorado RE's less than 1.5 as originally specified to be "excavatable"

Note2 : all LCC RE values, including at Max of 200 & 300psi, much less than

ACI229's recommendation of RE< 1.0 for hand excavatibility.

Long-Term Strength Gain Estimates of LCC

While LCC has been around since the 1940s, we were not able to locate any long-term compressive strength gain data in ACI 536.1R-06 Guide for Cast-In-Place Low-Density Cellular Concrete, or with internet research. However, we were able to find some information of long-term strength gain in concrete dams, and assuming the cement hydration mechanism in LCC is similar to aggregate-based concrete, this is one way of estimating long term strength gain.

The first study was an ASCE 2010 article by the USBR, in recognition of the Hoover Dam turning 75 years old, entitled "Long-Term Properties of Hoover Dam Mass Concrete". A coring program conducted in 1995 indicated an average core strength of 7230psi at 60 years of age. The average of Quality Assurance testing results at 28days was 3500; an increase of 207% in 60 years. Extrapolating the average 28day strength of the 30pcf LCC of the Pilot project would result in an estimate of **304psi at age 60 years; RE = 0.30**.

A second study with more intermediate data points was also a USBR Report from 2005 entitled Materials Properties Model of Aging Concrete (Report DSO-05-05.) Table 4 below, contained relevant strength gains out to 25 years. Please note Footnote 1 states that the 10year cores were tested dry, resulting in 10%-20% higher strengths. Assuming 10% higher when cores were tested dry, adjusted core strengths at 10years would be 6400psi, mid-way between 5year and 25 year data. With the 6400psi adjustment, the average of two data sets (0.5,1,5,10 & 25 years) and six data sets (0.5, 1 & 25years) were plotted in the graph below.

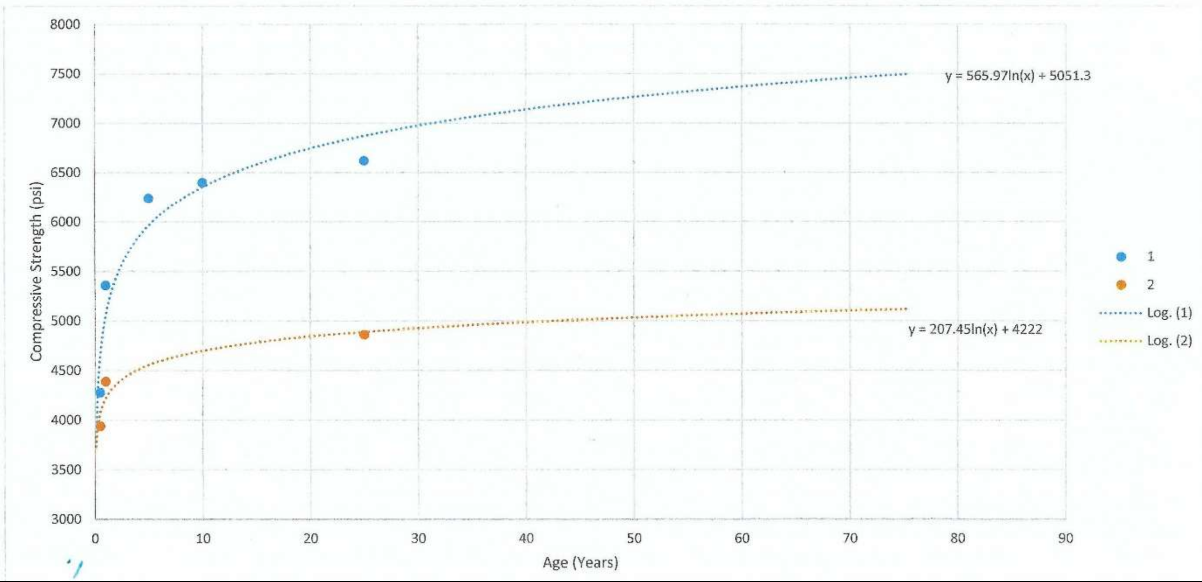
Table 4.—Compressive strength of 25-year cores compared to reference core tests by spatial orientation—Yellowtail Dam issue evaluation—Yellowtail Dam, Montana

			Compressive strength, lb/in^2					
Mix	Drill hole	Elevation	6 mo	1 yr	5 yr	10 yr[1]	25 yr	Percent 1 yr
INT9/1963	18-13-V	3179.8	4460	6310	6660	7520	7510	119
INT/9B1963	18-13-V	3176.6	*No comparable data for this lift*				4810	
INT6/1963R	10-9-V	3204.5	4100	4400	5810	6550	5730	130
INT6B/1963R	10-9-V	3198.5	*No comparable data for this lift*				3880	
INT6B/1963R	10-9-V	3194.7	*No comparable data for this lift*				3260	
INT2/1964	5-9-V	3459.6	3300	3250			3390	104
INT2B/1964	5-9-V	3450.1	*No comparable data for this lift*				3450	
INT8/1964	24-10-V	3459.6		3400			3440	101
INT8B/1964	24-10-V	3453.6	*No comparable data for this lift*				4520	
INT8C/1964	24-10-V	3447.9	*No comparable data for this lift*				3290	
EXT3/1964	5-10-V	3459.5	4410	5090			4580	90
EXT3B/1964	5-10-V	3453.7	*No comparable data for this lift*				5730	
EXT3B/1964	5-10-V	3449.7	*No comparable data for this lift*				5750	
EXT5/1964	24-11-V	3459.5	3440	3900			4490	115
EXT5B/1964	24-11-V	3452.5	*No comparable data for this lift*				2450	
Average[2]			4280	5360	6240	7040	6620	
Average (all tests)							4420	
Average[3]			3940	4390			4860[3]	110[3]
Standard deviation (25 years—all tests)							1283	

[1] 10-year cores tested dry (may test about 10-20% higher than saturated test specimens).
[2] Average based on two comparable tests each at 6 mo, 1, 5, 10, and 25 yr.
[3] Average of comparable tests at 25 yr. 25-yr tests as a percent of 1-yr tests only where comparable data exists from the same lift as previous core programs (6 tests). Insufficient comparable data available for 5- and 10-yr tests.

Long Term Concrete Strength Gain, Bureau of Reclamation Study (Report DSO-05-05, December 2005)								
Averaged Data Set	No. Data Sets	Compressive Strength (psi) @ Year 0.5	1	5	10	25	Est. 28 Day Compressive Strength (psi)	Projected 75 Year Compressive Strength (psi)	75 yr/0.5yr
1	2	4280	5360	6240	6400	6620	3640	7490	1.75
2	6	3940	4390	-	-	4860	3710	5120	1.30

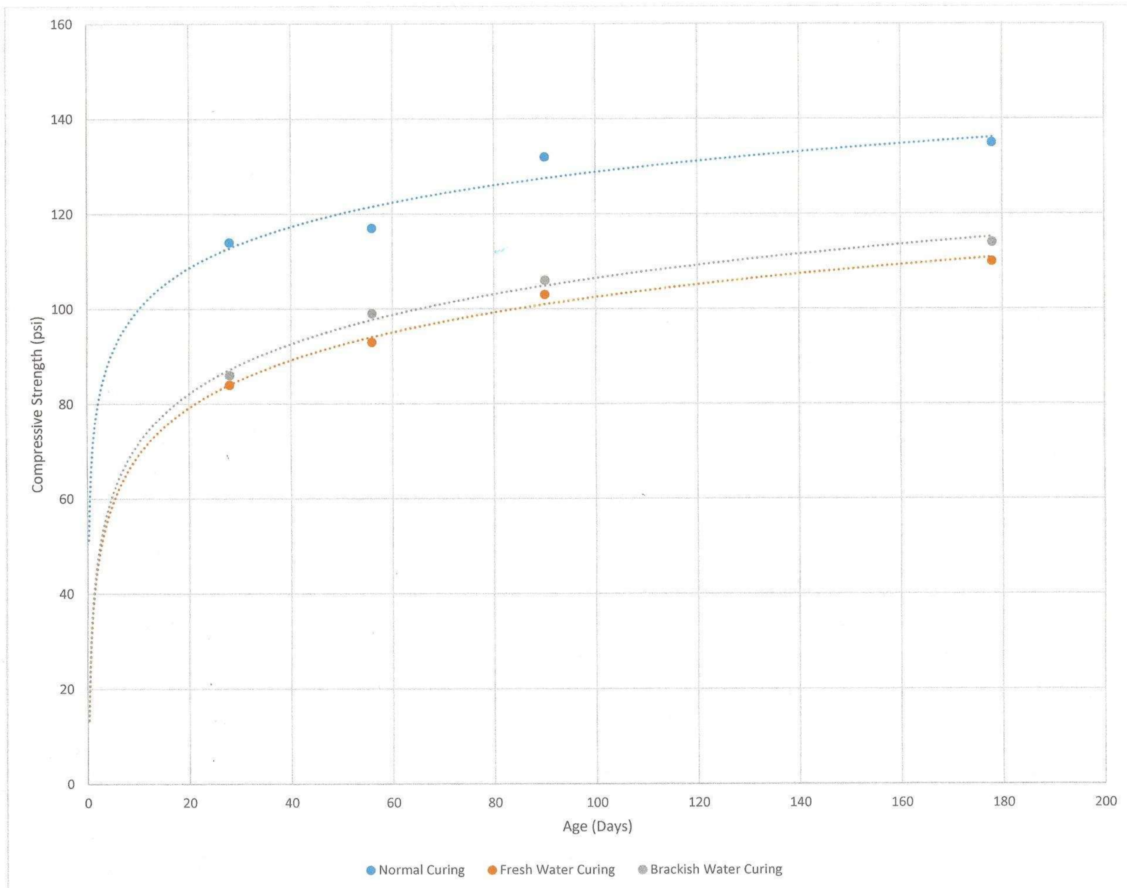
Note: Red value has been reduced by 10% from 7040 psi, per footnote in original publication regarding 10 year sample testing conditions.



Results of the long-term durability in fresh and salt water show a strength increase in normally cured 27pcf specimens of 18% from 28 to 178 days, and current saturation strength losses of 19% and 16% in fresh and salt water respectively. Laboratory values of this long-term durability are shown in the table below.

Long-Term Durability Testing of 27pcf LCC Submerged in Brackish Site Water

Description / Age	28 Days	56 Days	90 Days	178 Days
Normal Curing, psi	114	117	132	135
Fresh Water Curing, psi	84	93	103	110
Brackish Water Curing, psi	86	99	106	114
% Normal Curing / 28day psi	100%	103%	116%	**118%**
FW Submerged Strength Loss %	26%	21%	22%	19%
BW Submerged Strength Loss %	25%	15%	20%	16%



Long Term Durability Testing

Based on the 27pcf strength gain from 28days to 178 days (six months), the 30pcf top LCC mixture (147pcf @ 28) would have an estimated strength of 173psi at 6 months. Using the 10year data above, the 30pcf material might have a strength of 258psi at 10 years. Using the 75% and 30% gains from the table & graph above, **75 year strengths could reach 225psi to 303psi. These strengths would result in RE values of 0.26 to 0.30, both well under the ACI 229-13 criteria of 1.0 for CLSMs excavatable by hand.**

CASTLE ROCK CONSULTING
ENHANCING TRADITIONAL SOLUTIONS WITH INNOVATION

Constant Head Permeability Test of Granular Soils - ASTM-D2434

Test Results:

Client: Castle Rock Consulting
Project: Mission Rock PLDCC - Pervious & Non-Pervious Foam Solutions

Mix ID	Sample ID	Unit Weight (pcf)			K (cm/sec)
		Un-Saturated	Natural Sat.	Drained	
MR-27-55	MR-27-55-A	27.6	55.6	39.0	5.0E-01
	MR-27-55-B	27.5	57.2	39.8	4.6E-01
	Average	**27.5**	**56.4**	**39.4**	**4.8E-01**
MR-27-68	MR-27-68-A	27.8	53.4	38.9	4.8E-01
	MR-27-68-B	27.6	54.7	40.3	5.2E-01
	Average	**27.7**	**54.1**	**39.6**	**5.0E-01**
NP-27-68	NP-27-68-A	26.5	60.4	37.6	1.0E+00
	NP-27-68-B	26.6	59.1	38.5	9.4E-01
	Average	**26.6**	**59.8**	**38.1**	**9.9E-01**

Testing Notes:

CHAPTER 1—INTRODUCTION

Controlled low-strength material (CLSM) is a self-consolidating cementitious material used primarily as a backfill as an alternative to compacted fill. Terms used to describe this material include flowable fill, controlled density fill, flowable mortar, plastic soil-cement, and soil-cement slurry.

CLSM is a mixture intended to result in a compressive strength of 1200 psi (8.3 MPa) or less. Most CLSM applications require unconfined compressive strengths of 300 psi (2.1 MPa) or less. Long-term strengths (90 to 180 days) should be targeted to be less than 100 psi (0.7 MPa) for excavation with hand tools. Lower-strength requirements are necessary to allow for future excavation of CLSM.

The term "CLSM" is used to describe a family of mixtures for various applications. CLSM mixtures can also be developed as anticorrosion fills, electrically conductive materials, low-permeability fills, thermal fills, and durable pavement bases. For example, the upper limit of 1200 psi (8.3 MPa) allows use of this material for applications where future excavation is unlikely, such as structural fill under buildings. CLSM is a self-consolidated backfill or fill material that is used in place of compacted earth fill and should not be considered as a type of low-strength concrete. Generally, CLSM mixtures are not designed to resist freezing and thawing, abrasive or erosive forces, or aggressive chemicals. Using recycled materials can maximize recycled material content for sustainable construction. Nonstandard materials that have been tested and found to satisfy the intended application can be used to produce CLSM. Chapter 9 describes low-density (LD) CLSM produced using preformed foam as part of the mixture proportioning. Using preformed foam in LD-CLSM mixtures allows these materials to be produced having unit weights lower than those of typical CLSM. The distinctive properties of LD-CLSM and procedures for mixing it are discussed in Chapter 9.

CLSM typically requires no consolidation or special curing procedures to achieve desired strength and should not be confused with compacted soil-cement, as reported in ACI 230.1R. Long-term compressive strengths for compacted soil-cement often exceed the 1200 psi (8.3 MPa) maximum limit established for CLSM.

Long-term compressive strengths of 50 to 300 psi (0.3 to 2.1 MPa) are low when compared with conventional concrete. In terms of allowable bearing pressure, however—which is a common criterion for measuring the capacity of a soil to support a load—50 to 100 psi (0.3 to 0.7 MPa) strength is equivalent to a well-compacted fill.

Although CLSM generally costs more per cubic yard (cubic meter) than most soil or granular backfill materials, its many advantages often result in lower in-place costs. In fact, for some applications, CLSM is the only reasonable backfill method available (Adaska 1994, 1997; Ramme 1997). Table 1 lists a number of advantages to using CLSM (Smith 1991).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

E = modulus of elasticity, psi (MPa)
f_c' = 28-day specified compressive strength of concrete, psi (kPa)
k = coefficient of permeability, in./s (mm/s)
RE = removability modulus
W = dry mass density, lb/ft^3 (kg/m^3)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org.

CHAPTER 3—APPLICATIONS

3.1—General

The primary application of CLSM is as a structural fill or backfill in place of compacted soil. Because CLSM needs minimal consolidation and can be designed to be fluid, it is useful in areas where placing and compacting fill is difficult. If future excavation is anticipated, the maximum long-term compressive strength should generally not exceed 100 psi (0.7 MPa). The following applications present a range of uses for CLSM (Sullivan 1997).

3.2—Backfills

CLSM can be readily placed into a trench, hole, or other cavity (Fig. 3.2a and 3.2b). Compaction or consolidation equipment is not required; hence, trench width or excavation size can be reduced. Granular or site-excavated backfill, even if compacted or consolidated in the required layer thickness, cannot achieve the uniformity and density of CLSM (Sullivan 1997).

When backfilling against retaining walls, consideration should be given to lateral pressures exerted on the wall by flowable CLSM. Where lateral fluid pressure is a concern, are set on granular backfill. CLSM is then placed until it is 6 in. (150 mm) from the lower surface of the deck. At least 72 hours is required before the CLSM is brought up to the deck bottom through holes cored in the deck. Later, the railing is removed and the deck is widened. The same procedure is then completed on the opposite side of the bridge. The work is done under traffic conditions. The camber of the roadway over the culvert(s) is the only clue that a bridge had ever been present. Iowa DOT officials estimate that the cost of four reclamations is equivalent to one replacement when this technology can be employed (Larsen 1990; Buss 1989; Golbaum et al. 1997).

CHAPTER 4—MATERIALS

4.1—General

Conventional CLSM mixtures usually consist of water; portland cement; fly ash or other similar products; and fine aggregates, coarse aggregates, or both. Some mixtures consist of water, portland cement, and fly ash only. LD-CLSM mixtures, as described in Chapter 9 of this report, consist of portland cement, fly ash, or other cementitious or pozzolanic materials, water, and preformed foam.

Although materials used in CLSM mixtures normally meet ASTM or other standard requirements, the use of standardized materials is not always necessary. Materials selection should be based on availability; cost; specific application; and necessary mixture characteristics, including flowability, strength, excavatability, and density.

4.2—Portland cement

Cement provides cohesion and strength for CLSM mixtures. For most applications, Type I or Type II portland cement conforming to ASTM C150/C150M is normally used. Other types of cement, including blended cements conforming to ASTM C595/C595M or performance cements conforming to ASTM C1157/C1157M, can be used if prior testing indicates acceptable results.

4.3—Fly ash

Coal-combustion fly ash is sometimes used to improve flowability. Its use can also increase strength and reduce bleeding, shrinkage, and permeability. High-fly-ash-content mixtures result in lower-density CLSM when compared with mixtures having high aggregate contents. Fly ashes used in CLSM mixtures do not need to conform to either Class F or C as described in ASTM C618. For example, fly ashes containing carbon contents higher than traditionally used in concrete may be acceptable. Trial mixtures should be prepared to determine whether the mixture will meet the specified requirements. Refer to ACI 232.2R for further information (Naik et al. 1991; Landwermeyer and Rice 1997).

4.4—Admixtures

Air-entraining admixtures and foaming agents can be valuable constituents for the manufacture of CLSM. The inclusion of air in CLSM can help provide improved workability, reduced shrinkage, little or no bleeding, minimal segregation, lower unit weights, and control of ultimate strength development. Higher air contents can also help enhance thermal insulation and resistance to freezing-and-thawing cycles. Water content can be reduced as much as 50 percent when using air-entraining admixtures. Using these materials may require modifications to typical CLSM mixtures. To prevent segregation when using high air contents, mixtures need to be proportioned with sufficient fines to promote cohesion. Most air-entrained CLSM mixtures are pumpable but can require higher pump pressures when piston pumps are used. To prevent extended setting times, extra cement or an accelerating admixture may be required. In all cases, pretesting should be performed to determine acceptability (Hoopes 1997; Nmai et al. 1997).

4.5—Mineral admixtures and other additives

In specialized applications such as waste stabilization, CLSM mixtures can be formulated to include chemical additives, mineral additives, or both, that serve purposes beyond backfilling. Some examples include using swelling clays such as bentonite to achieve CLSM with low permeability. The inclusion of zeolites, such as analcime or chabazite, can be used to absorb selected ions where water or sludge treatment is required. Magnetite or hematite fines can be added to CLSM to provide radiation shielding in applications at nuclear facilities (Rajendran and Venkata 1997; Langton and Rajendran 1995; Langton et al. 2001). Slag cement conforming to ASTM C989/C989M may be used as a substitute for, or in addition to, portland cement. As is the case with portland cement, higher slag cement contents can produce excessive strengths and should be tested before use. Silica fume may also be used in a CLSM formulation.

4.6—Water

Water that is acceptable for concrete mixtures is acceptable for CLSM mixtures. ASTM C94/C94M provides additional information on water-quality requirements.

4.7—Aggregates

Aggregates are often the major constituent of a CLSM mixture. The type, grading, and shape of aggregates can affect the physical properties, such as flowability and compressive strength. Aggregates complying with ASTM C33/C33M are generally used because concrete producers have these materials in stock.

Granular excavation materials with somewhat lower-quality properties than concrete aggregate are a potential source of CLSM, and should be considered. Variations of the physical properties of the mixture components, however, will have a significant effect on mixture performance. Silty sands with up to 20 percent fines passing through a No. 200 (75 μm) sieve have proven satisfactory. Soils with wide variations in grading have also shown to be effective. Soils with clay fines, however, have exhibited problems with incomplete mixing, mixture stickiness, excess water demand, shrinkage, and variable strength. These soil types are not usually considered for CLSM applications. Aggregates that have been used successfully include (Tansley and Bernard 1981):

a) ASTM C33/C33M specification aggregates within specified gradations

b) Pea gravel or pea stone with sand

c) 3/4 in. (19 mm) minus aggregate with sand

d) Native sandy soils, with more than 10 percent passing a No. 200 (75 μm) sieve

e) Quarry waste products, generally 3/8 in. (10 mm) minus aggregates

4.8—Nonstandard materials

Nonstandard materials, which can be more available and economical, can also be used in CLSM mixtures, depending on project requirements. These materials, however, should be tested before use to determine their acceptability in CLSM mixtures.

There are numerous examples of nonstandard materials that can be substituted as aggregates (Naik et al. 1996; Naik and Singh 1997a,b). Such materials include various coal combustion products, crusher fines, discarded foundry sands (Tikalsky et al. 1998, 2000; Deng and Tikalsky 2008; Siddique and Noumowe 2008), glass cullet (Wang 2009), and reclaimed crushed concrete (Achtemichuk et al. 2009). In addition, nonstandard aggregate derived from stable organic sources, such as scrap tire rubber, can be used in CLSM mixtures (Pierce and Blackwell 2003).

Aggregates or mixtures that can swell in service due to expansive reactions or other mechanisms should be avoided. Wood chips, wood ash, or other organic materials may not be suitable for CLSM. Fly ashes with carbon contents up to 22 percent have been successfully used for CLSM (Ramme et al. 1995). Cement kiln dust, also a nonstandard material, may be used as a substitute for other cementitious materials (Pierce et al. 2003; Lachemi et al. 2010).

In all cases, nonstandard material characteristics should be determined, and the suitability of the material should be tested in a CLSM mixture to determine whether it meets specified requirements. Environmental regulations could require prequalification of the raw material, CLSM mixture, or both, before use.

4.9—Ponded ash or basin ash

Ponded ash—typically a mixture of fly ash and bottom ash slurried into a storage or disposal basin—can be used in CLSM. Proportioning of the ponded ash in the resulting mixtures depends on its particle size distribution. Typically, it can be substituted for all of the fly ash and a portion of the fine aggregate and water. Unless dried before mixing, ponded ash requires special mixing because it is usually wet. Basin ash is similar to ponded ash except it is not slurried and can be disposed of in dry basins or stockpiles (Rajendran and Venkata 1997; Langton and Rajendran 1995).

CHAPTER 5—PROPERTIES

5.1—Introduction

The properties of CLSM cross boundaries between soils and concrete. CLSM is manufactured from materials similar to those used to produce concrete, and is placed similarly to concrete. In-service CLSM, especially lower-strength CLSM, exhibits characteristic properties of soils. Characteristics of CLSM are affected by mixture constituents and proportions of the ingredients in the mixture. Because many factors can affect the characteristics of CLSM, a wide range of values can exist for the various properties discussed in the following sections (Glogowski and Kelly 1988).

5.2—Plastic properties

5.2.1 *Flowability*—Flowability distinguishes CLSM from other fill materials. It enables the materials to be self-leveling, to flow into and readily fill a void, and be self-consolidating. This property represents a major advantage of CLSM compared with conventional fill materials that must be mechanically placed and compacted. Because fresh CLSM is similar to fresh concrete and grout, its flowability is best viewed in terms of concrete and grout technology.

A major consideration in using highly flowable CLSM is the hydrostatic pressure it exerts. Where fluid pressure is a concern, CLSM can be placed in lifts, with each lift being allowed to harden before placement of the next lift. Examples where multiple lifts can be used are limited-strength forms used to contain the material or where buoyant items, such as pipes, are encapsulated in the CLSM.

Flowability can be varied from stiff to fluid, depending on requirements. Methods of expressing flowability include using a 3 x 6 in. (75 x 150 mm) open-ended cylinder modified flow test (ASTM D6103), the standard concrete slump cone (ASTM C143/C143M), and flow cone (ASTM C939).

Good flowability, using the ASTM D6103 method, is achieved where there is no noticeable segregation and the CLSM spread is at least 8 in. (200 mm) in diameter.

Flowability ranges associated with the slump cone can be expressed as follows:

a) Low flowability: slump less than 6 in. (150 mm)

b) Normal flowability: slump 6 to 8 in. (150 to 200 mm)

c) High flowability: slump greater than 8 in. (200 mm)

ASTM C939, for determining grout flow, has been used successfully with fluid mixtures containing aggregates not greater than 1/4 in. (6 mm). Chapter 8 briefly describes this method.

5.2.2 *Segregation*—Separation of materials in the CLSM mixture can occur when flowability is primarily produced by adding water. This situation is similar to segregation experienced with some high-slump concrete mixtures. With proper mixture proportioning and materials, a high degree of flowability can be attained without segregation. For highly flowable CLSM without segregation, adequate fines are required to provide suitable aggregate suspension and stability. Fly ash and other mineral admixtures generally account for these fines (refer to Table 5.2.2), although silty or other noncohesive fines up to 20% of total aggregate have been used. Using plastic fines, such as clay, should be avoided because they can produce deleterious results, such as increased shrinkage. Some CLSM mixtures have been designed without sand or gravel, using only mineral admixtures as filler material.

5.2.3 *Subsidence*—Subsidence deals with the reduction in volume of CLSM as it releases water and entrapped air

Table 5.2.2—Examples of CLSM mixture proportions

Source	Cement content, lb/yd³ (kg/m³)	Fly ash content, lb/yd³ (kg/m³)	Coarse aggregate, lb/yd³ (kg/m³)	Fine aggregate, lb/yd³ (kg/m³)	Approximate water content, lb/yd³ (kg/m³)	28-day compressive strength, psi (MPa)
✗ CO DOT	50 (30)*	—	1700 (1010)	1845 (1096)	325 (193)	60 (0.4)
IA DOT	100 (60)	300 (178)	—	2600 (1543)	585 (347)	—
FL DOT	50 to 100 (30 to 60)	0 to 600 (0 to 356)†	—	2750 (1632)‡	500 (297) maximum	50 to 150 (0.3 to 1.0)
IL DOT	50 (30)	300 (178) Class F 200 (119) Class C	—	2900 (1720)	375 to 540 (222 to 320)	—
IN DOT MIXTURE*	60 (36)	330 (196)	—	2860 (1697)	510 (303)	—
IN DOT MIXTURE 2§	185 (110)	—	—	2675 (1587)	500 (297)	—
OK DOT	50 (30) minimum	250 (148)	—	2910 (1727)	500 (297) maximum	—
MI DOT MIXTURE 1	100 (60)	2000 (1187) Class F	—	—	665 (395)	—
MI DOT MIXTURE 2§	50 (30)	550 (326) Class F	Footnote ‖	Footnote ‖	330 (196)	—
OH DOT MIXTURE 1	100 (60)	250 (148)	—	2850 (1691)	500 (297)	—
OH DOT MIXTURE 2	50 (30)	250 (148)	—	2910 (1727)	500 (297)	—
SC DOT	50 (30)	600 (356)	—	2500 (1483)	460 to 540 (273 to 320)	80 (0.6)
DOE-SR#	50 (30)	600 (356) Class F	—	2515 (1492)	500 to 550 (297 to 326)	30 to 150 (0.2 to 1.0)
Unshrinkable fill**	60 (36)	—	1705 (1012) (3/4 in. [19 mm] maximum)	1977 (1173)	257 (152)††	17 (0.1) at 1 day
Pond ash /basin ash mixture‡‡						
Mixture AF‡‡	165 (98)	810 (481)§§	2190 (1300)	—	700 (415)	65 (0.4)
Mixture D‡‡	100 (60)	550 (326)‖‖	2515 (1492)	—	507 (301)	65 (0.4)
Coarse aggregate CLSM##						
Non-air entrained##,***	50 (30)	250 (148)	1900 (1127) (1 in. [25 mm] maximum)	1454 (863)	270 (160)†††	100 (0.7)
Air entrained##,‡‡‡	50 (30)	250 (148)	1900 (1127) (1 in. [25 mm] maximum)	1340 (795)	255 (151)†††	—
Flowable fly ash slurry						
Mixture S-2§§§	98 (58)	1366 (810) Class F	—	—	1068 (634)	40 (0.3) at 56 days
Mixture S-3‖‖‖	158 (94)	1264 (749) Class F	—	—	1052 (624)	60 (0.4) (75 [0.5] at 56 days)
Mixture S-4###	144 (85)	1155 (685) Class F	—	—	1146 (680)	50 (0.3) (70 [0.5] at 56 days)

Note: Table examples are based on experience and test results using local materials. Yields will vary from 27 ft³ (0.76 m³). This table is given as a guide and should not be used for design purposes without first testing with locally available materials.

*Cement quantity can be increased above these limits only when early strength is required and future removal is unlikely.

†Slag cement can be used in place of fly ash or used in combination with fly ash.

‡Adjust to yield 1 yd³ (0.76 m³) of CLSM.

§5 to 6 fl oz of air-entraining admixture produces 7 to 12 percent air contents.

‖Total granular material of 2850 lb/yd³ (1690 kg/m³) with 3/4 in. (19 mm) maximum aggregate size.

#Department of Energy (DOE) Savannah River Site CLSM mixture.

**Emery and Johnston (1986).

††Produces 6 in. (150 mm) slump.

‡‡DOE Savannah River Site CLSM mixture using pond/basin ash.

§§Basin ash mixture.

‖‖Pond ash mixture.

##Fox (1989).

***Produces approximately 1.5 percent air content.

†††Produces 6 to 8 in. (150 to 200 mm) slump.

‡‡‡Produces 5 percent air content.

§§§Produces modified flow of 8-1/4 in. (210 mm) diameter (Table 8.1a); air content of 0.8 percent; slurry density of 93.7 lb/ft³ (1500 kg/m³).

‖‖‖Produces modified flow of 10-1/2 in. (270 mm) diameter; air content of 1.1 percent; slurry density of 91.5 lb/ft³ (1470 kg/m³).

###Produces modified flow of 16-3/4 in. (430 mm) diameter; air content of 0.6 percent; slurry density of 90.6 lb/ft³ (1450 kg/m³).

✗ $\frac{50+1700+1845+325}{27} = 145.2$ pcf

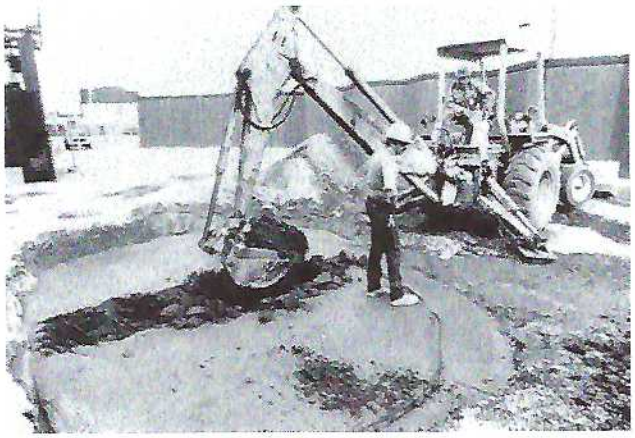


Fig 5.3.7—Excavating CLSM with a backhoe.

aggregate contents are increased (Smith 1991). However, materials normally used for reducing permeability, such as bentonite clay and diatomaceous soil, can affect other properties and should be tested before use.

5.3.6 *Shrinkage (cracking)*—It is believed that shrinkage and shrinkage cracks do not affect the performance of CLSM in the same manner as conventional concrete. Several reports indicate that minimal shrinkage occurs with CLSM. Ultimate linear shrinkage ranges from 0.02 to 0.05 percent (Naik et al. 1990; Tansley and Bernard 1981; McLaren and Balsamo 1986). Recent research indicates that CLSM with high volumes of fly ash (965 lb/yd^3 [360 kg/m^3]) exhibit higher amounts of linear shrinkage.

5.3.7 *Excavatability*—The ability to excavate CLSM is an important consideration on many projects. In general, CLSM with a compressive strength of 100 psi (0.7 MPa) or less can be excavated manually. A removability modulus (*RE*) can be used to determe the excavatability of CLSM. The *RE* can be determined as follows

Use 104 with pcf + psi

$$RE = \frac{W^{1.5} \times 0.619 \times C^{0.5}}{10^6} \quad (5.3.7)$$

where W is the dry mass density (kg/m^3), and C is the 28-day unconfined compressive strength (kPa). If the *RE* is less than 1.0, the CLSM is removable. CLSM with *RE* values greater than 1.0 are not easily removed.

Mechanical equipment, such as backhoes, can remove materials with compressive strengths of 100 to 300 psi (0.7 to 2.1 MPa) (Fig. 5.3.7). Excavatability limits are arbitrary guidelines and depend on the CLSM mixture constituents. Mixtures using high coarse aggregate quantities can be difficult to remove by hand, even at low strengths. Mixtures using fine sand or only mineral admixtures as aggregate filler have been excavated with a backhoe up to strengths of 300 psi (2.1 MPa) (Krell 1989).

When excavatability of CLSM is a concern, the type and quantity of cementitious materials is important. Acceptable long-term performance has been achieved with cement contents from 40 to 100 lb/yd^3 (24 to 59 kg/m^3) and Class F fly ash contents up to 350 lb/yd^3 (208 kg/m^3). Lime (CaO) contents of fly ash that exceed 10 percent by weight can be a concern where long-term strength increases are not desired (Tansley and Bernard 1981).

Because CLSM typically continues to gain strength beyond the conventional 28-day testing period, it is suggested, especially for CLSM with high cementitious content, that long-term strength tests be conducted to estimate the potential for excavatability. In addition to limiting the cementitious content, entrained air can be used to maintain low compressive strength.

* Tests On-Going...

5.3.8 *Shear modulus*—The shear modulus, which is the ratio of unit shearing stress to unit shearing strain, of normal-density CLSM typically ranges from 3400 to 7900 ksf (160 to 380 MPa) (Larsen 1988; Rajendran and Venkata 1997; Langton et al. 2001). Shear modulus is used to evaluate the expected shear strength and deformation of CLSM.

5.3.9 *Potential for corrosion*—The potential for corrosion on metals encased in CLSM has been quantified by a variety of methods specific to the material in contact with CLSM. Electrical resistivity tests can be performed on CLSM in the same manner that natural soils are compared for their corrosion potential on corrugated metal culvert pipes using California Test 643 (California Department of Transportation 1999). Moisture content of the sample is an important parameter for sample resistivity, and the samples should be tested at their expected long-term field moisture content. Unlike soil, high pH values characteristic of CLSM can be beneficial. The high pH of CLSM can provide a protective passive film for iron-based materials, thus reducing potential for corrosion.

The Ductile Iron Pipe Research Association (DIPRA) (Horn 2006; AWWA 2010) has a method for evaluating the corrosion potential of backfill materials. The evaluation procedure is based on information drawn from five tests and observations—soil resistivity, pH, oxidation-reduction (redox) potential, sulfides, and moisture. For a given sample, each parameter is evaluated and assigned points according to its contribution to corrosivity (Straud 1989; AWWA 2010; Hill and Sommers 1997). Although applicable for soils, this procedure in its entirety may not be applicable to CLSM. The DIPRA method indicates that high-pH soils are deleterious for corrosion protection. High pH associated with CLSM, as with concrete, is believed to be beneficial for corrosion protection. These procedures are guides for determining a soil's potential corrosivity to ductile iron pipe and should be used only by qualified engineers and technicians experienced in soil analysis and evaluation.

A continuous metallic material that passes through soils of varying composition may exhibit galvanic corrosion due to differences in its corrosion potential in different soils. The uniformity of CLSM reduces the probability of galvanic corrosion due to dissimilarities in the surrounding environment, which may otherwise occur from the use of dissimilar backfill materials and non-uniform compaction of similar materials. Because of the high pH associated with CLSM and the more neutral pH of conventional soils, however, care must be taken when partially encasing iron-based products

Table 8.1a—Test procedures for determining consistency and unit weight of CLSM mixtures

Consistency	Fluid mixtures	ASTM D6103—Procedure consists of placing 3 in. (75 mm) diameter by 6 in. (150 mm) long open-ended cylinder vertically on level surface and filling cylinder to top with CLSM. Cylinder is then lifted vertically to allow material to flow out onto level surface. Good flowability is achieved where there is no noticeable segregation and material spread is at least 8 in. (200 mm) in diameter.
		ASTM C939—Florida and Indiana DOT specifications require efflux time of 30 seconds ± 5 seconds. Procedure is not recommended for CLSM mixtures containing aggregates greater than 1/4 in. (6 mm).
	Plastic mixtures	ASTM C143/C143M
Unit weight		ASTM D6023
		ASTM D4380
		ASTM D1556
		ASTM D2922

Table 8.1b—Test procedures for determining in-place density and strength of CLSM mixtures

ASTM D6024	This specification covers determination of ability of CLSM to withstand loading by repeatedly dropping metal weight onto in-place material.
ASTM C403/C403M	This test measures degree of hardness of CLSM. California DOT requires penetration number of 650 before allowing pavement surface to be placed.
ASTM D4832	This test is used for molding cylinders and determining compressive strength of hardened CLSM.
ASTM D1196/D1196M	This test is used to determine modulus of subgrade reaction (K values).
ASTM D4429	This test is used to determine relative strength of CLSM in place.

8.3—Consistency and unit weight

Depending on application and placement requirements, flow characteristics can be important. CLSM consistency can vary considerably from plastic to fluid; therefore, several methods of measurement are available. Most CLSM mixtures perform well with various flow and unit weight properties. Table 8.1a describes methods that can be used to measure consistency and unit weight. CLSM generally exhibits large shrinkage. When CLSM is being placed in the ground, this may not be a problem. When used to backfill a pipe or other containment structure, shrinkage may be important to the designer. ASTM C157/C157M can be used for measuring CLSM shrinkage.

8.4—Strength tests

CLSM is used in a range of applications requiring different load-bearing characteristics. Maximum loads to be imposed on the CLSM should be identified to determine minimum strength requirements. In many cases, however, CLSM needs to be limited in its maximum strength. This is true where removal of the material at a later date is anticipated.

The strength of CLSM can be measured by several methods. Table 8.1b describes some of these methods. Unconfined compressive strength tests are the most common; however, other methods, such as penetrometer devices or plate load tests, can also be used. Compressive-strength specimens range in size from 2 x 2 in. (50 x 50 mm) cubes to 6 x 12 in. (150 x 300 mm) cylinders. Special care should be used when removing very-low-strength CLSM mixtures from test molds. Additional care in the handling, transporting, capping, and testing procedures should be taken because specimens are often fragile. Mold stripping techniques have included using a drill or hot probe to place a central hole in the bottom of standard watertight cylinder molds and adding a dry polyester fleece pad on the inside of the cylinder bottom for easy specimen release with or without air compression; splitting the molds with a hot knife; and presplitting molds and reattaching with duct tape for easier specimen removal.

When CLSM is used as subgrade for a pavement or slab, its in-place bearing strength may be important for the designer of the structural element. Bearing ratio tests may be performed in the laboratory or field and subgrade modulus may be determined from field plate load tests. In the field, a properly calibrated pocket penetrometer can be used to determine initial set.

CHAPTER 9—LOW-DENSITY CLSM USING PREFORMED FOAM

9.1—General

CLSM is a self-consolidating cementitious mixture that is intended to result in a compressive strength of 1200 psi (8.3 MPa) or less. Low-density (LD) CLSM not only meets this definition, but its final density is controllable from 20 to 120 lb/ft^3 (320 to 1920 kg/m^3). Because of its low density, LD-CLSM is preferred when reducing dead load is a critical requirement.

Generally, CLSM mixtures contain supplementary cementitious materials (SCM) with some portland cement and other fillers. LD-CLSM usually contains portland cement, possibly some SCM, and preformed foam for most of the volume. Most LD-CLSM applications are alternate solutions to conventional geotechnical solutions such as surcharging soils, bridging poor soils, removal and replacement of poor soils, pile support, and other foundation treatments. In addition, LD-CLSM is easily excavated, a requirement in some applications. The air void or cell structure inherent in LD-CLSM mixtures controls the final density of the mixture, provides thermal insulation, and adds shock mitigation properties to the fill material.

9.2—Applications

LD-CLSM has a very low density, which is a major advantage in most applications. All of the following applications can be constructed with LD-CLSM.

9.2.1 *Backfill*—LD-CLSM is placed against structures such as bridge abutments, retaining walls, and building walls to reduce dead load as much as 75 percent over poor soils. Once LD-CLSM sets, it does not exert active lateral pressure against the wall structure as standard granular backfill does. LD-CLSM is a cementitious material that is consolidated and does not require compaction like soil fills. Settlement is minimal because of its low density. Bridge approach applications are often 10 to 40 ft (3.0 to 12.2 m) or more in height. LD-CLSM is a low-density, self-consolidating fill that is a preferred alternative to standard compacted fill. Usually, LD-CLSM with a maximum in-service density of 30 lb/ft^3 (480 kg/m^3) is cast for most of the fill thickness. The top 2 to 3 ft (0.61 to 0.91 m) may be LD-CLSM with a maximum in-service density of 42 lb/ft^3 (690 kg/m^3), which has excellent resistance to freezing and thawing and provides a solid base for the approach slab or pavement structure.

9.2.2 *Roadway bases*—LD-CLSM is often used as a roadway base over poor soil. Using the material becomes even more important when raising or widening the roadway over poor soil, because added weight and settlement are design concerns (Fig. 9.2.2). These designs often involve load-balancing and buoyancy calculations. Specific site conditions may require special drainage details.

When constructing a roadway over poor soil, a geotextile fabric may be placed after the excavation is complete. The LD-CLSM is cast directly onto the geotextile fabric. This fabric acts as a tension skin and, in conjunction with LD-CLSM, can span most localized settlements.

9.2.3 *Pipeline and culvert fills*—LD-CLSM is often a supporting fill in pipeline applications over poor soils or a containment fill cast around these drainage structures to provide support and stability. Compaction is not necessary as it is with granular fill.

Culvert applications include concrete box culverts, segmented or pipe sections, and metal culvert systems including multi-plate culverts of significant size.

LD-CLSM reduces dead weight on the culvert. The cohesive nature of all CLSM mixtures provides erosion control, which is an advantage over standard granular fills that erode when subjected to moving water. CLSM mixtures may need to be evaluated for freezing-and-thawing resistance.

Placing LD-CLSM on both sides of the culvert simultaneously minimizes eccentric loading. In addition to supporting the culvert from below, LD-CLSM cast around these drainage structures provides lateral support of the culvert or pipeline.

9.2.4 *Void fills*—LD-CLSM is commonly used as a void fill when dead load reduction is critical. It is also applicable to mass structures where access may be limited and flowability is important. Void fill applications include pipeline abandonment, filling around excavations, annular space fills between slip-lined pipes, and structures that are to be abandoned rather than demolished (Fig. 9.2.4).

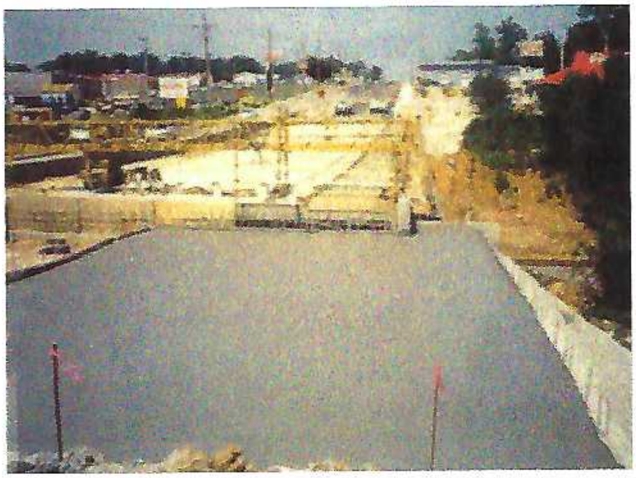


Fig. 9.2.2—Geotechnical roadway base at bridge approach.

Fig. 9.2.4—Filling an abandoned swimming pool with LD-CLSM.

Because every void fill application is unique, each should be examined for special conditions. To contain LD-CLSM, the entire fill area should be sealed, including pipes, drains, and structural discontinuities such as holes in walls or under footings. Lift heights for void fills may be greater than normal if the LD-CLSM can be reasonably contained by earth, forms, or a structure.

9.2.5 *Tank fills*—An acceptable abandonment alternative to the excavation and removal of underground fuel- or oil-storage tanks required by many agencies is a LD-CLSM tank fill (Fig. 9.2.5). The 53 FR 37082-37247 regulations refer to LD-CLSM fills as an "inert substance."

9.2.6 *Insulation and isolation fills*—The discrete air-cell structure within the cementitious matrix of LD-CLSM provides thermal-insulation and physical shock-mitigation properties to this material for applications such as walls (Fig. 9.2.6), roofs, and other similar structures. Giannakou and Jones (2004) describe using LD-CLSM to thermally insulate foundations and slabs.

Table 9.4.2—Physical properties for geotechnical applications (ACI 523.1R-06, 3.11; Elastizell Corporation of America 2013)

Maximum cast density, lb/ft³ (kg/m³)	Minimum compressive strength, psi (MPa)	Bearing capacity, ton/ft² (MPa)
24 (385)	10 (0.07)	0.7 (0.07)
30 (480)	40 (0.28)	2.9 (0.28)
36 (575)	80 (0.55)	5.8 (0.56)
42 (675)	120 (0.83)	8.6 (0.82)
50 (800)	160 (1.10)	11.5 (1.10)

and wall insulation, tunnel and mine fills, energy absorption or shock mitigation, and backfills in sewer and highway construction per ACI SP-29 (ACI Committees 213 and 523 1971).

9.4.3 *Permeability*—Generally, LD-CLSM has a low coefficient of permeability (k) that is constant throughout the lower density ranges (Kearsley and Wainwright 2001a). The coefficient of permeability is inversely related to the effective confining pressure on the sample. Because LD-CLSM is a rigid material rather than a yielding soil, its permeability is measured using a modified triaxial test including a confining pressure to prevent direct water passage (short-circuiting) along the interface between specimen and confining membrane. A constant head should be maintained during the test. Reported k-values at a confining pressure of 2.0 psi (13.8 kPa) range from 5.5×10^{-4} to 4.3×10^{-8} in./s (1.4×10^{-3} to 1.1×10^{-6} cm/s) per ASTM D2434. Recent developments in LD-CLSM mixtures have resulted in greater permeability values due to changes in the preformed foam formulation and, therefore, in its properties. As a result, recently reported values range from 3.9×10^{-1} to 3.4×10^{-6} in./s (1.0 to 1.0×10^{-5} cm/s).

9.4.4 *Freezing-and-thawing resistance*—Freezing-and-thawing resistance of LD-CLSM is evaluated using Procedure B (rapid freezing and thawing) of ASTM C666/C666M, with a modified cycling protocol involving a longer thawing period. This modification is necessary because the insulating properties of LD-CLSM prevent rapid lowering and raising of temperatures at the interior of the specimen and prevent completion of a freezing-and-thawing cycle in the originally prescribed maximum 4-hour period. LD-CLSM intended for exterior exposure should have a relative dynamic modulus of elasticity (E) at least 70 percent of its original value after 120 cycles, when tested according to Procedure B of the modified ASTM C666/C666M. Because the freezing-and-thawing resistance of LD-CLSM increases with increasing density, LD-CLSM within 2 to 3 ft (0.6 to 1 m) of a surface subjected to freezing-and-thawing cycles while exposed to water should have a density of at least 36 lb/ft³ (575 kg/m³). MacDonald et al. (2004) provides an evaluation of the freezing and thawing performance and testing of LD-CLSM.

9.5—Proportioning

Mixture proportioning guidance is generally available from the foam concentrate manufacturers. The mixture proportion specifies the range of proportions of the ingredients needed to attain the desired physical properties (density and compressive strength). The user should test mixture proportions when nonstandard materials or special applications are involved.

9.6—Construction

9.6.1 *Batching*—Materials for LD-CLSM are typically proportioned and batched on site directly into a specialized mixer. The cement, SCM, and other dry materials are weighed on a calibrated scale, and mixing water is metered. Preformed foam is metered into the mixture through a calibrated nozzle. The accuracy of each batching device is critical to the final mixture density and its subsequent reproducibility. Each batching device (scales, water meter, and foam-generating nozzle) should be calibrated before starting a project and during the project if necessary.

9.6.2 *Mixing*—Standard ready-mix equipment is normally not acceptable for LD-CLSM mixtures because the mixer does not combine ingredients with the correct speed and mixing action. A high-speed paddle mixer is preferable because it properly combines the ingredients and blends the preformed foam rapidly and efficiently to produce a uniformly consistent LD-CLSM mixture. Other mixers and processes that produce uniform mixtures include high-shear mixers and some continuous mixers.

In batch mixing, the mixer should be charged with mixture water and dry ingredients, followed by special admixtures and preformed foam. As-cast density should be monitored at the point of placement every 30 to 60 minutes based on consistency of the density. Allowance should be made for any density changes that result from placing methods or conditions, such as pumping distances and extreme weather. Ingredients should be added in proper proportions and sequence during continuous mixing operations. This ensures reasonable uniformity and achieves the required as-cast density at the point of placement.

9.6.3 *Placing*—LD-CLSM should be placed by a progressive-cavity pump or a peristaltic pump. The pump hose should be large enough in diameter (usually 2 to 2-1/2 in. [51 to 64 mm]) to provide uniform delivery of LD-CLSM at the point of placement without damage to the structure or substrate. LD-CLSM can be pumped over 1500 ft (460 m), which is a major advantage over other materials and placing methods, and is important on large, congested projects with difficult access.

9.6.4 *Forming and finishing*—For geotechnical applications, lift thicknesses ranging from 2 to 4 ft (0.61 to 1.2 m) are typical. Lift thickness is job-specific and related to project layout and casting procedure. A greater lift thickness is acceptable for specific job conditions. The heat of hydration developed within the mass, material density, cement content, and the ambient temperature also influence lift thickness. Thinner castings reduce the heat buildup from cement hydra-

Trench Sections

Mission Rock
Lightweight Cellular Concrete (LCC)

Typical Trench Section Exhibit

- Storm Trench

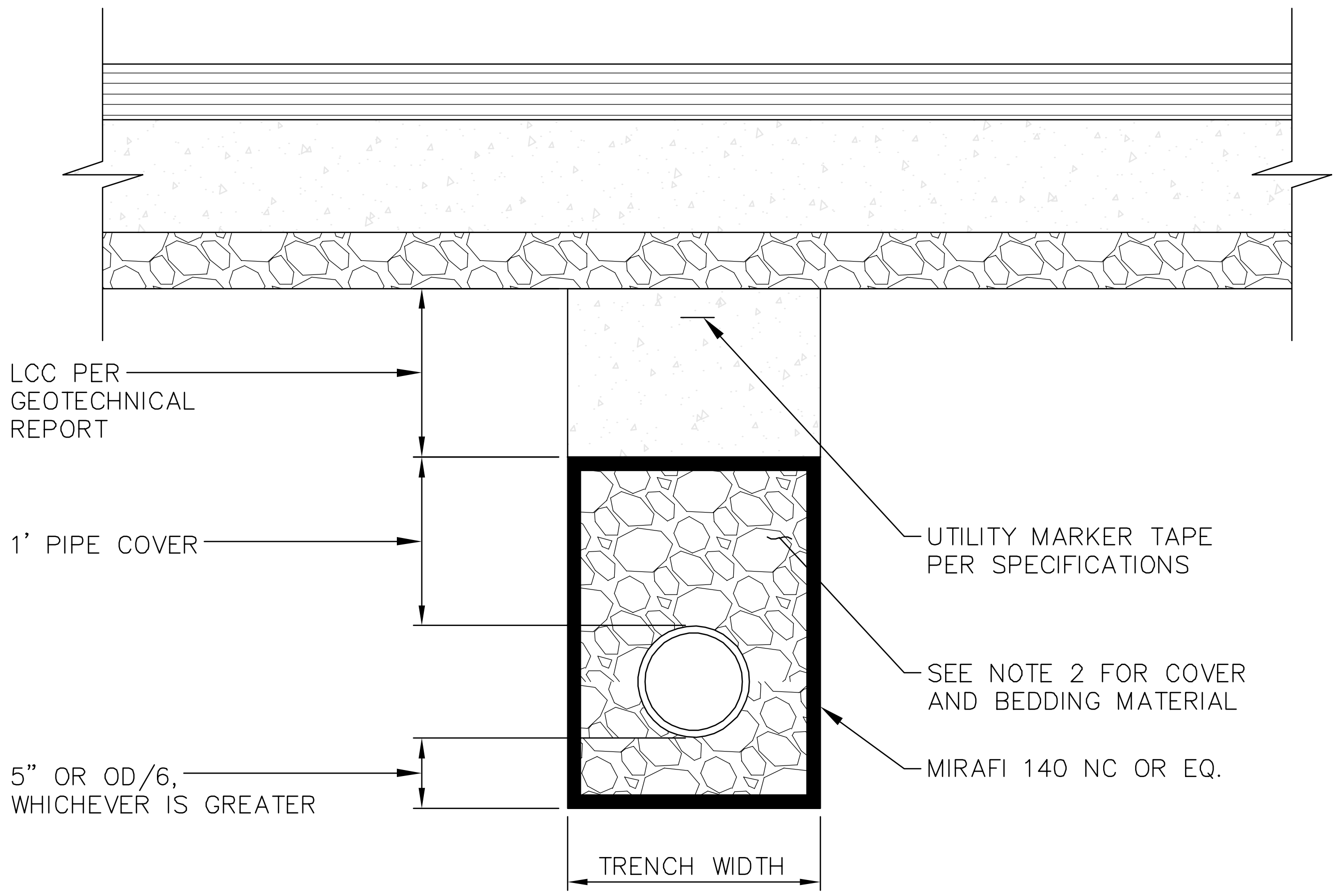
- Sewer Trench

- Low Pressure Water Trench

- Non-Potable Water Trench

- AWSS Trench

- Joint Trench

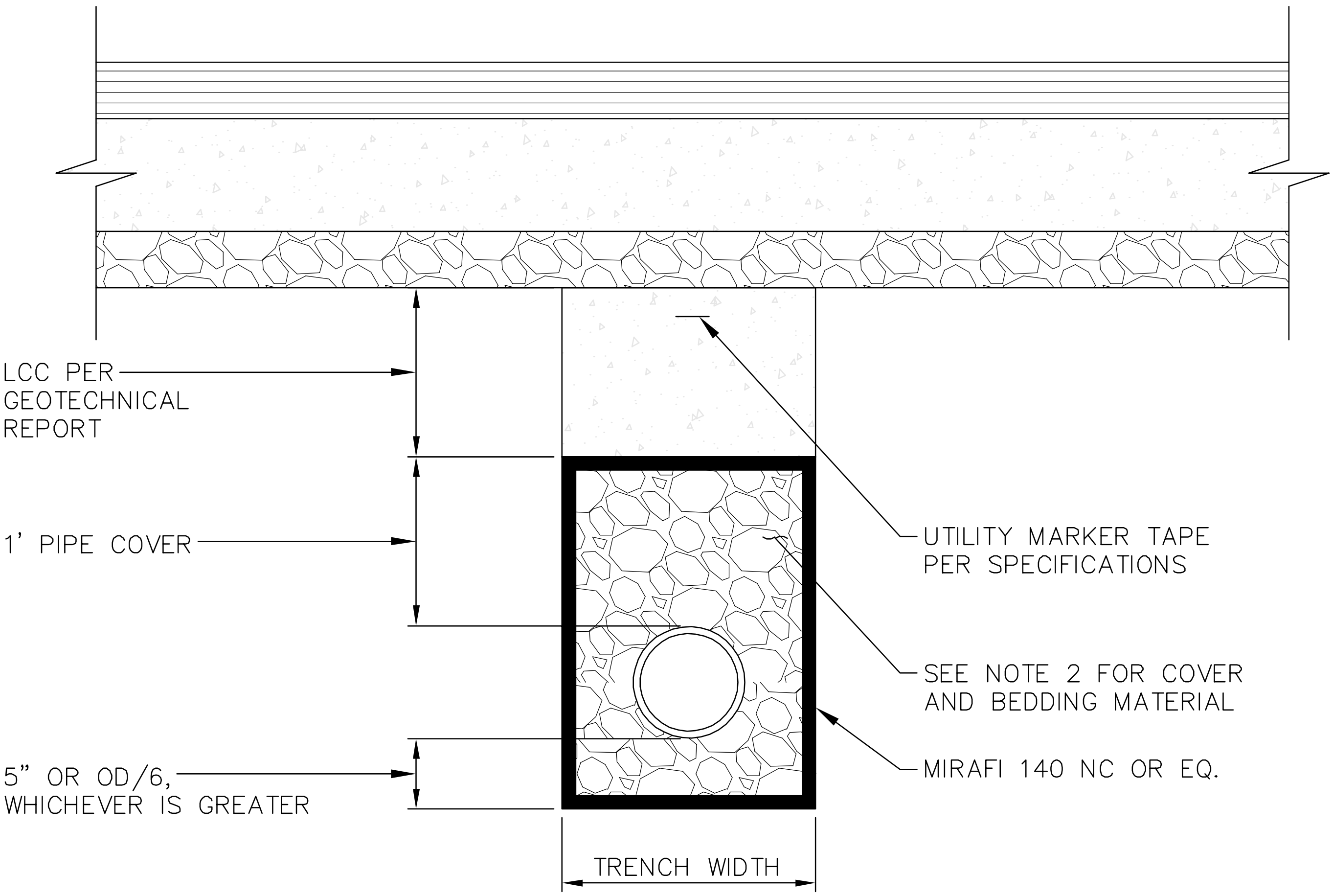


NOTES:

1. ALL WORK SHALL BE DONE PER SECTION 701 "PAVEMENT EXCAVATION," SECTION 702 "TRENCH EXCAVATION," AND SECTION 703 "TRENCH BACKFILL" OF SFDPW STANDARD SPECIFICATIONS AND ALL REFERENCES AND ALL REFERENCES MADE WITHIN, AS WELL AS SECTION 2.4.55 OF THE CITY PUBLIC CODE.
2. PIPE COVER AND BEDDING MATERIALS SHALL BE CRUSHED ROCK PER SPECIFICATIONS.

STORM TRENCH

NTS

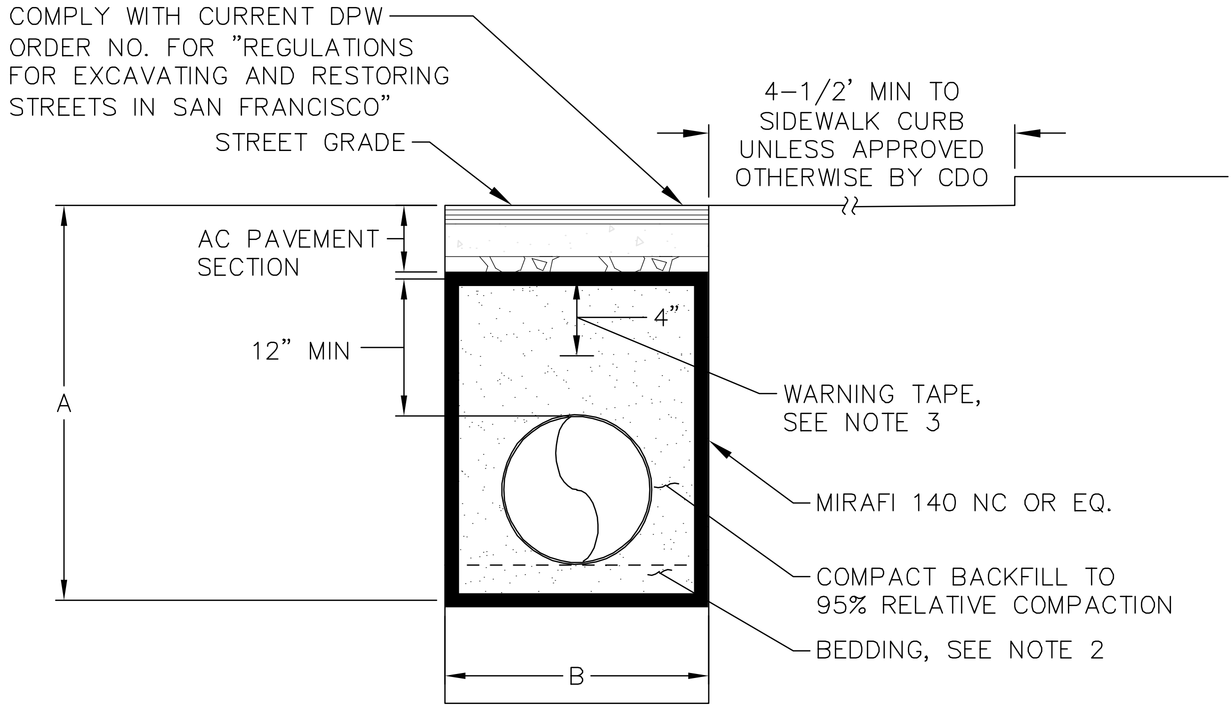


NOTES:

1. ALL WORK SHALL BE DONE PER SECTION 701 "PAVEMENT EXCAVATION," SECTION 702 "TRENCH EXCAVATION," AND SECTION 703 "TRENCH BACKFILL" OF SFDPW STANDARD SPECIFICATIONS AND ALL REFERENCES AND ALL REFERENCES MADE WITHIN, AS WELL AS SECTION 2.4.55 OF THE CITY PUBLIC CODE.
2. PIPE COVER AND BEDDING MATERIALS SHALL BE CRUSHED ROCK PER SPECIFICATIONS.

SEWER TRENCH

NTS



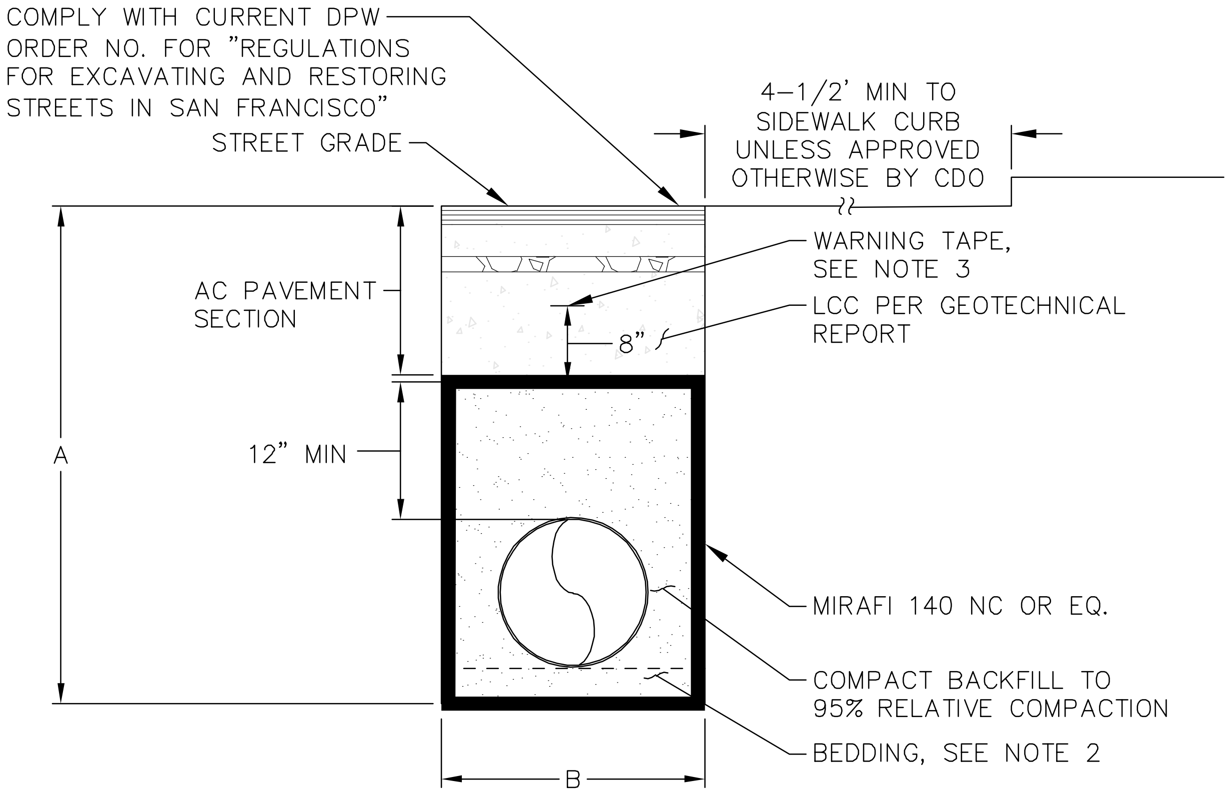
NOMINAL PIPE DIAMETER	MINIMUM TRENCH DEPTH (A)	MINIMUM TRENCH DEPTH (B)
1", 2"	24"	12"
4", 6", 8"	36"	18"
12"	44"	24"
16"	54"	30"
20"	54"	38"
24"	55"	44"

NOTE:

1. MINIMUM TRENCH DEPTHS AND TRENCH WIDTHS MUST BE ADHERED TO UNLESS APPROVED OTHERWISE BY THE CITY DISTRIBUTION DIVISION
2. OVEREXCAVATING FOR BEDDING IS NOT REQUIRED UNLESS:
   A. BOTTOM OF TRENCH EXCAVATION IS IN BEDROCK, WHERE BEDDING SHALL BE 6" THICK
   B. FOR 20" AND 24" DIA. PIPE, WHERE BEDDING SHALL BE 4" THICK
3. WARNING TAPE SHALL BE 6" WIDE, BLUE COLORED FOR LPW, METALLIC FOIL BONDED TO SOLID BLUE PLASTIC FILM. INSCRIPTION MESSAGE, USING 1.5" MINIMUM HEIGHT BLACK TEXT, SPACED AT 3-FT MAXIMUM INTERVALS, SHALL READ "CAUTION: WATER LINE BELOW" FOR LPW. WARNING TAPE SHALL OVERLAP 12" MINIMUM AT SPLICES.
4. TRENCH CONSTRUCTION SHALL CONFORM TO OSHA AND CAL OSHA.
5. PIPE MAY BE INSTALLED DEEPER THAN DEPTH SPECIDIED HEREIN ONLY WHEN TO AVOID SUBSURFACE OBSTACLES AND ONLY WHEN APPROVED BY THE CITY REPRESENTATIVE.
6. TRENCH SECTION APPLICABLE TO MAIN AND LATERAL INSTALLATION.

LOW PRESSURE WATER TRENCH

NTS



NOMINAL PIPE DIAMETER	MINIMUM TRENCH DEPTH (A)	MINIMUM TRENCH DEPTH (B)
1", 2"	24"	12"
4", 6", 8"	36"	18"
12"	44"	24"
16"	54"	30"
20"	54"	38"
24"	55"	44"

NOTE:

1. MINIMUM TRENCH DEPTHS AND TRENCH WIDTHS MUST BE ADHERED TO UNLESS APPROVED OTHERWISE BY THE CITY DISTRIBUTION DIVISION

2. OVEREXCAVATING FOR BEDDING IS NOT REQUIRED UNLESS:
   A. BOTTOM OF TRENCH EXCAVATION IS IN BEDROCK, WHERE BEDDING SHALL BE 6" THICK
   B. FOR 20" AND 24" DIA. PIPE, WHERE BEDDING SHALL BE 4" THICK

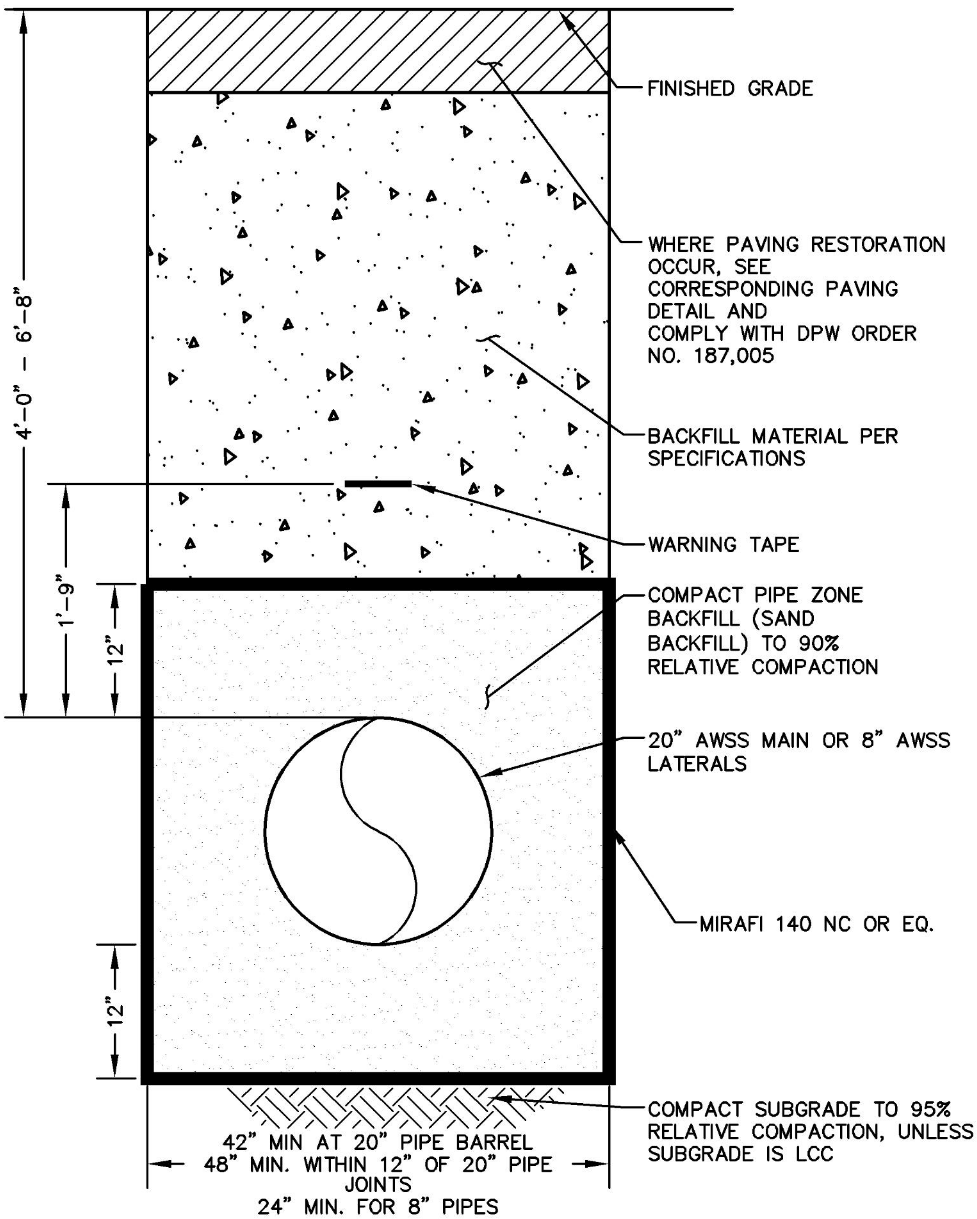
3. WARNING TAPE SHALL BE 6" WIDE, PURPLE COLORED FOR RW, METALLIC FOIL BONDED TO SOLID BLUE PLASTIC FILM. INSCRIPTION MESSAGE, USING 1.5" MINIMUM HEIGHT BLACK TEXT, SPACED AT 3-FT MAXIMUM INTERVALS, SHALL READ "CAUTION: RECYCLED WATER LINE BELOW" FOR RW. WARNING TAPE SHALL OVERLAP 12" MINIMUM AT SPLICES.

4. TRENCH CONSTRUCTION SHALL CONFORM TO OSHA AND CAL OSHA.

5. PIPE MAY BE INSTALLED DEEPER THAN DEPTH SPECIDIED HEREIN ONLY WHEN TO AVOID SUBSURFACE OBSTACLES AND ONLY WHEN APPROVED BY THE CITY REPRESENTATIVE.

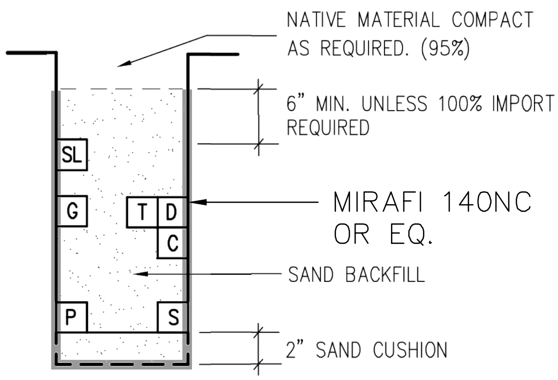
NON-POTABLE WATER TRENCH

NTS

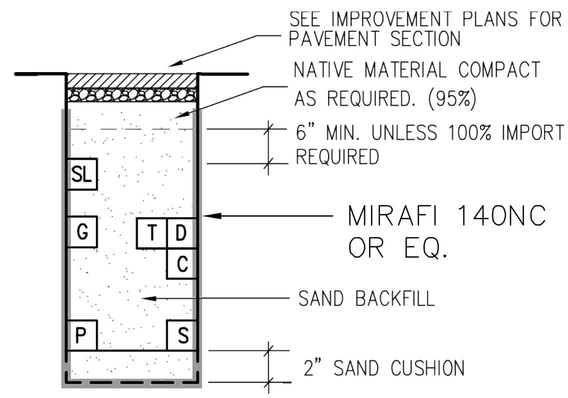


TYPICAL AWSS TRENCH DETAIL

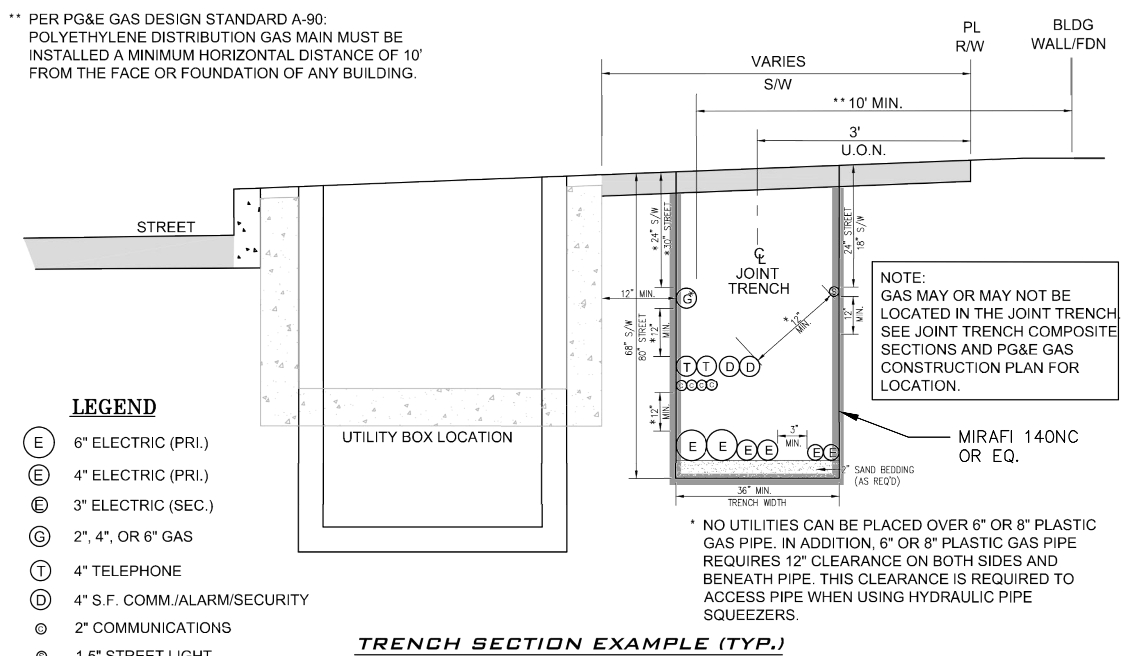
NTS



TRENCH IN DIRT AREA



TRENCH IN STREET AREA



TRENCH SECTION EXAMPLE (TYP.)

DETAIL F
N.T.S.

NOTE: ALL SECTIONS WILL REQUIRE MIRAFI 140 NC OR EQ. ENCASING GRANULAR TRENCH BACKFILL.

JOINT TRENCH DETAIL

NTS

LCC Specification

(TAP Report Volume 1 - Section 1.9)

31 23 23.33
Permeable/Open-Cell Lightweight Cellular Concrete (P-LCC)

Geotechnical aspects of the specification were prepared by Langan Engineering and Environmental Services, Inc.

1. GENERAL
   1.1. DESCRIPTION
      1.1.1. Work Included: This work shall consist of batching, mixing, placing and testing P-LCC of the appropriate density as indicated by the specifications. A trained P-LCC installer shall furnish labor, material, equipment, and supervision for the installation of the P-LCC in accordance with the drawings and specifications.

   1.2. QUALITY ASSURANCE
      1.2.1. Use skilled labor that is thoroughly trained, experienced, and familiar with the specified requirements and the methods for proper performance of this work.
      1.2.2. The P-LCC installer shall be approved in writing by Owner.

   1.3. SUBMITTALS
      1.3.1. The prime contractor shall list the product and qualified installer of the P-LCC and shall not employ any product or producer without the prior approval of the geotechnical engineer of record (GEOR).
      1.3.2. Product data: within 30 calendar days after award of the contract, the prime contractor shall submit a mix design for approval by the GEOR and civil engineer of record (CEOR)
         1.3.2.1. Manufacturer's specifications, catalog cut sheet, and other engineering data needed to demonstrate to the issuing authority compliance with the specified requirements.
      1.3.3. Mix Design: Submit a mix design that will produce a cast density that complies with those listed in Section 2.2.1 of this specification at point of placement and a compressive strength within the range listed in Section 2.2.1. Include laboratory data using the mix design verifying un-foamed density, final foamed density, permeability (cm/sec) and compressive strengths. Mix design shall include water/cementitious ratio and foam solution dilution ratio, in accordance with manufacturer's recommendations. The mix design should also include Field Permeability Check Testing, by testing the percolation rate in modified 6" x 12" cylinder molds, filled half-way. The mix design should also include field saturation testing by the special inspector.
      1.3.4. Work Plan: Submit a work plan before placement of P-LCC material. The plan shall include:
         1.3.4.1. Proposed construction sequence and schedule
         1.3.4.2. Type of equipment and tools to be used.
         1.3.4.3. Material list of items and manufacturer's specifications
         1.3.4.4. P-LCC lift thickness
         1.3.4.5. P-LCC cure time and minimum strength prior to placing the next lift
         1.3.4.6. QA/QC and testing items and protocols frequency.

2. PRODUCTS

2.1. MATERIALS

2.1.1. Foaming Agent: A foaming agent shall be used and shall comply with the standard specifications of ASTM C 869 when tested in accordance with ASTM C 796. Admixtures shall be tested by the foam concentrate manufacturer for compatibility with the foaming agent.

2.1.2. Cement: the Portland cement shall comply with ASTM C 150. Other supplemental cementitious material such as fly ash may be used when approved by the project engineer. Supplementary cementitious materials shall be tested prior to the start of the project for compatibility with the foaming agent.

2.1.3. Admixtures: admixtures for accelerating, water reducing, and other specific properties may be used when specifically approved by the GEOR. Admixtures shall be tested in mix design prior to the start of the project for compatibility with the foaming agent.

2.1.4. Water: use water that is potable and free from deleterious amounts of alkali, acid, and organic materials, which would adversely affect the setting or strength of the P-LCC.

2.1.5. Filter Fabric: Shall have permeability equal to or greater than that of the P-LCC. Filter fabric shall also have a maximum apparent opening size (AOS, ASTM D4751) of 0.212 mm (U.S. sieve size 70).

2.2. PROPERTIES

2.2.1. Two types of P-LCC are to be supplied for the project: (1) general P-LCC to be applied across the site at multiple depths and (2) high density P-LCC to be cast only in the upper two feet of the LCC section. P-LCC shall meet the following properties:

General P-LCC			
	Target	Maximum	Minimum
General Cast Density, pcf (ASTM C 796)	26	28	24
Compressive Strength at 28 Days, psi (ASTM C 495)	NA	200	50
Coefficient of Permeability, cm/sec (ASTM D 2434 – modified)	0.1 (1E-1)	NA	0.005 (5E-3)
Saturated Density, pcf	55	68	50

High Density P-LCC – to be cast only within upper two feet of overall P-LCC section			
	Target	Maximum	Minimum
Cast Density of LCC, pcf (ASTM C 796)	30	32	28
Compressive Strength at 28 Days, psi (ASTM C 495)	NA	200	80
Coefficient of Permeability, cm/sec (ASTM D 2434 – modified)	0.1 (1E-1)	NA	NA
Saturated Density, pcf	55	68	50

3. EXECUTION
   - 3.1. Subgrade: Subgrade to receive P-LCC material shall be free of all loose and extraneous material. Subgrade shall be uniformly moist, and any excess water standing on the surface shall be removed. The subgrade shall be approved by the GEOR before placing P-LCC material.
   - 3.2. Curing: A minimum 12-hour curing period between lifts is required. Backfill or other usual loadings, including additional lifts of P-LCC, on the P-LCC shall not be permitted until the P-LCC has attained a compressive strength of at least 5 psi.
   - 3.3. Weather Conditions: If ambient temperatures are anticipated to be below 40 degrees F within 24 hours after placement, the mixing water shall be heated when approved by the manufacturer of the foaming agent or placement shall be prohibited. Placement shall not be allowed on frozen ground.
   - 3.4. Batching and Mixing: Cellular concrete shall be job site batched, mixed with the foaming agent and placed with specialized equipment certified by the manufacturer of the cellular concrete lightweight material. Cement and water may be premixed and delivered to the job site and the foaming agent added on site. Dilution ratio shall be adjusted as needed per manufacture's recommendation to achieve required end product.
   - 3.5. Placement:
     - 3.5.1. Place P-LCC in lifts not to exceed 36 inches in thickness, unless otherwise recommended by the P-LCC manufacturer and approved by the GEOR.
     - 3.5.2. After curing for minimum of 12 hours, any crumbling area on the surface shall be removed before the next layer is placed. Surface stepping to achieve grade and super elevation shall not be less than 6 inches in thickness. Grades of up to 5 percent may be made by adding a thickening agent to the mix in conformance with the manufacturer's recommendation.
     - 3.5.3. Subgrade and P-LCC should be protected from water inundation until the P-LCC is sufficiently cured and has sufficient overlying weight so it does not become buoyant.
     - 3.5.4. Freshly placed P-LCC should be protected from rain until it has been sufficiently cured to prevent damage.
     - 3.5.5. Freshly placed P-LCC should be cured at least 3 hours before exposed to

vibrations higher than a peak particle velocity 0.05 inches per second – such as those that may be generated during ground improvement activities.

3.6. Handling: Avoid excess handling of P-LCC according to industry standards.

3.7. Filter Fabric: Use filter fabric between P-LCC and adjacent soil and between P-LCC and shoring, where shoring will be removed after P-LCC placement.

4. QUALITY CONTROL TESTING BY CONTRACTOR AND OWNER

4.1. DENSITY CONTROL

4.1.1. During placement of the initial batches, check the un-foamed and foamed densities for each 100 cubic yards of P-LCC or as recommended per the GEOR and adjust the mix as required to obtain the specified cast density at the point of placement per ASTM.

4.1.2. Field saturated density test procedures developed and prepared by the special inspector shall be performed on one sample for each 100 cubic yards of P-LCC or as recommended per the GEOR. GEOR to review and approve test procedures prior to commencement of work.

4.2. COMPRESSIVE STRENGTH: The compressive strength shall be tested under ASTM C 495 except as follows:

4.2.1. Four (4) specimens (one 7-day and three 28-days) shall be taken for each 100 cubic yards of P-LCC or as recommended per the GEOR. Unless otherwise approved, the specimens shall be 3 x 6 inch cylinders. During molding, place the LCC in 2 equal layers and raise and drop the cylinders 1 inch, 3 times on a hard surface or lightly tap the side or bottom of the cylinder to close any accidental entrained air. No rodding is allowed.

4.2.2. Specimens must be covered and protected immediately after casting to prevent damage and loss of moisture. Specimens shall be moist cured in the molds for 7 days and air dry a minimum of 24 hours and minimum of 72 hours before the 7-day and 28-day compressive strength testing, respectively. Specimens shall not be oven dried.

4.2.3. Contractor should maintain process control “run” charts of un-foamed and foamed density, field percolation result, and compressive strength data, updated daily for review by Owner’s representative, and distributed weekly to applicable project team members.

4.3. PERMEABILITY:

4.3.1. Proof of permeability (per ASTM D 2434 – Modified) of the proposed P-LCC mix design shall be provided in the mix design submittal. If there is any change to the mix design during production, additional permeability testing will be required. Two samples per week should be cast per ASTM D 2434 and shipped to Castle Rock Consulting for testing.

4.3.2. Field falling head permeability per procedures prepared by the special inspector performed on two samples per day. Falling Head permeability test procedures to be reviewed and approved by GEOR prior to commencement of work.

4.4. MOCK UP TEST SECTION: One mock up test section shall be installed prior to construction to prove out the contractor’s construction methods.

4.5. Side-by-side sampling and testing by QC and QA staff should occur once daily during the LCC placement on the Pilot Project to identify any issues. At least one set of permeability samples should also be taken for saturation and drain down density and a permeability verification.

4.6. UNFOAMED SLURRY TESTING: Test unfoamed slurry density periodically during foaming to verify actual density (PCF) is +/- 1.5% of target. Target to be established in mix submittal.

4.7. QUALITY ASSURANCE INSPECTIONS & ACCEPTANCE TESTING BY OWNER'S AGENCY

4.7.1. Owner shall employ a qualified Special Inspector to observe LCC placement and test LCC as described below.

4.7.2. Daily Inspections should include review of previous day's density testing of un-foamed and foamed test data, field percolation test results, any 7-day & 28-day compressive strength data, and location of samples taken. Initially use mix design for 7-day to 28-day strength correlation, switching to project data when three sets are available to predict 28-day strengths.

4.7.3. Perform one side-by-side comparison test with Contractor every 1000 cubic yards, and verify saturation & drain-down densities and permeability (per ASTM D 2434) values every 1000 cubic yards placed, or whenever the field percolation rates are more than 20% lower than the mix design values.