Foamed Flash-Fill to Mitigate Frost Heaving of Street Repair Patches

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INTRODUCTION

The use of flash-fill for backfilling trenches after utility repairs in existing streets has proven to be a fast, economical, and successful way of preventing settlement of pavement repairs caused by insufficient compaction of trench backfill materials. Heaving of street patches over flash-fill has been observed in the past. Agencies in the Denver metropolitan area observed that heaving of asphalt patches were more pronounced during the winter of 2009-2010. Jefferson County and other jurisdictions in the Denver-metro area issued a moratorium on flash-filling trenches until a cause was determined and a solution could be implemented. Flashfill Services, LLC retained our firms to achieve these goals.

BACKGROUND

The use of flash-fill began in the Denver metropolitan area in approximately 1994. Flash-fill is a patented product, consisting of cementitious Class C fly ash, a non-cementitious Class F fly ash, and sufficient water to provide the desired fluidity. The ratio of Type F to Type C is often 3:1, but can be varied depending on the time of set desired, as well as the performance of the specific fly ashes being utilized. The original performance parameters of the Bennett patent (US 5,106,422 in 1992) were achieving about 20 pounds per square inch (psi) in approximately four hours, with an ultimate maximum strength of about 150 psi.

In February of 2010 we met representatives of Jefferson County, as well as various water districts, regarding the asphalt patch heaving over flash-filled trenches during the winter of 2009-2010. As part of this study, a listing of heaved patches constructed during the last two years was compiled and analyzed. Of the 41 patches reported, 37 percent were constructed in the winter, 10 percent in the spring, 29 percent in the summer and 24 percent in the fall. This distribution essentially rules out a seasonal explanation for the time of installation as a factor. It was our understanding that the flash-fill in this listing was placed by two separate suppliers; however, insufficient records were available to differentiate the sources of flash-fill in the list of heaved trenches. All patches were reported to have 1-inch or less of vertical displacement, with the exception of one that was reported to have 3 to 4-inches of vertical displacement.

We reviewed an “unpublished” 2008 report for a local municipality, investigating frost heave of flash-fill placed in December 2002. Potential causes of heaving investigated were

- ice lenses between the asphalt and flash-fill,
- swelling of surrounding soils,
- freeze-thaw action in the flash-fill, and
- a chemical reaction forming expansive ettringite.

Part of that report included discussions with various municipalities; some had observed similar frost heave and some had not. All municipalities that observed heaving also noticed that the patches are receding as the weather warms up. Testing of laboratory produced flash-fill under different curing scenarios indicated that frost-heave could be induced in the flash-fill when wetted and subjected to freezing conditions. The study concluded that frost-heave in the flash-fill was the cause of the patch uplift.

We also reviewed a report from another geotechnical engineering firm dated April 2008. Their report comments on possible causes and can be summarized as follows:

- Vertical heaving is related to freezing temperatures.
- Observed heaving is not likely from swelling soils.
- Elevated moistures were measured in the upper zones of flash-fill.
- The presence of soluble salts tends to attract water, increasing freeze-thaw issues.
- The soluble salts likely originated from the Valmont Class F fly ash.
- The flash-fill material is fragile to freeze-thaw fracturing, but competent as backfill.
- The fractured flash-fill retained significant resistance to loading.
- Recommended not using “scrubber fly ash”, due to the soluble salts involved.

We also reviewed the 2008 NCHRP Report #597 titled “Development of a Recommended Practice for Use of Controlled Low-Strength Material in Highway Construction” (2) and the ACI 229R report, entitled “Controlled Low-Strength Materials” (2). These materials are normally referred by their acronym CLSM in the construction industry. Both documents indicate that purposely entrained or introduced air contents serve to limit ultimate strength gain for future excavatability. The NCHRP report indicates that higher air content also improves resistance to freeze-thaw damage of the CLSMs.

Jefferson County personnel provided us with frozen specimens they obtained from their internal coring investigations of heaved asphalt trenches. As shown in the picture below, these core samples had several ice lenses formed in horizontal cracks in the hardened flash-fill.


Jefferson County core with ice lenses

We cored heaved patches at two locations in February of 2010**.** The flash-fill material below the 8-inch asphalt patch was highly fractured to a depth of approximately 4 inches, but was more competent below that. No ice lenses were present in either core.

POTENTIAL CAUSES FOR UPLIFT

Several possible causes for the heaving of asphalt patches were discussed initially. First was potential chemical reaction of the sulfates in the flash-fill, in which the formation of ettringite in the trench fill would have caused the vertical displacement. Cores obtained by Jefferson County personnel were tested for ettringite levels, both at the crack surfaces and within larger pieces of intact flash-fill. The intact flash-fill sample contained approximately 30 percent ettringite by weight, whereas the surface material within the cracks was 28 percent, essentially the same amounts. Ettringite formation within flash-fill or Portland-cement based concrete is one of the normal chemical compounds formed when the cementaceous product is in the plastic state and any volume change is harmless. Delayed formation of ettringite, when the ettringite dissolves, reacts with additional sources of minerals, and reforms in cracks is the typical mechanism that causes expansion and deterioration. Ettringite can dissolve again and shrinkage would result. This process takes time, often years. The expansion and shrinkage of patches has occurred over months thus this potential explanation for asphalt patch heaving was eliminated early.

Due to the reduction in vertical displacement in the spring, the cause appears to be associated with frost heave in the matrix of the flash-fill itself, like silts and base courses with significant silt fractions, or to the formation of ice lenses in cracks. Cores and excavated flash-fill material indicated the formation of ice lenses in horizontal cracks. We therefore concentrated our study to investigate the cause of cracks.

POTENTIAL CAUSES OF HORIZONTAL CRACKS

Several potential causes of the horizontal cracks, making flash-filled trenches susceptible to ice lens formation were discussed and evaluated in various laboratory and field tests. Cold joints in the flash-fill caused by bleed-water and/or segregation of the unburned carbon particles floating to the surface are possibilities. Horizontal cracking originating from these cold joints will be more permeable than the main flash-fill matrix. Water entering the cold joints may freeze forming ice lenses.

Another possible cause is that that the cracks originate from stresses from equipment compacting surface courses before the flash-fill has achieved sufficient strength to withstand these stresses without fracturing. A simple analogy is the flexural strength of plywood is less if loaded before the internal adhesives are fully cured; premature loading would result in horizontal slippage and permanent fractures. While the desired strength (per the patent) was 20 psi within 4 hours, and the normal waiting time should be at least 90 minutes, we understand that some contractors have begun asphalt patching within 30 minutes.

Another potential source of the horizontal cracking observed in the upper zones of the flash-fill may have occurred during post-placement excavation to allow asphalt patching one or more days after flash-filling the trench. The stresses of the backhoe bucket teeth could exceed the compaction stresses described before.

LABORATORY TESTING

Various flash-fill mixtures were proportioned and tested at the J.A. Cesare & Associates, Inc. / CTS laboratory. Initial mixtures were proportioned to replicate the currently used mixtures and materials. These mixtures were subjected to compressive strength testing, freezing, vibration with subsequent freezing, and time-temperature graphs. Additionally, other proportions and material sources were similarly tested to evaluate the durability potential of other mixtures.

To obtain relevant strength data, flash-fill material was placed in 4-inch diameter by 8-inch tall cylinder molds. Compressive strength data was collected by removing the hardened flash-fill from the mold and placed in a compression testing machine. Additional test specimens were placed in the freezer in the mold at various time intervals. Companion specimens to the freezing test were vibrated on the top surface with a vibration hammer in an effort to mimic post-placement construction methods and subsequently placed in the freezer. The remaining cylinder mold of flash-fill had a time-temperature probe inserted while the flash-fill was still in the viscous state. This allowed for the monitoring of the temperature and elapsed time of the material. Based on the data collected from the inserted probes, maturity graphs were created. These graphs allow for the estimation of strength based on the material's temperature evolution and elapsed time.

Our observations of flash-fill specimens placed into the laboratory freezer, at similar successive times, were that no freeze induced cracking occurred after the flash-fill had achieved approximately 120 psi. This was independent of whether the cylinders were vibrated or not. The time to obtain this strength in the field is unreasonable for most construction schedules and the ultimate strength of these mixtures would make excavations into the flash-fill more difficult. At this point, using cellular foam to reduce frost heave was investigated.

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FOAMED FLASH-FILL TESTING

Field trials were performed in May 2010 with mixtures batched with volumetric mixing trucks using readily available fly ash products in the Denver area. Multiple proportions and material types were tested. Testing included: unit weight, air content, compressive strength, and modulus of elasticity. Modulus of elasticity testing was done while applying an axial load and recording the resultant deformation. The linear-elastic portion of the graph was used for determining the modulus of elasticity. Modulus values could easily be lowered using higher amounts of cellular foam, making the flash-fill less rigid and less prone to compaction fracturing.

Flash-fill Description	Initial Unit Weight, pcf	Foamed Unit Weight, pcf	% Air	28-day psi	Modulus of Elasticity, psi	RE*
1:1 Class F: Class C, No Foam	110.8	110.8	0	518	38,982	2.76
1:1 F:C, high foam	110.8	79.0	29	86	7,689	0.68
1:1 F:C, medium foam, less water	114.5	79.5	31	136	12,962	0.86
1:1 F:C, lower foam	114.5	91.0	21	249	27,634	1.42
Arapahoe, No Foam	112.7	112.7	0	232	22,232	1.90
Arapahoe, Foamed	112.7	83.0	26	61	7,704	0.61
Arapahoe, High-water + foam	104	81.0	22	26	1,061	0.39
Arapahoe, Hi-water+foam+citric acid	104	79.0	24	124	NA	0.81

* Removability Modulus, as discussed in the section titled REMOVABILITY MODULUS

Full sized trench trials were performed off site in June 2010 to further test the compaction cracking theory. Three trenches were excavated, and subsequently backfilled with a full truck load each of three different mixes. First was the "high-strength" 1:1 (Class F:Class C), followed by the 2:1 mixture foamed to about 12 percent air content, and finally the traditional 3:1 mix that was the subject of the frost-heave study.

When each flash-fill mixture had sufficiently set, representing when a contractor would begin patching, approximately 4 inches of native sandy on-site soil was spread over the flash-fill to simulate the cushioning of loose asphalt, and compacted. A 3,000 pound steel-wheeled vibratory roller and a vibratory plate were used to compact the soil over the flash-filled trenches immediately after spreading, as well as one-hour later. Samples were obtained for compressive strength and freeze-thaw testing. A small freezer was on-site to place test cylinders in immediately after casting, and at 30 minutes and 60 minutes afterwards. All the 3:1 samples developed cracking when frozen while the 2:1 foamed and 1:1 samples did not develop any cracking. Other cylinders were transported back to the laboratory later that day for strength and freeze-thaw testing.

Freeze-thaw testing of flash-fill from the trench trials was performed after 7 days of curing. Testing was in accordance with ASTM D560 for soil-cement mixtures as recommended by the NCHRP report, except that a 24-hour cycle was utilized. Two specimens of each mixture were intended to be subjected to 12 cycles of freezing and thawing, with the weight loss recorded at the conclusion. The 3:1 mixture specimens fell apart after one and three cycles. The 1:1 mixture specimens fell apart after four and six cycles. The 2:1 foamed mixture specimens completed twelve, indicating better freeze-thaw resistance. The 1:1 and 3:1 mixes developed horizontal and vertical cracking, whereas the 2:1 foamed mix developed surface deterioration without cracking.

After 13 days the compacted soil was removed in several locations, and the flash-fill was cored with a 6-inch core barrel to depths up to 24 inches. No horizontal cracks were observed in the cores. The cores were taken back to the laboratory for preparation and testing for density and strength at 15 days. Test results for these trench trial cores are reported in the table in the section titled REMOVABILITY MODULUS.

REMOVABILITY MODULUS (RE)

An approach to predict excavatability was developed and used by Hamilton County, Ohio, based on a CLSM's compressive strength and unit weight. The removability modulus is calculated with the equation shown below for standard English units; a metric formula is also available. Their studies and field experience have shown that while CLSMs may have similar compressive strengths, those with fine aggregate in them are harder to excavate than flash-fill materials, and flowable fills with coarse and fine aggregates are harder still. Similarly, our trench trials demonstrated that the foamed flash-fill was easier to excavate than traditional the flash-fill.

$$RE = \frac{W^{1.5} \times 104 \times C^{0.5}}{10^{6}}$$

where W = in-situ unit weight (pcf) and C = 28-day compressive strength (psi)

The values listed below were either tested as part of the trench field study, or averaged from a local jurisdiction's approved flowable fill mix designs for comparison purposes. The RE was also calculated for a flowable fill with fine and course aggregate at the highest strength ACI 229R says backhoes can still excavate, which is 200 psi. ACI indicates that CLSMs with either sand or fly ash as the filler can be backhoe excavated up to 300 psi.

To further help put relative excavatability into perspective, an A-7-6 clay and a crushed stone, Class 6 base course material were compacted to 99 percent standard and 97 percent modified densities respectively, and tested for unconfined compressive strength. One sample from each compacted material was tested immediately after fabrication, the other sample was air-dried in the laboratory for seven days before testing.

Material	Unit Weight, pcf	Strength, psi	RE
1:1 "high-strength" flash-fill (trench cores)	110	340	2.21
2:1 foamed flash-fill (at approx.12% air)	95	100	0.96
3:1 traditional flash-fill (trench cores)	106	150	1.39
A-7-6 Clay soil, moist	119	27	0.70
A-7-6 Clay soil, air-dried	104	489	2.44
Class 6 Base course, moist	141	43	1.14
Class 6 Base course, air-dry	136	176	2.19
Typical flowable fill, at 200 psi	142	200	2.49

CONCLUSIONS & FINDINGS

Observations from cores taken from heaved patches indicate ice lenses form in horizontal cracks with traditional flash-fill. Cracking is they due to combinations of cold-joints, premature compaction efforts, and/or post-placement excavation.

While best practices for sealing the surface patches against water intrusion would reduce the frost-heave risks, we realize this is not a practical solution long-term for most agencies. We believe the use of a preformed, cellular foam to ensure an adequate air content is the correct modification for traditional flash-fill to resist frost heave. The foam adds fluidity normally gained by higher water contents. This allows the flash-fill to set faster than traditional flash-fill, yet the ultimate strength will be reduced by the use of foam. The cellular foam also makes a more homogenous mixture reducing the layering caused by the unburned carbon. Moreover, the air void structure was noted in the NCHRP report to increase freeze-thaw resistance in CLSMs. This was demonstrated in our last round of freeze-thaw testing where the 2:1 foamed mixture was six times more durable than the traditional 3:1 mixture, and twice as durable against freeze-thaw damage as the 1:1flash-fill.

High strength mixtures are more difficult to excavate than the 2:1 foamed mixture, based on the RE values of 2.21 and 0.96, respectively. The lower modulus values during stress-strain testing indicate the foamed mixtures are "softer", and this property would tend to lessen the tendency to crack during compaction or post-placement excavation for patching.

In August 2010 we revisited the trench trial site and had an operator excavate the southern half of the flash-filled trenches. The front end loader was a Caterpillar 950G with a straight edged bucket. The loader operator stated that the two non-foamed flash-fills were comparably more difficult to excavate than the foamed flash-fill and the 1:1 was somewhat more difficult than the 3:1. The wheels quickly spun when the non-foamed flash-fill was encountered and rocking the bucket with the hydraulic controls was necessary to break up the flash-fill. These observations are in general agreement with the RE values calculated from cored specimens.

A draft specification was presented to Jefferson County for their review and potential implementation. The moratorium of flash-fill has been lifted, provided the flash-fill is foamed.

Six months after the study concluded, most of our client's mixes are foamed and performing well. Air contents are averaging approximately 20%, Set times are ranging from 10 to 20 minutes with the contractor placing asphalt patches within 60 minutes. Depending on the ratio of Type C to F fly ash, RE's of 0.90 to 1.4 have been achieved.

A US patent application has been filed, on behalf of Flashfill Services, LLC on this improvement of flash-fill to reduce the risk of frost-based, patch-heave, due to formation of ice lenses. For more information, contact Flashfill Services, LLC in Denver, Colorado, or Stan Peters.

LOCAL SPECIFICATION FOR AIR-ENTRAINED FLASH-FILL

Many of the pavement engineers and managers in the Denver metropolitan area belong to a pavement group known as the Metropolitan Government Pavement Engineers Council (MGPEC) for concrete and asphalt street design procedures, construction specifications, and other common interests.

A task force was convened to work on improvements to their flowable backfill specifications, which include Portland cement and aggregate based flowable fill, and now air entrained flash-fill. This specification was presented on March 3, 2011 to the MGPEC Steering Committee, and will soon be distributed to the member agencies for final comments. A copy of the pertinent sections follows.

ITEM 18

UTILITY CUT AND BACKFILL

18.1 DESCRIPTION OF FLOWABLE BACKILL MATERIALS

This work shall consist of the excavation and backfill of trenches for the accommodation of substructures including, but not limited to, conduits, for electrical, communications, fiber optic, traffic signal or other small utilities, gas and water lines, sanitary and storm sewer lines, and other types of utility under existing pavements or ground surfaces to be later improved. Other suitable applications include structural support for utilities, replacement of unstable subgrade during pavement repairs, backfilling behind retaining walls and abutments, filling areas including pipe abandonment, annular spaces, undercut areas and other void filling.

The objectives of the flowable backfill materials specified below is to provide a self-leveling, frost heave-resistant, non-settling, controlled low-strength material (defined by ACI as a CLSM), that does not require compactive effort and testing. A high slump is required to aid in the self leveling and void filling objective. The visual consistency may appear to range in appearance from thin batter or mud to thick water. It must be foremost removable with light machinery in the future, and also quickly stable to support paving operations and traffic quickly. The flash-fill products will allow pavement repairs to occur more quickly than flowable fill, to open the streets back to traffic.
Air contents at or above 15% are required in the top 4 feet of flowable fill to limit permanent frost heave. This air content should be used for the entire depth (to aid in excavatability), unless forbidden for thrust blocks or as bedding normally used for lateral support of pipes.

18.2 MATERIALS

18.2.1 Flowable Fill

Flowable fill shall consist of a controlled low-strength, self-leveling concrete material composed of various combinations of cement, fly ash, aggregates, water, chemical admixtures and/or cellular foam for air-entrainment. It shall have a minimum air content of 15%, when tested in accordance with ASTM C231, to provide suitable resistance to frost-heave. It shall have typical design compressive strengths of 50 to 150psi at 28 days, when tested in accordance with ASTM D4832. However, the flowable fill shall be limited to a maximum Removability Modulus (RE, as described in 18.2.3) of 1.5, which may require the lower strengths towards the 50 psi minimum, and/or higher air contents over 15%. The mix shall result in a product having a slump in the range of 7 to 10 inches, when tested in accordance with ASTM C143. Slumps of less than 7” will not be permitted for placement, since the flowability to avoid settlement is impaired, and strengths may increase. The CONTRACTOR shall submit a mix design for approval by the AGENCY, prior to placement. The mix design shall be supported by laboratory test data verifying compliance with air content, slump, strength and removability (RE) requirements.

18.2.2 Flashfill

Flashfill shall consist of a controlled low-strength, self-leveling cementitious material composed of various combinations of cement, fly ash, water, chemical admixtures and/or cellular foam for air-entrainment. No aggregate or sand is usually needed. It shall have an air content of 15% to 25%, when tested in accordance with ASTM C231, or by volumetric calculations shown below in 18.2.4, to provide suitable resistance to frost-heave. It shall have typical design compressive strengths of 100 to 300 psi at 28 days, when tested in accordance with ASTM D4832. Higher strengths may be permitted, however the flashfill shall be limited to a maximum Removability Modulus (RE) of 1.5, which may require lower strengths and/or higher air contents. The mix shall result in a product having a slump in the range of 8 to 11 inches, when tested in accordance with ASTM C143. Fluidity may also be measured by ASTM D6103, as described below, with typical spreads of 8 to 12 inches, or greater. Slumps of less than 8 inches or spreads of less than 8 inches will not be permitted for placement, since the flowability to avoid settlement is impaired and the strength may increase. The CONTRACTOR shall submit a mix design for approval by the AGENCY, prior to placement. The mix design shall be supported by laboratory test data verifying compliance with air content, slump, strength and removability (RE) requirements.

18.2.3 Removability

The removability modulus* , RE, is a value calculated by

$$RE = \frac{W^{1.5} \times 104 \times C^{0.5}}{10^6}$$

W = in-situ unit weight (pcf) and C = 28-day compressive strength

*RE was developed & is used by Hamilton County, Ohio; per the NCHRP #597 CLSM Report. A lower RE means easier to excavate or remove.

18.2.4 Air Content Volumetric Calculation

Air content can be calculated as follows (based wet densities before and after foaming) :

$$\text{Air Content} = \frac{(\text{Unit Weight No Air-Entrainment} - \text{Unit Weight Air-Entrained}) \times 100\%}{\text{Unit Weight No Air-Entrainment}}$$

18.2.5 D6103, Flow Consistency of CLSMs

D6103 utilizes a moistened 3” diameter, 6” high open-ended cylinder, filled with the flashfill. When the cone is lifted, the resulting “pancake” is measured at its longest and shortest dimensions and averaged.

18.2.6 Cement

Cement shall meet the standard chemical requirements of Type II or Type IP, ASTM C150 or ASTM C595, respectively.

18.2.7 Fly Ash

Fly ash shall meet the requirements of ASTM C618 Type C or Type F. Fly ash not meeting the requirements of ASTM C618 may be used if prior testing indicates acceptable results.

18.2.8 Water

Potable water or reasonably clean and free chemicals injurious to the final product are to be used.

18.2.9 Chemical Admixtures

Air-entraining admixtures shall conform to ASTM C260 requirements; other chemical admixtures shall conform to ASTM C494 requirements.

18.2.10 Foaming Agents
Foaming agents shall conform to ASTM C869 and C796, or as approved by the engineer.

18.2.11 Suitability of Flowable Backfill Constituents
Flowable backfill materials may not contain any material deemed toxic or hazardous. Material Safety Data Sheets (MSDS) must be available for any cement, fly ash or admixture component of the mixture upon request. Backfill shall be compatible with bedding materials, electrochemically and otherwise if used as a metal pipe backfill application.

REFERENCES

[1] NCHRP Report 597, “Development of a Recommended Practice for Use of Controlled Low-Strength Material in Highway Construction, TRB, 2008.

[2] ACI 229R-99 (Reapproved 2005) Controlled Low-Strength Materials, ACI Manual of Concrete Practice.