Self-Leveling Underlayment and Bonded Topping Two-Course Slab Construction

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ABSTRACT

The American Concrete Institute's 302.1R-04 Guide for Concrete Floor and Slab Construction states that underlayment can be used as a remedial measure if the composite or minimum local F-numbers measure less than either the specified overall or individual section F-numbers. The purpose of this work is to verify the results of field testing that a bonded monolithic high-performance self-leveling underlayment installed using a two-course floor slab construction method will produce a superflat floor and accelerate the building schedule. The effects of the self-leveling concrete as the topping course when it is installed on the concrete base slab in less than 28 days are examined. Modified lab testing procedures for are conducted in the field to measure essential performance characteristics during installation.

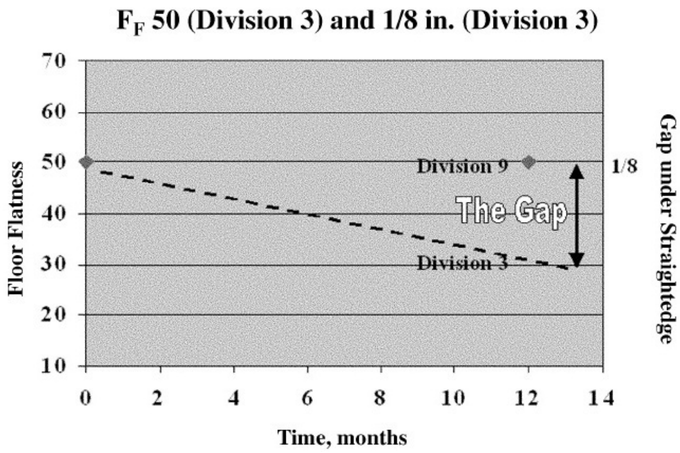
Keywords: self-leveling, underlayment, floor flatness, floor levelness, bonded overlay, concrete floor, slab construction, moisture vapor retarder

INTRODUCTION

The American Concrete Institute cites, "Time-dependent changes in floor profiles occur on every project, but the magnitude of the profile change can vary[1]." Curling or warping causes slabs that are built flat not to stay flat. This loss of flatness over time creates the gap between Division 3 and Division 9 floor tolerances as shown in Fig. 1. The extent or degree of the gap is influenced by many variables and time. The discussion of these variables is for the most part, outside the scope of this study. This study focuses on established ACI guidelines that use materials and an installation method that reduces or eliminates the gap.

ACI 302.1R-04 classifies floors on the basis of intended use, discusses special considerations, and suggests finishing techniques for each class of floor. Two-course floors are divided into two categories: (1) Unbonded topping over base slab and (2) Bonded topping over base slab. The latter is used for Class 3 or Class 7 floors, either of which can utilize a bonded topping that is a proprietary product applied per manufacturers' recommendations[2].

Fig. 1 – The gap (ACI 302.2R-06)



Approach and goal of this study

The research presented in this paper focuses on a 25,000 ft^2 suspended metal deck slab where high-performance self-leveling underlayment (HPSLU) was installed as the bonded topping over base slab using a proprietary computer controlled mobile blending unit that mixes HPSLU onsite. The objective of this study was to quantify the effects of the HPSLU over a newly poured concrete slab, characterize the performance of the HPSLU, and assess the impact of this installation method on the construction of the entire project. The impact of this installation method and materials to the overall construction cycle is evaluated; plus how this installation method & materials reduces risks to a concrete slab specified for resilient flooring.

RESEARCH SIGNIFICANCE

The installation method and material performance being studied in this paper represent an enhancement to existing concrete slab construction that will receive interior floor coverings. This installation method and type of material will reduce problems that result from the disparity of Division 3 and Division 9 floor flatness tolerances[3]. Despite this incompatibility of tolerance measuring methods and the concrete contractor performing to the specification, subsequent trades follow and find that tolerances are not adequate which generally results in remediation costs, including time delays, materials, labor, safety issues, and sometimes litigation, all of which can be substantial and often less reliable than a planned approach to these issues as described here.

BACKGROUND

High-performance self-leveling underlayment (HPSLU) is mortar that has high flow characteristics and does not require the addition of excessive amounts of water for placement. HPSLU is typically used to create a flat and smooth surface over existing concrete and also rough finished or bull-floated concrete slabs. HPSLU has compressive and flexural strengths similar to or higher than that of traditional concrete. It can be left exposed to trade traffic for months during building construction and also provides an excellent substrate for installing interior floor coverings such as vinyl, rubber, VCT, wood, ceramic tile, stone, and carpet.

The phrase "self-leveling" was reportedly coined in the United States by a producer of first generation materials in 1978 to reference their product and the labor savings to place it. Self-leveling refers to the flow characteristic that allows it to seek gravitational leveling under its own weight. Once the material is placed and the final thickness is achieved, finishing is accomplished by lightly breaking the surface tension of the product using a tool called a smoother. Traditional self-leveling underlayment materials have been used over cured concrete (≥28d) with a relative humidity of ≤80%. These materials are typically installed just prior to the installation of the finished floor at thicknesses ranging from 0.25" – 1.50". The typical installation is performed using small bags ~50lbs (~25 kg), a mixing drum, a commercial electric drill, and a mixing paddle inside enclosed buildings that have controlled climate conditions. The batch measuring and mixing method utilized for this type of installation of underlayments is also known as bucketing or barreling. Greater production efficiency has been achieved through the use of continuous mixing and pumping machines. These machines are portable and can be moved inside the building near to the point of installation. However, machine application poses a challenge at a construction site when access is limited and sometimes is not available or otherwise not readily accessible to load with materials and equipment. Both bucketing and machine installation methods result in significant dust from breaking small bags that can be disruptive to the critical path of the construction schedule; as this work displaces all trades working on the floor nearby or in adjacent areas at the time of mixing and placement. These applications are often performed during off-hours to lessen the impact to other trades and the construction schedule, which further increases the cost of remediation due to overtime, night work, and weekend shifts.

PROJECT SITE OVERVIEW

Swedish Medical Center broke ground in October 2009 for a new 175-bed hospital and five-story medical office building (MOB) on 12.5 acres just off I-90/Exit 18 in Issaquah, WA (Swedish Hospital Issaquah Campus). It has 500,000+ ft^2 of built space, with the MOB targeted to open in July 2011 and the hospital seven months later. The general contractor for this project also performs their own concrete work. The general contractor has gone on record stating, "For many years, we have struggled to get flooring installed due to moisture content issues and floor flatness issues. Within the past 5-10 years, the requirement for moisture content has become more and more stringent as the flooring industry has changed their adhesives and sheet goods. The impacts to project cost and schedule due to these issues can be enormous. Sequencing of underlayment is a continuous challenge. Getting a building enclosed, temperature and humidity stabilized is also a timing issue we struggle with. In addition, we have continued to see an increase in flooring failures in many of our projects.

From the outset of Swedish Issaquah, we took a proactive role regarding the flooring issues. We did not want to experience any floor flatness issues or failures as experienced in the past. First, we worked with the engineers of record to determine how much deflection to expect for the steel structure after the decks were poured. They estimated a 5/8" (15.875 mm) average thickness. We evaluated a number of options for underlaying to bring them to the specified flatness of F_F 35. Among those were self-performing cementitious underlayment after walls were framed. The most economical solution was to apply this HPSLU system directly after the slab on deck pours and prior to framing and overhead rough-in. We also poured the slabs and bull floated a finish rather than hard troweling. This saved cost in placement of the concrete as finishers weren't on site on overtime waiting for the slab to cure.[4]"

Construction scheduling

The general contractor was able to pour and place concrete for the entire project without consideration for finishing. This allowed them to keep pouring concrete regardless of rain or other conditions that typically cause interruptions and also disrupt many of the other trades working on site. The HPSLU Contractor required 4-days to install approximately 30,000 ft^2 of HPSLU as shown in Table 1:

Table 1 – Typical HPSLU 30,000 ft^2 Installation

Shotblasting & Survey	2 days
Moisture vapor reduction system, & set grade	1 day
HPSLU installation (prime & pour)	1 day

HPSLU INSTALLATION

The contractor who was responsible for all HPSLU work on this project is headquartered in Woodinville, WA, (Seattle) and specializes in moisture vapor mitigation and the application of self leveling underlayment. They are the exclusive operators of pump trucks; proprietary computer controlled mobile blending units that mix HPSLU onsite at street level to exact manufacturer specifications. The general contractor worked closely with HPSLU contractor during the preconstruction phase. Known issues and challenges utilizing a new concrete construction method were identified. The difficulties to meet stringent concrete specifications while maintaining compatibility with flooring goods requiring minimal vapor emissions and unachievable F_L/F_F numbers were addressed too. This proactive strategy was intended to:

1) Accelerate concrete placement schedule – no rain-outs
2) Increase concrete placement production and efficiency, thus reducing labor cost and overtime
3) Eliminate concrete finishing – labor, equipment, and mobilization
4) Increase predictability of floors, i.e., floor flatness, moisture vapor emission rate, floor preparation
5) Create a flat floor for all trades to establish a benchmark
6) Allow off-site fabrication of headwall millwork, reducing the need for long cut materials and shimming
7) Reduce/eliminate change orders related to floors
8) Accelerate the overall construction cycle

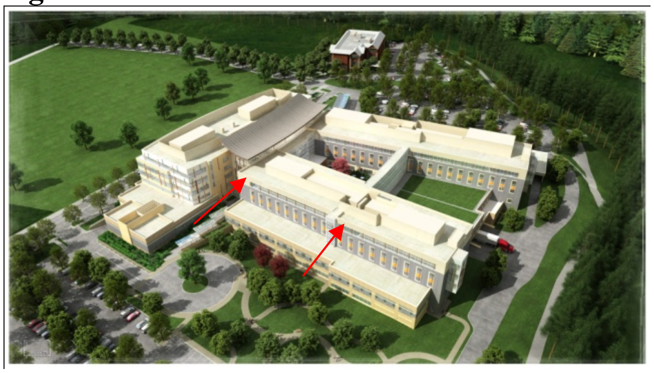
The goal was to offset the cost of planned moisture mitigation and HPSLU installation with the savings opportunities from the above items.

EXPERIMENTAL INVESTIGATION

Concrete slab

Swedish Hospital is a braced steel frame structure. The structure is comprised of composite primary and secondary beams rigidly connected to the floor slab using shear/nelson studs. The floor make up consists of metal decking with an in situ concrete slab as shown in Fig. 3. The majority of data for this study was generated in the field under actual jobsite conditions on one of the full-scale concrete slabs. The slab study site was the 4th floor of the West Wing (hospital) that totaled 25,116 ft^2 consisting of 12,074 ft^2 on the North section, 11,740 ft^2 on the south section and 1,302 ft^2 on the sky bridge, connecting the West Wing to the East Wing as shown in Fig 2.

Fig 2.



It should also be noted that the slab construction in this study is representative of all ~500,000 ft^2 slab construction for the entire hospital project. All concrete slab construction on this project was performed as described here. The primary activities of this study are outlined in Table 2:

Table 2 – Study activities

Date	Activity	Location	Comment
Sep-15	Concrete slab poured	South section	Bull float
Sep-17	Concrete slab poured	North section & Sky Bridge	Bull float
Sep-17	F_L & F_F testing of slab	South section	3rd party agency
Sep-19	F_L & F_F testing of slab	North section	3rd party agency
Oct-06	Shotblasting-cleaning	South section	CSP 3
Oct-07	Shotblasting-cleaning	North section	CSP 3
Oct-08	Map concrete cracking	North & South sections	3rd party agency
Oct-09	Pull-off tests-concrete surface	North & South sections	ASTM C1583M
Oct-09	Survey for HPSLU depth	North & South sections	Rotating laser
Oct-11	pH tests of slab	North & South sections	ASTM F710
Oct-11	Filled cracks in slab	North & South sections	Gravity
Oct-11	Applied moisture retarder	North & South sections	Liquid membrane
Oct-13	Installed HPSLU (& completed)	North & South sections	To specified depth
Oct-13	Sampled HPSLU for testing	From end of hose	As per test schedule
Oct-14	F_L & F_F testing of slab	North & South section	3rd party agency
Oct-22	Pull-off tests-HPSLU	North & South sections	ASTM C1583M
Nov-13	Pull-off tests-HPSLU	North & South sections	ASTM C1583M
Nov-16	F_L & F_F testing of slab	North & South section	3rd party agency

The South section was poured on September 15, and the North section of the slab and the Sky Bridge were poured on September 17, 2010. The representative concrete mix design is shown in Table 3[14] as reported on September 17. Both sections of the suspended slab were accessible by a concrete pump boom truck positioned at ground level next to the building. The concrete was consolidated with a vibrating screed and bull floated to achieve a rough, uniform texture; flatness and levelness were not priorities of this operation. The information in Table 4[14] and the corresponding compression testing in Table 5[14] was obtained from the same truck as represented in Table 3[14].

Fig 3. – Cross section of West Wing Level 4 Slab

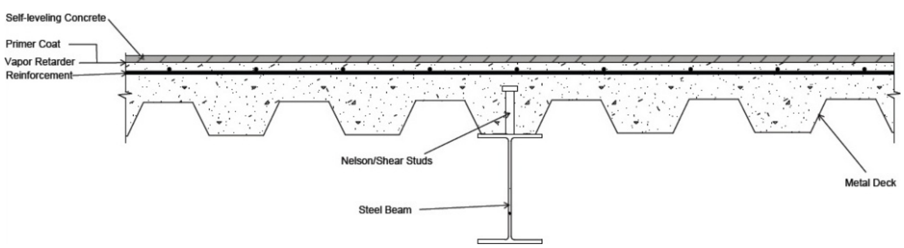


Table 3 – Concrete mixture proportions (Actual)

Components	Weight per yd^3	
Cement Slag	83.0	lbs
Cement – Type I-II	449.0	lbs
Coarse Aggregate	1,932.0	lbs
Fine Aggregate	1,423.0	lbs
HRWRA	10.5	oz
MRWRA	21.0	oz
Water	226.0	lbs

*Placement location and notes: West Wing, 4th Floor, North section, pour #2. 20 gallons of water added onsite.

Table 4 – Concrete Field Data (Actual)

Air Temperature	59° F
Weather	Overcast
Sample Temperature	73° F
Water/Cement Ratio	0.425
Slump	7.5”
Required Strength	3500 psi @ 28 days

Table 5 – Compression Test Results

Date Made	Lab#	Date Tested	Age	Size (in)	Load (lbs)	Dia (in)	Area	Strength (psi)	Type of Fracture
09/17/10	#10555	09/24/10	7	4 x 8	51810	4.00	12.57	4120	Type 3
09/17/10	#10556	10/15/10	28	4 x 8	79850	4.00	12.57	6350	Type 3
09/17/10	#10557	10/15/10	28	4 x 8	75730	4.02	12.69	5970	Type 3
09/17/10	#10558	10/15/10	28	4 x 8	76070	4.01	12.63	6020	Type 3

F_L/F_F testing of rough slab

The first of three F_L/F_F tests[5] was carried out by the third-party independent testing company of record according to ASTM E1155 and ACI 117-06, prior to all surface preparation work for the HPSLU. Subsequent tests were made the day following the HPSLU installation and another approximately 30-days after the HPSLU installation. Loading of building materials and the exterior curtain wall assembly installation would make the later test representative of this slab under early load. The results of these tests will be discussed later in this paper; but it is important to note that the requirement for the new concrete F_L/F_F was not stringent.

Shotblasting

Shotblasting was utilized to mechanically create an open, absorptive surface in preparation for the application of the moisture vapor reduction system. Shotblasting removes laitance and other superficial contaminants from the concrete slab surface. Large, electrically-powered machines requiring a three-phase, high-voltage power source were selected for the job. The pulverizing effect of steel shot impacting the surface at high velocity profiled the concrete surface. The CSP-5 (ICRI) profile depth was largely influenced by the bull floating technique, as well as the shot size, machine setup, and rate of travel. Limited access areas, edges and corners were detailed to within ¼" inch (6 mm) of the vertical surfaces with hand-held diamond grinders. A magnetic broom was also used to retrieve fugitive steel shot. The floor was carefully inspected for any remaining steel media that remained on the surface, in edges, corners, or trapped in cracks; and it was removed by a combination of air blast, vacuum, and stiff bristle broom.

Topographic Survey

Achieving a specific flat floor and levelness specification that will satisfy the requirements for today's resilient floors demands a high degree of engineering, skill and experience on the part of the HPSLU Contractor. The precise topography of the concrete floor was determined by a survey conducted after the shotblasting process utilizing the following application & measuring principle:

1. Apparatus: rotating laser level, receiver, tripod, telescopic staff
    a. The rotating laser level is placed on a tripod, turned on and allowed to calibrate. Once calibrated a rotating horizontal beam is emitted from the level.

b. The receiver, which is secured to a telescopic staff, is adjusted until a zero datum is established *(usually the highest point on the slab).*

c. Once moved from the point of zero datum, the receiver calculates the difference in height between the point of placement and the zero datum, established in the initial set up.

d. Height values are placed on the concrete base slab on a specified grid.

2. Level Pegs

a. Used for defining heights up to 65 mm on concrete or other floors, where an even floor and the capture of the correct quantity of material are important.

b. Recommended to use ~1 pin per 4'x4' square surface, depending on the precision required.

c. Level pegs are cut and placed with consideration to the survey values to determine HPSLU volume of the second course.

The data points are then mapped as shown in Fig. 4 & Fig. 5 and the HPSLU pour was engineered to meet a 1" maximum depth specification.

Fig. 4

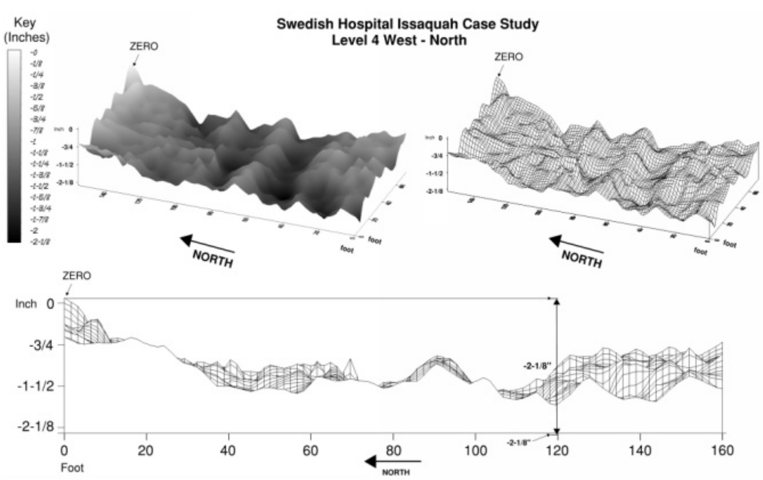
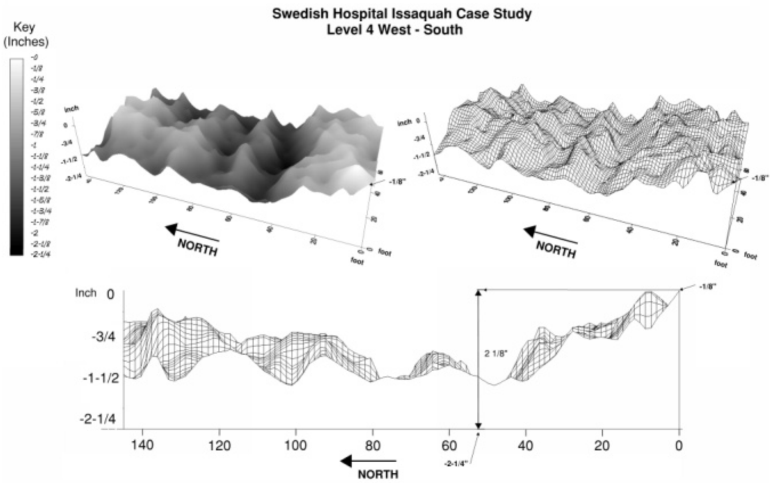


Fig. 5



Crack Mapping

Cracks in concrete are caused by many conditions. It is not a focus of this study to address the cause of the cracks that occurred on this concrete slab. However, determining the location and extent of concrete cracking by direct observation was of interest. The locations of cracks were noted on sketches of the North and South sections of the concrete slab in Fig. 4.1 and 4.2. The HPSLU Contractor utilized the "Gravity Filling[6]" method to cosmetically repair and seal the surface cracks of the concrete prior to the application of the bonded overlay to minimize any leakage of the HPSLU that could occur during the pour. Structural repairs were not in the scope of this work.

Fig. 4.1

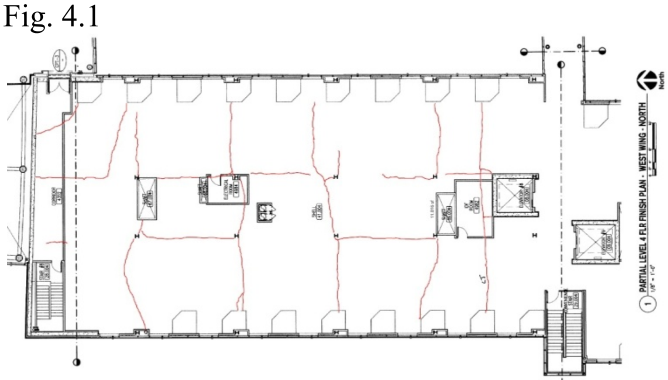
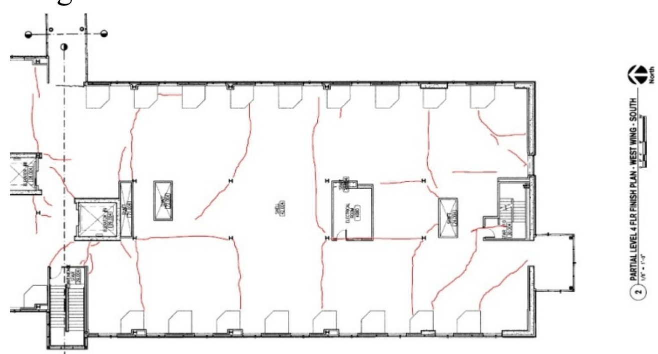


Fig. 4.2



Method of Crack Repair

The concrete surface was profiled by shotblasting and the cracks were cleaned pneumatically. The gravity filling method used a solvent-free, low viscosity, 100% solids epoxy resin mixed with a specified fine sand (2:1) for filling the cracks. The epoxy-sand mixture was poured into the cracks and onto the surface; it was worked back and forth with a hand trowel over the crack to obtain the maximum filling. All of the cracks in this slab were covered with the moisture vapor reduction system, then the bonded HPSLU overlay. It is not known if the cracks have reopened, but none have reflected through the HPSLU after four months.

Moisture vapor reduction system

The solvent-free, low viscosity, 100% solids epoxy resin was mixed according to the manufacturer's instructions and poured onto the concrete surface directly from the mixing buckets and spread with a long handled notched squeegee followed with a non-shed roller to achieve uniform coverage. The survey grid provided a visual guide to control the quantity of resin per unit area. Moisture tests were conducted before and after application of the system; but climate control conditions did not exist and therefore results would not be considered valid as per current ASTM standards.

Primer

The HPSLU manufacturer required a 1-part acrylic primer-slurry (using HPSLU powder) to be applied over the moisture vapor reduction system prior to the application of the HPSLU. The following procedure was used:

1. Allow epoxy to cure for ~24 hours, maintain clean surface free of dirt and contaminates throughout installation
2. Prime with liberal slurry coat (3:1 w/10 lb powder in 4 gallons of primer) with a spread rate of 200 sq ft per gallon
3. Allow Primer to dry for minimum 2 hours, but no more than 12 hours.
4. Install HPSLU within 12 hours of the primer application.

Pump truck – the delivery system

The pump truck HPSLU binder and sand are stored in individual silo chambers that can refilled/recharged using bulk sacks through weather-tight doors on the roof of the pump truck. The pump truck has its own on-board combination knuckle/telescope crane that is used to lift the bulk sacks from the ground to the roof hatches. Water is stored in an on-board tank which can also be refilled from a local water source. All systems are interconnected so that once they are calibrated and set to produce a specific HPSLU product; all ingredients are continuously measured into the mixer until the operator stops production.

The volumetric-measuring and continuous-mixing of material is accomplished by a programmable computer software and hardware that monitors both weight and volume by weigh cells and sensors connected to the screw conveyors. One screw conveyor is used to continuously feed dry HPSLU binder; while a secondary screw conveyor is used to the specified HPSLU fine dry aggregate into a high-shear, auger-style pre-mixer where both components are combined and blended. The material exits the pre-mixer into the continuous mixer which also utilizes a high sheer auger that rotates in a tube. Water is metered through a computerized flow meter, and then added through an injection port where the pre-mixed HPSLU dry powder is introduced into the continuous mixer and the mixed HPSLU is discharged at the other end. The material reservoir is mounted below the continuous mixer. The precise mixing time, mixer rpm, mixer flighting configuration, throughput rate, and combination of these is proprietary and protected under U.S. and international patent laws by the inventor of these systems. Actual mixing time from input to output is usually less than 10 seconds. With this type of mixing configuration, output is always equal to input, with a relatively small amount of material being mixed at any one time. These methods and systems ensure the production of a consistent and high-quality HPSLU.

The high-pressure, high-output progressive cavity (eccentric screw pump or rotor stator) pump is specified for the pump truck design. This pump will generate sufficient force to pump vertically up to 35-40 stories from ground level. The design of the progressive cavity pump consists of a single-threaded screw or rotor, turning inside a double-threaded stator. The rotor seals tightly against the rubber stator during rotation, forming a set of fixed-size cavities in between. The cavities move when the rotor is rotated but their shape or volume does not change. As the rotor rotates inside the stator, cavities form at the suction end of the stator, with one cavity closing as the other opens. The cavities progress axially from one end of the stator to the other as the rotor turns, moving the HPSLU through the pump. New spaces/cavities are created when the rotor is turning that move axial from the suction side towards the pressure side. The suction side and the pressure side are always sealed off; and a continuous flow of HPSLU is created[7]. The material exits the pump and is conveyed hydraulically, under pressure through rubber hose or steel pipe, to the point of placement.

High Performance Self Leveling Concrete (HPSLU)

This material can be characterized as thixotropic with a rapid time-dependant change in viscosity during placement, excellent bond strength, rapid strength development, and dimensional stability. HPSLU's are generally composed of fine aggregate, polymers, fillers, other additives, and a binder system. The binder systems usually contain proprietary blends of three reactive ingredients – calcium aluminate cement (CAC), calcium sulfate (CS), and ordinary Portland cement (OPC). The calcium sulfate may be in the form of gypsum, anhydrite or plaster (calcium sulfate hemihydrate). Other pozzolanic materials such as fly ash from coal burning power generation plants and blast furnace slag from producing iron for making steel are also commonly used. A pozzolan is a material which, when combined with calcium hydroxide, exhibits cementitious properties. Many pozzolans available for use in construction materials today were previously seen as waste products, often ending up in landfills.

TEST SETUP AND PROCEDURE

First, individual properties of the HPSLU such as setting time, flow, compressive strength, flexural strength, bond strength, length change (shrinkage), and viscosity were determined using standard ASTM test procedures. Second, the crack bridging compatibility between HPSLU material and substrate concrete was investigated by crack mapping and visual observations. Third, a correlation between the rough concrete slab prior to the application of the HPSLU and the performance of the final composite floor was investigated to predict floor flatness and levelness using standard ASTM test procedures. All activities are summarized in Table 6.

Table 6 – Tests (Actual)

Test	Standard	Comments	Where	Age
Set time	C191M	Modified for field	Point of placement	During placement
Compressive strength	C109M	Modified for field	Point of placement	During placement
Flexural strength	C348M	Modified for field	Point of placement	During placement
Efflux	D5125	Sheen cup	Point of placement	During placement
Surface pH	F710	Digital pH meter	Concrete surface	24 days
Surface pH	F710	Digital pH meter	HPSLU surface	30 days
Length Change	C157M	Modified for field	Point of placement	1,3,7,14,21,28d
Tensile strength of concrete surfaces	C1583M	50mm dollies	2 random areas (3x)	22 days
Bond strength of overlay	C1583M	50mm dollies	4 random areas (3x)	31 days

Surface temperature		IR digital thermometer	Slab, Supercap	During placement
Temp & Humidity	C1064	Hygrometer	Point of placement	During placement
Floor flatness & levelness (F_F & F_L)	E1155	3d after placement, 1d after SC, prior to finish floor installation	As per standard	See comment

Sampling & specimen preparation

This procedure was used for obtaining representative samples of the fresh HPSLU as it was being installed on the concrete slab at the Swedish Hospital, West Wing-Level 4, for these tests to be performed. The procedures used every precaution that would assist in obtaining samples that were truly representative of the nature and condition of HPSLU being installed. This procedure also included preparing the samples of HPSLU for further testing because it was desirable and necessary to move the specimens to a designated off-site independent 3rd party laboratory.

Procedure (Note 1)

1. Size of sample – samples were obtained in a 2 L plastic receptacle with a handle and spout to allow handling and pouring of molds. (Note 2) Smaller samples were taken throughout the day for rheological tests that are not reported.
2. The sampling was performed by passing the receptacle completely through the discharge stream of the rubber hose (whip) as material was being placed and smoothed on the concrete slab. (Note 3)
3. Samples were moved from the point of placement to where HPSCL tests were performed and test specimens were molded maximum time limits specified by the manufacturer of the HPSCL.
4. Tests were started for flow, viscosity, temperature, and density within 2 min after obtaining the sample.
5. The tests were completed expeditiously.
6. Strength specimens were molded within 6 minutes after sampling.
7. Molds conformed to applicable requirements of ASTM C109, ASTM C348, and ASTM C157.
8. C109, C348, C157 are laboratory testing procedures and were modified for field conditions.
9. The HPSLU was consolidated in the molds by hand tamping in layers as specified by the test method.
10. All hardened specimens were demolded at the off-site laboratory at 4 hours.

11. Temperature measurement of samples conformed to the applicable requirements of Test Method ASTM C 1064/C 1064M.

Note 1 – Procedure and sampling were observed by the technical representative of record from the compliant ASTM E329 independent testing laboratory.

Note 2 – Composite sampling is not possible with HPSLU due to rapid time-dependant change in viscosity.

Note 3 – The HPSLU technical representative of record and responsible for making specimens for testing is a current certified ACI Concrete Field Testing Technician – Grade I (certification ID #01071141).

HPSLU INSTALLATION

The portability of the pump truck made it practical to bring it on the building site without the need for moving materials and equipment inside of the building; which was advantage on this project. Having the unit on site allowed close control of the HPSLU and all aspects of the installation. Before initiating any material calibration, a check was performed to ensure all components critical to production were functioning properly.

A lubricating mix was first pumped through the 550' of flexible hose that ran from the Pump Truck to Level 4. This mix was followed with the HPSLU which was also fluid and highly mobile after initial mixing and calibration. These materials were discharged into a moveable 55-galllon drum until the material stream was void of the lubricant. The discharge hose (whip) was then directed to the floor. High-volume pumping and placement commenced at approximately 1:00 PM and continued until approximately 7:00 PM without interruption. 87 tons of material (70 – 2,500 lb bulks bags) of material was placed in 6 hours for a production rate of 14.5 tons of material per hour (29,000 lbs/hour). This was equal to approximately 4.5 truckloads of dry powder material.

The entire 25,000 square foot Level 4 slab and sky bridge were completed; hoses were back-washed and extracted from the side of the building, rolled back onto the pump truck, all empty bulk bags were compacted inside of themselves only leaving a relatively minor disposal for the dumpster. The pump truck left the jobsite shortly after 8:00 PM. The following day a crew was observed snapping lines on the floor and the fireproofing contractors were setting-up for their production the day following.

TEST RESULTS & DISCUSSION

Compressive[15], flexural[16], and length change[17] tests were conducted by two 3rd party independent accredited laboratories. It is important to recognize the degree of difficulty in obtaining representative results under actual field conditions. Most if not all standards are specified with laboratory results. Compressive data is shown in Table 7 and flexural data is shown in Table 8. Other test results and conditions are reported in Table 12.

Table 7 – Compressive Strength Test Results 2"x2"x2" cubes – ASTM C109M*

Cube I.D.	Date Tested	Age (days)	Area (in^2)	Maximum Loads (lbs)	Compressive Strength	Average PSI (MPa)
4339-1	10/14	1	4.0	10,730	2,670	2,710 (18.7)
4339-2			4.0	11,050	2,760	
4339-3			4.0	10,860	2,700	
4339-1	10/16	3	4.0	13,210	3,300	3,290 (22.7)
4339-2			4.0	13,260	3,310	
4339-3			4.0	13,030	3,260	
4339-1	11/10	28	4.0	19,220	4,800	4,870 (33.6)
4339-2			4.0	20,000	5,000	
4339-3			4.0	19,260	4,820	

*Specimens were cast in the field on Oct-13, transported to 3rd party laboratory and demolded at 4 hours.

Table 8 – Flexural Strength Test Results 1.5"x1.5"x6" prisms – ASTM C348M*

Cube I.D.	Date Tested	Age (days)	Width (in)	Depth (in)	Support Span (in)	Maximum Loads (lbs)	Flexural Strength (psi)	Average Flexural Strength PSI (MPa)
1	10/20	7	1.55	1.55	4.50	256	465	520 (3.6)
2			1.55	1.55	4.50	371	670	
3			1.55	1.60	4.50	252	430	
4	11/10	28	1.55	1.60	4.50	533	935	945 (6.5)
5			1.60	1.60	4.50	535	880	
6			1.60	1.55	4.50	579	1,015	

*Specimens were cast in the field on Oct-13, transported to 3rd party laboratory and demolded at 4 hours, then shipped to another 3rd party laboratory with the appropriate testing equipment apparatus.

Table 9 – F_L/F_F testing (1,090 points)

Date	Section	Min Required Flatness / Levelness	Achieved Flatness / Levelness
			As Placed Concrete:
Sep 17	West Wing-South	24 / 17	15.1 / 11.5
Sep 19	West Wing-North	24 / 17	17.1 / 14.9
	Overall Surface	**35 / 25**	**16.1 / 13.2**
			As Placed HPSLU:
Oct 14	West Wing-South	24 / 17	90.6 / 43.6
Oct 14	West Wing-North	24 / 17	97.6 / 44.2
Oct 14	**Overall Surface**	**35 / 25**	**94.1 / 43.9**

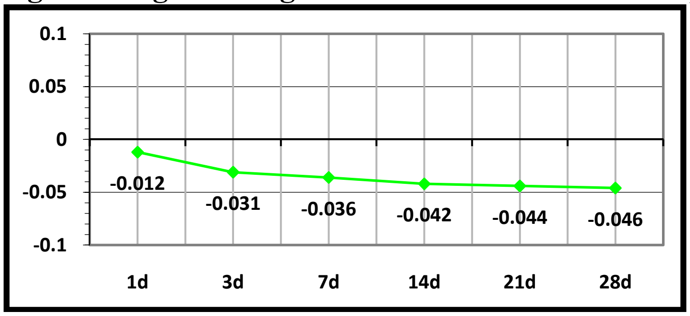
Table 10 – F_L/F_F testing (814 points)

Date	Section	Min Required Flatness / Levelness	Achieved Flatness / Levelness
			As Placed HPSLU (amended):
Oct 14	West Wing-South	24 / 17	89.4 / 42.0
Oct 14	West Wing-North	24 / 17	94.8 / 54.2
Oct 14	**Overall Surface**	**35 / 25**	**92.1 / 47.7**
			30-Day HPSLU:
Nov 16	West Wing-South	24 / 17	88.2 / 39.3
Nov 16	West Wing-North	24 / 17	85.0 / 54.9
Nov 16	**Overall Surface**	**35 / 25**	**86.6 / 46.2**

HPSLU Shrinkage and Expansion Testing

Shrinkage and expansion deformations of HPSLU start to develop as soon as the material is placed. The results shown from ASTM C157 shown in Fig 5, measures length change on a 1"x1"x11.25" prisms and specifies a demold time of 23.5 hours (± ½ hour). Therefore the HPSLU specimen is to a certain extent constrained, during a peak period of the length change profile which goes completely unmeasured. The C157 test in this study is modified in five ways: (1) Sampled in field with procedure outlined in Note 1 rather than mixed according to the mixing sequence of Practice C305. (2) The specimens were molded in one layer and not in 2 layers and tamped. (3) The specimens were demolded in 4 hours and initial readings were taken, instead of 23.5 hours. (4) Molded specimens were moved from the jobsite to the testing laboratory at the time of final set. (5) Only two specimens were molded due to handling, logistics and travel restrictions. C157 provides one window to the deformation of linear shrinkage and expansion, but other test methods are also useful for HPSLU.

Fig 5 – Length Change Test Results 1"x1"x11.25" prisms – ASTM C157M*



*Specimens were cast in the field on Oct-13, transported to 3rd party laboratory and demolded at 4 hours. Submerged prism was placed in a bath of plain water.

CONCRETE and HPSLU TENSILE BOND TESTS

The pull test results shown in Table 11 were obtained using portable hand-held equipment that is subject to some movement during core drilling. This may have impacted the results to a certain extent. In addition, the pour depth of the HPSLU made it difficult on several core drills to approximate core depth. The objective was to drill ½' into the concrete substrate. Current ASTM Committee activities may find that a greater depth may produce better results. This testing was limited due to its destructive nature and the cost to subsequently repair. It appears that more work is needed in the future to find the optimum methods to test these materials in the field.

Fig 6 – ASTM C1583 Schematic of Failure Modes

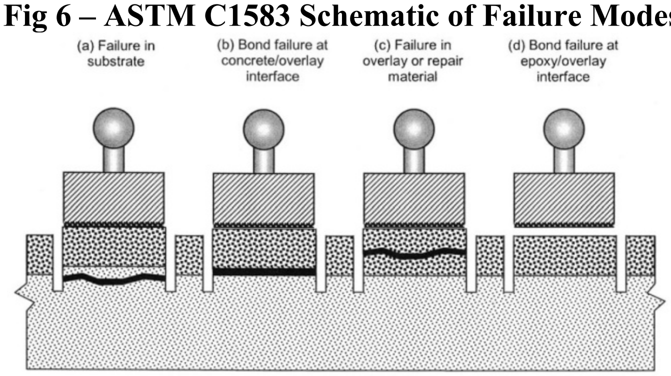


FIG. 3 Schematic of Failure Modes

Table 11 – Tensile Strength of Concrete Surface & Bond Strength of Overlay – ASTM C1583M*

Disk I.D.	Date Tested	Age (days)	Core/ Disk Size	Temp (°F)	RH	Failure Mode	Tensile Bond Strength PSI	Avg Flexural Strength PSI (MPa)
Conc-N1	10/9	24	50 mm	62°	80%	B	334	345 (2.4)
Conc-N2			50 mm			A	365	
Conc-N3			50 mm			B	341	
Conc-S1	10/9	22	50 mm	61°	82%	B	303	335 (2.3)
Conc-S2			50 mm			B	345	
Conc-S3			50 mm			B	353	

SCF-N1	10/22	9	50 mm	57°	55%	B	289	260 (1.8)
SCF-N2			50 mm			C	131	
SCF-N3			50 mm			A	362	
SCF-S1	10/22	9	50 mm	57°	55%	C	156	175 (1.2)
SCF-S2			50 mm			B	238	
SCF-S3			50 mm			C	128	
SCF-N1A	11/13	31	50 mm	45°	84%	C	200	175 (1.2)
SCF-N2A			50 mm			C	183	
SCF-N3A			50 mm			C	148	
SCF-N1B	11/13	31	50 mm	45°	84%	C	214	190 (1.3)
SCF-N2B			50 mm			C	158	
SCF-N3B			50 mm			C	196	
SCF-S1A	11/13	31	50 mm	45°	84%	C	253	270 (1.9)
SCF-S2A			50 mm			C	326	
SCF-S3A			50 mm			C	230	
SCF-S1B	11/13	31	50 mm	45°	84%	B	184	240 (1.7)
SCF-S2B			50 mm			C	312	
SCF-S3B			50 mm			C	221	

*Test were executed using a handheld SDS core drill without the aid of a surface mounted drill stand due to travel and equipment logistics, a DeFelsko Automatic PosiTest pull-testing instrument: set to 50 mm dollies @ 35 psi load rate.

Table 12 – HPSLU Tests on 10/13/2011

	Results	Time
Flow - 2" ring	11.25"	13:20
Flow - ASTM ring	137 mm	13:20
Material temp	69°F	14:30
Theoretical density	2.078	14:30
Set time: I/F	75/90 min	14:30
Floor temp	52.3° F	14:30
Ambient temp	66.0° F	14:30
Relative Humidity	41.9%	14:30
Powder temp	69.0° F	14:30
Water temp	63.0° F	09:55
Pump pressure (bar)	25 bar	15:35
Free water bleed	None	
Avg pour thickness	1"	

Table 14 – pH Tests (ASTM F710)

Extech-ExStik II	Location	Date	Time	Age	Results
Concrete surface	L4-North	10/11	17:14	24 d	12.0
Concrete surface	L4-South	10/11	17:30	26 d	12.1
HPSLU surface	L4-North	11/13	15:30	30 d	8.5
HPSLU surface	L4-South	11/13	15:00	30 d	8.4

CONCLUSION

The General Contractor and Swedish Hospital benefited in more ways than originally planned by using this construction method for their concrete floors. Placing concrete without finishing alone avoided rain-outs and accelerated the concrete placement schedule. Concrete production, placement and efficiency were increased, thus reducing labor cost & overtime. Eliminating the concrete finishing and the cost attributed to labor plus equipment mobilizations were enormous. Change orders and the resulting impacts to the construction schedule related to floor issues have been eliminated on the entire project. All trades worked from the same zero benchmark and off-site fabrication of headwall millwork was the standard. All of these factors led to the General Contractor reducing 30-days from their construction schedule.

Concrete characteristics are strongly dependent on design, environmental conditions, load history, etc., it is almost impossible to correlate the F_L & F_F from Division 3 to the point where a Division 9 flooring contractor would normally install a finished floor on a concrete slab of this size. The effect of changes in moisture content on the creep of concrete under a sustained load is also known as the Pickett effect[8]. That early work established that changes in moisture content do more than cause volume changes. ACI Committee 209 defines shrinkage after hardening of concrete, as the decrease with time of concrete volume[9]. Creep is the time-dependent increase of strain in hardened concrete subjected to sustained stress. As the concrete slabs shrink, the steel reinforcement imposes a tensile restraining force within the concrete. This gradually increases tensile force, acting at some eccentricity to the centroid of the concrete cross-section, producing a curvature and a gradual warping of the slab[10]. One hypothesis resulting from this study is that the bonded two-course slab construction method results in the eccentricity of the resultant tension being reduced in the concrete slab and consequently, so is the shrinkage curvature. Evidence is based on the extremely high F_L & F_F results and that the concrete slab has no visible cracking since the HPSLU was installed. The second hypothesis of this study is that the moisture vapor reduction system and HPSLU reduces the shrinkage curvature of a concrete slab by changing the drying gradient. The unique attribute of this study is that rarely does anyone have almost full access to a concrete slab of this size for this period of time to conduct F_L & F_F testing and observation without walls and flooring.

The low pH, low alkali formulation of this HPSLU offers an excellent surface for resilient flooring as shown in Table 14. The water-based adhesives used for today's flooring materials are subject to alkali attack, which in turn causes secondary emissions. This phenomenon actually caused the new South Shore School (Seattle) to be closed on April 16, 2010, with a report from the toxicologist that found the odor was caused by high pH and moisture content in the concrete flooring; which reacted with the carpet adhesive and carpet backing to produce the chemical methylhexanol[11]. The benefits of adhering the flooring to a low alkali leveling compound on top of concrete rather than adhering flooring directly to concrete are documented in studies conducted at a well-known Swedish University, The Lund Institute of Technology[12].

FUTURE WORK

Standards for SLU testing and practices are being developed in the U.S. SLU technology is one means of resolving the disparity that exists between concrete and floor covering specifications. Many standard practices already exist in Europe. ASTM Committee C09 has a Task Group under the jurisdiction of sub-committee C09-43, that is close to finishing new testing standards for self-leveling underlayments. ASTM Committee F06 on Resilient Floor Coverings has an initiative underway for installation guidelines of self-leveling underlayments under sub-committee F06.43-Practices. Also, the Materials & Methods Standards Association (MMSA) is creating similar standard testing procedures for the tile industry. In lieu of any current recognized industry standard for HPSLU and a high-volume delivery system such as the pump truck described here, the author respectfully submits this work to the members of ACI Committee 302 and other committees mentioned above for review so that industry standards being developed can be inclusive of this trend and method of concrete leveling plus the benefits it brings. A skeleton of the application guidelines already exist in the current ACI 302.1R-04 "Guide for Concrete Floor and Slab Construction". ACI 302.2R-06 "Guide for Concrete Slabs that Receive Moisture-Sensitive Flooring Materials" which references underlayments could also be expanded.

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