Final Report

PERFORMANCE EVALUATION OF GROUT MATERIALS FOR CONNECTING PRECAST CONCRETE BRIDGE DECK PANELS

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16. Abstract: The use of full-depth precast concrete panels for rehabilitation of bridge decks allows fast installation and all-weather construction. The panel joints that are connected later with grout materials may degrade prematurely, leading to a less desirable composite action. As a result, testing of various types of grout materials is essential to establish the quality and the serviceability of grouts for TDOT. A variety of 25 prepackaged commercial grout products from 16 manufacturers across US were collected and evaluated in this study. Most grouts showed good flowability, adequate early-age and high 28-day compressive strength, and acceptable bond strength. While these properties were essential for the closure pour, the high dry shrinkage and the slow setting would be the major concerns for these products. In addition, most grout products showed medium to low permeability and high freeze and thaw durability. The surface moisture of substrate had noticeable effects on the flexural bond capacity of grout products. However, there was no clear trend and different products showed different results. In comparison, the surface moisture of substrate had less effect on the slant shear bond capacity. The temperature change had great impacts on the flowability, time of setting, compressive strength development, and bond capacity. Increasing temperature generally reduced the flowability of fresh grout. High temperature typically accelerated the setting of fresh grouts and increased the compressive strength of grouts. In a rare case, the grout showed a reduced compressive strength. Conversely, an increase in temperature mostly reduced the flexural and the slant shear bond strength. Only a few products first showed an increased bond strength. Adding steel fibers into the fresh grout mostly reduced its flowability, but some grouts showed no changes in flowability after the fiber addition and some grouts showed a slightly increased flowability. For most grout products, the steel fiber addition had positive effects on the compressive strength particularly at late ages; however, some products showed a reduced compressive strength especially at the early age. For grout products with high bond strength, adding 3% steel fibers normally caused a reduced bond strength. For grout products with low bond strength, the steel fiber addition significantly improved the bond strength.

17. Key Words
Grout, Precast Concrete Deck Panel, Performance Evaluation, Flowability, Setting, Strength, Bond Strength, Shrinkage, Permeability, Freeze and Thaw Durability

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1.0 INTRODUCTION AND SCOPE OF RESEARCH

1.1 Introduction

The use of full-depth precast concrete panels for rehabilitation of bridge decks allows fast installation and all-weather construction. Typically, precast panels are prefabricated in a well-controlled environment resulting in strong and durable products. Undoubtedly, they will perform well under the traffic loading and weathering. However, the panel joints that are closed later with grout pour may degrade prematurely, leading to a less desirable composite action. Obviously, the lack of overall system performance causes concerns that limit the wider application of this innovative construction method.

Conventionally, cementitious grouts, epoxy mortars or polymer concretes are used for the closure pour. While cementitious grouts are easier to mix and more compatible with the substrate; they are more prone to shrinkage. As a result, deficient bonding may occur, particularly when longitudinal post-tensioning is not provided, causing leaking and rusting. Also, fracture and spalling may take place due to the insufficient resistance of materials to mechanical and environmental loads. Voids may form as a consequence of incomplete grout filling, entrapped air pockets, or excessive bleeding, leading to weakened bonding as well as reduced protection to steel. Oppositely, epoxy mortars or polymer concretes have extremely low permeability and dry shrinkage, as well as good adhesion with the substrate; but they are very sensitive to moisture variations and thermally incompatible with the substrate. More recently, advances in cementitious materials resulted in the development of Ultra-High Performance Concrete (UHPC). While this material has demonstrated exceptional performance when used for the closure pour; it requires special mixing to well disperse the particles and careful attention must be paid to the construction and curing practices to achieve enhanced mechanical and durability properties. As a result, testing of various types of grout materials under similar service conditions is essential to establish the quality and serviceability of materials. It is the intention of this project to evaluate the performance of different grouting materials and to provide TDOT professionals with realistic guidelines as to what materials allow for easy and fast construction while delivering a desirable overall system performance.

Additionally, the Accelerated Bridge Construction (ABC) process using precast concrete panels allows all-weather (e.g. hot/cold, sunny/rainy) installations, which minimizes weather incurred construction delays. However, very limited information is available regarding how various grout materials would perform under on-site weather conditions. Clearly, materials with high bonding capacity with a wet substrate are more preferred for rainy day construction. One objective of this project is to examine the changes of material's bonding capacity when the surface moisture of substrate varies. This research will also test how temperature variations affect the time of setting and flow behaviors of materials so that a suitable material can be chosen for construction under a specific weather condition.

1.2 Scope of Research

This project focused on evaluating the performance of various grout materials that could be potentially used for closure pour in the accelerated bridge construction. One special goal of this project was to identify the materials and proportions that were most suitable for applications in the state of Tennessee under local weather conditions. The main tasks of this project included:

Task 1-literature review, which summarized all the information related to the grout materials and their construction procedures; Task 2 - evaluate basic properties of various closure pour materials that were available in the market, especially those on the TDOT Qualified Product List. This included cementitious grouts/mortars, epoxy mortar/polymer concrete, and ultra-high performance concrete. Special attentions were paid on the flowability and filling capacity, shear and flexural bond capacity, as well as setting time and compressive strength development; Task 3 - evaluate effects of weather conditions on the performance of grout materials, particularly the effects of moisture conditions on the bonding capacity and temperature variations on flowability and bonding capacity of grout materials; and Task 4 - modify existing products and develop new grout materials. Steel fibers were introduced into cementitious grouts to enhance the crack resistance of these materials. New grout materials such as cementitious mortar and ultra-high performance concrete were developed using locally available materials to best fit the local moisture and temperature variations as well as to reduce the cost.

2.0 LITERATURE REVIEW

The precast concrete deck system has been successfully used in the bridge construction for past decades.[1-4] It has increasingly become a viable option for the bridge engineers as it accelerates the construction process, allows the rapid public access, and minimizes the construction accidents and delays. It also uses high quality precast elements, thus increasing the service life and lowering life-cycle cost.[5] One of the primary challenges is the connection between the precast components because an inadequate joint may result in poor load transfer and facilitate the intrusion of aggressive chemicals.[6] Typically, the joint is achieved by pouring various grout materials. As a result, the selection of closure pour materials plays a key role in achieving the monolithic behavior of precast panel system.

Limited information is available on the grout materials specified for the closure pour between the precast deck panels. Early documentation on the closure pour materials can be traced back to Mrinmay's work,[7] in which various grout materials were reported for applications in different precast bridge constructions after 1973. These materials mainly included the resin-based and cement-based mortars or concretes. The resin-based materials primarily comprised epoxy, latex, and polymer-based or modified mortar or concrete; while the cement-based materials consisted of Portland cement and calcium aluminate cement-based mortars and concretes.

The conventional Portland cement-based concrete remains the most widely used grout materials for the closure pour.[8] This is because it is easy to mix and place, readily available, relatively economical, and more compatible with the concrete panels; however, its main disadvantages include relatively slow setting, high dry shrinkage, and slow strength development especially at the early age.

The calcium aluminate cement-based materials have the advantage of rapid setting and strength gain as well as the enhanced resistance to high temperature, abrasion, and chemical attacks.[9-10] The main disadvantages are the high cost due to the restricted sources of raw materials and the meta-stable hydration product that would cause a decrease in the strength of mortars/concretes.

The epoxy grout generally consists of epoxy resin and aggregates. Upon mixing, the hardening of epoxy takes places, forming the paste that combines the aggregates. The main benefits of this material include fast setting and rapid strength development. It also exhibits extremely low permeability, excellent bonding capacity, and negligible dry shrinkage. However, the hardening of epoxy typically generates high heat at the early age and the epoxy paste is incompatible with the concrete panels due to its high thermal expansion/contraction and low modulus of elasticity, which may cause high risks of debonding or detachment under mechanical or environmental loading.[11-12]

Polymer-modified cementitious grouts are the combination of Portland cement, aggregate, and polymer resin. Upon mixing, the resin is dispersed or redispersed into water and then mixed with concrete. As cement reacts with water, hardening of polymers also takes place, forming a co-paste of cement hydration products and polymer films[13]. One of the great benefits of introducing polymers into concrete is the reduced permeability and the increased chemical resistance. Other advantages include higher strength, higher bonding capacity, and lower shrinkage as compared with the cement-based concrete[14]. The primary limitations of polymer-modified concrete are its relatively lower modulus of elasticity, entrapped air during mixing, and special requirements on the placing temperature.

Later, Gulyas et al.[15-17] investigated the application of conventional non-shrink grout and magnesium phosphate cement-based grout to the field-casting shear key connections between box beams. It was reported that the magnesium phosphate cement-based grout showed a better performance as compared with the non-shrink grout. The magnesium phosphate cement-based grout materials generally set quickly and gain strength very rapidly particularly at the early age.[18-19] This allows the fast construction and early opening of precast bridge system. However, a rapid or flash set material requires the use of small batches because only very limited time is available for mixing, placing and finishing. In particular, these materials exhibit negligible dry shrinkage, thus reducing potential shrinkage cracking. However, the rapid-set cement would typically liberate high heat at the early age, thus making them more susceptible to the early thermal cracking or detachment. In addition, the magnesium phosphate cement reacts with carbonate aggregates, which may cause poor bonding between the grout material and the precast panel due to the releasing of carbon dioxide gas.

In addition, Nottingham[20] reported that Portland cement-based mortars were applied to joint grouting in Alaskan bridges; however, shrinkage cracking was observed. Mailvaganam et. al.[21] investigated the use of expansive admixtures to compensate for the dry shrinkage and noted that possible shrinkage compensation can be achieved by adding adequate dosage of these admixtures. Also, Issa et. al.[22] studied in details the performance of four different types of commercial prepackaged grout materials including two magnesium phosphate cement-based grouts, one rapid set cementitious grout, and one polymer concrete. It was concluded that polymer concrete demonstrated best performance in shear, tensile, and flexural bond tests; while the magnesium phosphate cement-based materials performed relatively poorly in all bonding tests. The polymer concrete was impermeable, developed strength very fast, and exhibited negligible dry shrinkage; however, it was more expensive and difficult to mix and place. In contrast, the cement-based grouts were easy to handle and apply; but very high shrinkage was noted for the rapid-set cementitious grout.

More currently, the engineered cementitious composite (ECC)[23] and the ultra-high performance concrete (UHPC) were developed and their potential applications in connecting the precast concrete deck panels were studied.[24-27] It was reported that these materials exhibited good bond capacity. Specifically, ECC showed no leaking after 3 months in service[24] and desirable deflection hardening under loading. In contrast, UHPC allows the use of small joints with less reinforcements and longer durability[25] as well as low volumetric change[27].

Also, French et.al.[28] examined the early-age compressive strength development of four rapid-set prepackaged materials (referred as overnight cure materials, which were mainly magnesium phosphate cement-based mortars) and four special concrete mixes (referred as 7-day cure materials). Then, two materials from each category were chosen and undergone bonding and long-term durability tests including freeze/thaw, permeability, and dry shrinkage. A final performance criterion was developed based on the results of those tests. Similarly, Scott et. al.[29] studied the two types of grout materials (a proprietary grout and a conventional cement-based mix) for a composite connection between the grid and the full-depth precast concrete panels. It was reported that both the proprietary grout and the conventional cement-based grout exhibited good performance, but the latter provided potential cost savings. Lu et. al.[30] compared the use of conventional Portland cement-based concrete and a proprietary high early strength concrete for the closure strips in the accelerated bridge construction. It was found that the proprietary high early strength concrete did not have significant effect on the long-term structural performance of bridge.

In addition, the calcium sulfoaluminate (CSA) cement-based materials may be used as the closure pour grout. These materials typically have the characteristics of quick-set, rapid strength development, low shrinkage, and high durability[31]. They are receiving growing attentions in the fast track construction due to its desirable properties[32]. The primary limitation are the limited availability and high cost due to the lack of raw material (bauxite)[33-34]. CSA cement is essentially composed of belite (mainly dicalcium silicates or C_2S), tetracalcium trialuminate sulfate ($C_4A_3\bar{S}$), and gypsum[35]. The rapid early strength development and high dimensional stability are due to the fast hydration reaction of $C_4A_3\bar{S}$ at early age and the formation of expansive hydration product (i.e. ettringite) that compensates shrinkage.

3.0 MATERIALS, PROPORTIONS, AND EXPERIMENTAL PROGRAMS

3.1 Materials and Proportions

3.1.1 Commercial Grout Products

All grout materials that were commercially available and could be potentially used for joint connection (or closure pour), particularly those on the TDOT's Qualified Product List, were reviewed. The TDOT engineers and the investigators assessed and finalized the list of candidate materials for the laboratory evaluation. These materials were then requested from the manufacturers. A total of 25 grout products were received from 16 different manufacturers. All products were prepackaged in 50-60lbs bags or buckets. Table 3.1 summarizes the source, the brand name, and the characteristics of each grout product received in this study. As can be seen, 23 products were cementitious mortars/concretes and two products were epoxy-based mortars.

Each product was proportioned following the instruction in the material's data sheet. The materials were mixed in a 2.0 ft^3 rotating drum mixer or in a bucket using a paddle mixer with a typical batch size of 55 -70 lbs. The paddle mixer (DeWalt DW130) was used in this study when the conventional rotating drum mixer was unable to provide the uniform mixing. For example, some grout products displayed a significant amount of lumps after extended mixing with the rotating drum mixer. This did not occur when the paddle mixer was used possibly owing to more intensive mixing delivered by the drill. Water was first added to the mixer or bucket and then the grout material was introduced. An average water content recommended by the manufacturer was used, which typically resulted in a flowable mixture. The water added and the mixer used in this study are summarized in Table 3.2. All materials were mixed for approximately 2 minutes after water was added and the mixture was immediately transferred to the specimen preparation site for casting.

Table 3.1 Characteristics of 25 grout products received in this study

Manufacturer	Product Name	Characteristics
BASF Corporation 889 Valley Park Drive Shakopee, MN 55379	Masterflow 928	Hydraulic cement-based mineral-aggregate grout (High-precision, Non-metallic, and non-shrink)
Sika Corporation 201 Polito Ave Lyndhurst, NJ 07071	SikaGrout 328	High performance cementitious grout with extending working time (Non-shrink, precision)
	SikaGrout 212	High performance cementitious grout (Non-shrink with 2-stage shrinkage compensating mechanism, non-metallic)
Dayton Superior Corporation 1125 Byers Road Miamisburg, OH 45342	1107 Advantage Grout	Cementitious grout (Non-shrink, non-corrosive, non-metallic)
	Sure Grip High Performance Grout	High performance cementitious grout (Non-shrink, non-corrosive, non-metallic)
W. R. Meadows Inc. P.O. Box 338, Hampshire, IL 60140	SEALTIGHT 588-10K	Hydraulic-cement-based, Non-Shrink, Non-Ferrous, Mineral-Aggregate-Based Precision Grout
CTS Cement Manufacturing Corp. 11065 Knott Ave., Suite A Cypress, CA 90630	Rapid Set CEMENT ALL	High performance, High Strength, Rapid setting, Non Shrink Grout
Hilti, Inc. (U.S.) 10660 E 31st St. Tulsa, OK 74146	Epoxy Grout CB-G EG	Three component (Resin, hardener, aggregate), High performance grout
Simpson Strong-Tie Company Inc. 825 Armourdale Parkway, Kansas City, KS66105	FX-228	High-Strength Non-Shrink Precision Cementitious Grout (Non-metallic)
	FX-229	Non-metallic, Non-shrink Precision Cementitious Construction Grout
Ceratech 1500 N. Beauregard St. Suite 320 Alexandria, VA 22311	Pavemend DOTLine	Fiber-reinforced Rapid setting Cementitious materials-based concrete
	Pavemend SL	Rapid-set self-leveling, cementitious materials-based concrete
VEXCON Chemicals, Inc. 7240 State Road, Philadelphia, PA 19135	CERTI-VEX Grout 1000	High performance, Non-shrink, non-ferrous cementitious grout
The Quikrete Companies 3490 Piedmont Rd., NE, Suite 1300, Atlanta, GA 30305	Non-Shrink Precision Grout	High strength, non-metallic, Portland cement-based material with expansive additives
ChemMasters 300 Edwards Street, Madison, OH 44057	ConsetTM Grout	Non-shrink, non-metallic Cementitious Construction Grout
Ash Grove Packaging Group 10816 Executive Center Drive, Ste.100 Little Rock, AR 72211	No-shrink grout	High strength, non-shrink, non-metallic, Portland cement-based construction grout
KAUFMAN Products Inc. 3811 Curtis Ave., Baltimore, Maryland 21226	SureGrout	Non-shrinking, non-metallic precision cementitious grout
The Euclid Chemical Company 19218 Redwood Rd., Cleveland, OH 44110	E3-DP Epoxy Grout	High strength deep placement precision grout, Three components
	TAMMSGROUT SUPREME	Heavy duty, multi-flow, high early strength, non-shrink, non-staining, cement-based grout
	Euco Pre-cast Grout	High strength, non-shrink, non-metallic, hydraulic cement-based grout (non-staining, positive expansion)
	NC Grout	Non-corrosive, non-shrink, non-staining, cementitious grout with multi-flow characteristic
	NS Grout	Non-shrink, non-staining, non-metallic hydraulic cement-based grout
	Hi-Flow Grout	High strength, high flowability, shrinkage compensating, hydraulic cement-based grout
Phoscrete Corporation 7777 Glades Road, Suite 200, Beca Raton, FL 33434	Phoscrete Four-Seasons	MALP Concrete (Dry mix + Liquid activator)
	Phoscrete VO-Plus	MALP Concrete (Dry mix + Liquid activator)

Table 3.2 Mixing water and mixer used in this study for different grout products

Mix # and product name	Package	Water added, lb	Mixer used
#1 - BASF Masterflow 928	55 lb bag	9.0	Paddle
#2 - SikaGrout 328	50 lb bag	7.82	Rotating drum
#3 - SikaGrout 212	50 lb bag	8.86	Rotating drum
#4 - Dayton Superior 1107 Advantage Grout	50 lb bag	8.35	Rotating drum
#5 - Dayton Superior Sure Grip High Performance Grout	50 lb bag	7.78	Rotating drum
#6 - W.R Meadow SEALTIGHT 588-10K	50 lb bag	7.48	Rotating drum
#7 - CTS Rapid Set CEMENT ALL	55 lb bag	10.45	Paddle
#8 - Hilti Epoxy Grout CB-G EG	65 lb bucket	N/A	Paddle
#9 - Simpson StrongTie FX-228	55 lb bag	10.19	Rotating drum
#10 - Simpson StrongTie FX-229	55 lb bag	10.56	Paddle
#11 - CeraTech Pavemend DOTLine	53.5lb bag	4.17	Rotating drum
#12 - CeraTech Pavemend SL	51.8 lb bag	4.2	Paddle
#13 - VEXCON CERTI-VEX Grout #1000	50 lb bag	10.93	Rotating drum
#14 - Quikrete Non-Shrink Precision Grout	50 lb bag	9.94	Paddle
#15 - ChemMasters Conset™ Grout	50 lb bag	9.46	Paddle
#16 - Ash Grove No-shrink Grout	50 lb bag	10.43	Rotating drum
#17 - KAUFMAN Non-Shrinking Precision Grout	50 lb bag	8.29	Paddle
#18 - Euclid E3-DP Epoxy Grout	1.4 gal resin, 0.97 gal hardener, and 32 lb aggregate filler	N/A	Paddle
#19 - Euclid TAMMSGROUT SUPREME	55 lb bag	7.78	Rotating drum
#20 - Euclid Euco Pre-cast Grout	50 lb bag	8.19	Paddle
#21 - Euclid NC Grout	50 lb bag	8.35	Paddle
#22 - Euclid NS Grout	50 lb bag	8.35	Paddle
#23 - Euclid Hi-Flow Grout	50 lb bag	8.35	Paddle
#24 - Phoscrete Four-Seasons	50 lb bag and 9 lb Jug liquid activator	N/A	Paddle
#25 - Phoscrete VO-Plus	56 lb bag and 9 lb Jug liquid activator	N/A	Rotating drum

3.1.2 Cementitious Grout Materials Developed in This Study

The cement-based mortars and concretes were developed in this study with the goal of maximizing the use of local materials and saving the cost. The materials mainly consisted of cement, sand, water, and admixtures. Three types of cements were used: type III Portland cement, CTS rapid-set cement, and CTS DOT cement. The type III Portland cement was a high early strength cement manufactured by Buzzi Unicem USA; while the CTS rapid-set and DOT cements both were very high early strength cements manufactured by the CTS Cement Manufacturing Corporation. Besides the cement, silica fume was used in some mixtures as a supplementary cementitious material to improve the performance of materials.

Two types of natural sand that were locally available were used in this study (a normal river sand and a fine masonry sand). The normal river sand had the fineness modulus of 2.58, the specific gravity (SSD) of 2.68, and the absorption of 0.7%. For some mixtures, the normal river sand was sieved and the particles passing No. 30 sieve (600 µm) were used. The fine masonry sand was from Southland, TN with the fineness modulus of 1.82, the specific gravity (SSD) of 2.6, and the absorption of 0.66%. The sand gradation is shown in Figure 3.1. In addition, a crushed limestone with the nominal maximum size of 3/8", the specific gravity of 2.88, and the absorption of 0.88% was used for proportioning conventional concretes. Its gradation is also shown in Figure 3.1.

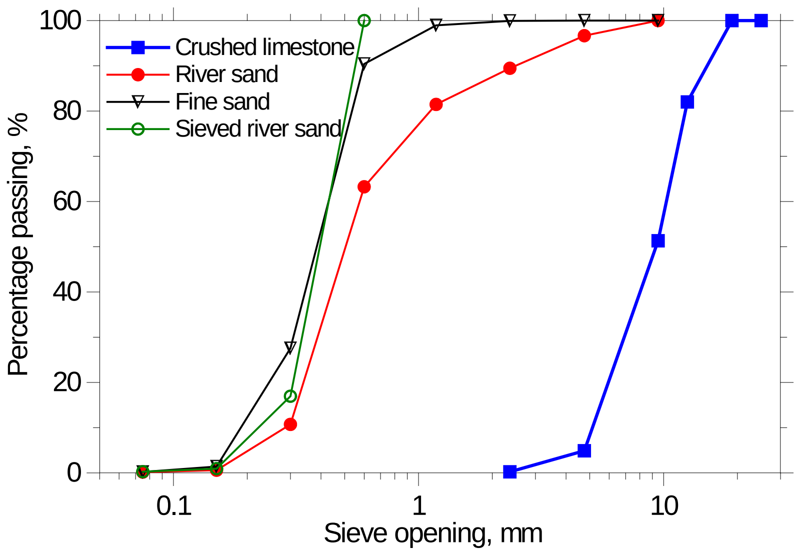


Figure 3.1 Gradation of aggregates used in this study

Additionally, a wide variety of chemical admixtures from different manufacturers (BASF, W.R. Grace, and Sika) were used in this study, which mainly included high-range water-reducing admixtures (i.e., superplasticizers) and accelerating admixtures. The high-range water-reducing admixtures consisted of BASF Glenium 7500, W.R. Grace Advacast 575, and Sika Viscocrete-2100. The accelerating admixtures included BASF AC534, W.R. Grace Polarset, Sika NC, and Sika Rapid-1. The main goal of adding these admixtures was to enhance the flowability and the early strength development of type III cement-based mortar or concrete. A total of 14 mixtures were designed and tested at three temperature levels (73°F, 85°F, and 95°F) using a small batch size (approximately 0.5 ft^3). The basic mixture proportion was type III Portland cement: sand: water =1: 0.3: 2. This proportion was finalized in this study based on the trial and error method. The detailed information on the type and dosage of chemical admixtures used in the these mixtures is provided in Table 3.3. After the small-batch testing, Advacast 575 and Polarset from W.R Grace were chosen for further big-batch testing; while an air-entraining admixture and a shrinkage-reducing admixture were used in some mixes to increase the long-term durability. In addition, a set-controlling and retarding admixture provided by CTS cement manufacture Inc.

was used in the CTS rapid-set cement-based mortars to stabilize the cement hydration and decelerate the setting.

Table 3.3 Types and dosages of superplasticizer and accelerator used for finalizing proportion of conventional mortars

Mix #	Superplasticizer		Accelerator		Temperature, °F
	Type	Dosage, fl oz/cwt	Type	Dosage, fl oz/cwt	
#26	BASF Glenium 7500	42	BASF AC534	100	73
#27	W.R. Grace Adva-Cast 575	13.3	W.R. Grace Polarset	100	73
#28	Sika Viscocrete 2100	8.2	Sika NC	45	73
#29	Sika Viscocrete 2100	9.0	Sika Rapid-1	48	73
#30	BASF Glenium 7500	42	BASF AC534	100	85
#31	W.R. Grace Adva-Cast 575	13.3	W.R. Grace Polarset	100	85
#32	Sika Viscocrete 2100	8.2	Sika NC	45	85
#33	Sika Viscocrete 2100	9.0	Sika Rapid-1	48	85
#34	BASF Glenium 7500	42	BASF AC534	100	95
#35	W.R. Grace Adva-Cast 575	13.3	W.R Grace Polarset	100	95
#36	Sika Viscocrete 2100	8.2	Sika NC	45	95
#37	Sika Viscocrete 2100	9.0	Sika Rapid-1	48	95

The Ultra High Performance Concrete (UHPC) was formulated in this study by optimizing the gradation of fine granular materials and using a very low water-to-cement ratio as well as a high dosage of silica fume, chemical admixtures, and steel fibers. A ground quartz flour was used in two mixes with the goal of further optimizing the combined gradation of particles. The largest particle in UHPC was sand primarily between 150 and 600 µm, followed by the cement with an average particle size of 15 µm. The next particle was the ground quartz flour (MIN-U-SIL-10) with a median diameter of 3.1 µm, which was provided by U.S. Silica Company. The smallest particle was silica fume with a mean particle size of 0.1 µm, which was incorporated to fill the interparticle voids between the cement and the quartz flour. The steel fiber was a straight wire fiber (Dramix OL 13/.20) provided by Bekaert Corporation with a nominal diameter of 0.2 mm (0.0079”) and a nominal length of 13 mm (0.5”). It was added to increase the toughness and the crack resistance. The materials and proportions of UHPC used in this study are summarized in Table 3.4.

Table 3.4 Materials and proportions used for finalizing UHPC

Mix	Type III cement	Silica fume	Water	Sand	Quartz powder	HRWR (W.R Grace Advacast 575)	Accelerator (W.R Grace Polarset)
#38 – sieved river sand	1.0	0.325	0.30	1.43	0	0.043	0.12
#39 – sieved river sand	1.0	0.325	0.25	1.43	0	0.043	0.12
#40 – sieved river sand	1.0	0.325	0.20	1.43	0	0.043	0.12
#41 – sieved river sand	1.0	0.325	0.20	1.43	0.30	0.043	0.12
#42 – natural river sand	1.0	0.325	0.30	1.43	0	0.043	0.12
#43 – natural river sand	1.0	0.325	0.30	1.43	0.136	0.043	0.12

#44 – fine masonry sand	1.0	0.325	0.30	1.43	0	0.043	0.12

Note: all proportions were by weight

A special mixing procedure was involved in this study for preparing UHPC. This was because UHPC contained extremely low water-to-cementitious materials ratio and very fine particles, which required very intensive mixing to disperse the particles. The well-dispersion of particles was essential to maximize the packing density and to reduce the water demand, which allowed UHPC to attain workability under a very low water-to-cement ratio. Consequently, a conventional rotating drum mixer was inappropriate for mixing UHPC due to the fact that it was unable to deliver sufficient energy into the mixture, leading to an unworkable mixture. In this study, a paddle mixer was employed to vigorously mix all materials. Initially, all dry granular materials (sand, cement, quartz flour, and silica fume) were pre-mixed in a container and water was pre-mixed with the High-Range Water-Reducer (HRWR) in a bucket. Half of the pre-mix was subsequently added into the bucket and mixed with the paddle for approximately 1 to 2 minutes. This typically resulted in a workable paste. The remaining pre-mix was gradually introduced into the bucket over a period of 2 minutes while the paddle kept running. Meanwhile, the accelerator was added alternately with the pre-mix. The mixing operation was continued after all pre-mix was added until a thick paste was attained (this approximately took 1 minute). Steel fibers were finally added and the mixing was continued for another minute to enable the even distribution of steel fibers.

After the small batch testing ($0.5ft^3$), some mixes that performed well were used for large scale testing with a big batch size ($3ft^3$). This included flexural bond test, slant shear bond test, rapid chloride penetrability test, dry shrinkage test, and freeze and thaw durability test. The materials and proportions for these mixes are summarized in Table 3.5.

Table 3.5 Materials and proportions for cementitious mortar and concrete developed in this study

Mix # and characteristics	Type III Cement	Silica Fume	Water	River sand	Accelerator (W.R Grace Polarset)	HRWR (W.R Grace Advacast 575)	AEA (W.R. Grace Darex)
#45 Normal mortar (natural river sand)	1	0	0.32	2	0.088	0.01	0
#46 Normal mortar (sieved river sand)	1	0	0.3	2	0.088	0.02	0
#47 Normal mortar (natural river sand) + AEA	1	0.08	0.32	2	0.088	0.02	0.0059
#48 High performance mortar	1	0.275	0.3	1.43	0.12	0.043	0
#49 High performance mortar +AEA+SRA*	1	0.275	0.3	1.43	0.12	0.043	0.0044
#50 High performance mortar (fine masonry sand)	1	0.275	0.3	1.43	0.12	0.043	0
#51 UHPC**	1	0.325	0.3	1.43	0.24	0.043	0
#52 Normal concrete + accelerator***	1	0	0.32	2	0.08	0.018	0.0053
#53 Normal concrete, no accelerator ***	1	0.08	0.37	2	0	0.019	0.0069
#54 CTS rapid-set cement mortar	1	0	0.4	2	0.0028 (CTS set control)	0.05 (BASF Glenium 7500)	0
#55 CTS DOT cement mortar	1	0	0.35	2	0.0036 (CTS set control)	0.067 (BASF Glenium 7500)	0

Note: All proportions were by weight; * the mix contained 0.026 Shrinkage Reducing Admixture (Sika Control 220); ** the mix contained 0.22 steel fiber and 0.15 quartz flour. *** the mixture contained 2 crushed limestone (3/8").

3.2 Experimental Programs

3.2.1 Flowability Test

A mini-slump test, similar to ASTM C1437[36] (without using the flow table and the 25 drops because most grouts had high flowability), was conducted in this study to assess the flowability of cementitious grout materials. The test used a mini-slump cone, having a top diameter of 2-¾ inches, a bottom diameter of 4 inches, and a height of 2 inches, to measure the spreading area of grouts. Before casting, the flow cone was dampened and placed on a smooth non-absorptive base. The fresh grout was then cast into the cone until it was full. Slight tamping was applied to avoid air entrapment and assure uniform filling. The top of the cone was flush finished with the sawing motion of a straightedge. After the area surrounding the cone was cleaned, the cone was lifted and the fresh grout began to flow and spread. After the grout stopped spreading, the diameter of spread was measured in two perpendicular directions and the average value was used for the data analysis. For each mixture, the mini-slump spread was measured at approximately 5 minutes after water was added (or 3 minutes after mixing), and then at 1 hour and 3 hours after mixing.

In addition, the flow cone method (ASTM C939-02[37]) was performed in this study on the cementitious grouts to evaluate their flowability. The flow cone test measures the flow time of a material (58.3 fl oz (1725 mL)) through a discharging tube of 0.5 inches (12.7 mm) in diameter. After mixing, the fresh grout was introduced into the moistened cone until the top surface of grout touched the point gage; while the outlet of the discharging tube was blocked with a finger. The finger was then removed to let the grout flow and a stop watch was started simultaneously to record the flow time. The watch was stopped when the first break of continuous flow occurred. The cone was then examined. If the light was visible through the discharge tube, which indicated that sufficient grout had passed, the test was valid and the time was recorded as the flow time of grout. Otherwise, the flow cone method was not applicable to this material.

3.2.2 Bleeding and Expansion

Bleeding and expansion of grouts were assessed following ASTM C940[38] under normal atmospheric conditions. Immediately after mixing, the fresh grout was introduced into a 1000 mL graduated plastic cylinder until the top level of grout reached approximately 800 mL mark. The initial volume of the sample was recorded and the top of cylinder was covered to avoid moisture loss. Then, the cylinder and the sample were placed on a leveled table that was free of vibration. The level of grout and the bleed water, if any, were monitored at a 15-minute interval for the first 1 hour and then at a 60-minute interval for 3 hours after the initial reading was taken.

3.2.3 Time of Setting

The pin penetration test (ASTM C403-06[39]) was used to evaluate the time of setting of cementitious grouts. The test measured the resistance of pin penetration into the grout. After mixing, the fresh grout was placed into a 6x6" cylindrical plastic container. The side of the container was then tamped slightly to help release the entrapped air voids. A pin of adequate size was selected and attached to the apparatus. A vertical force was gradually applied downward on the pin until it penetrated into the grout for approximately 1 inch. This operation was repeated at adequate time intervals (varying from 5 to 30 minutes in this study) until the final setting was reached. The penetration resistance was calculated by dividing the recorded force by the bearing area of the pin. The initial setting time was determined as the time at which the penetration resistance reached 500 psi; while the time when the penetration resistance approached 4000 psi was defined as the final setting time.

3.2.4 Compressive Strength Test

The compressive strength development of grout was evaluated following ASTM C942[40]. After mixing, the fresh grout was poured into 2" plastic cubic molds. Slight tamping was applied on the side of the mold with a finger for 5 times. For grouts with low flowability, the mold was filled with two layers and each layer was puddled five times with a finger. After filling, the surface of specimen was finished with a trowel. After finishing, the specimen was covered with a plastic sheet and initially cured at room temperature (73°F) for 24 hours. After the initial curing, the specimen was demolded and cured in the lime-saturated water at the same temperature as the initial curing until the time of testing. The unconfined compressive strength testing (ASTM C109[41]) was performed at 1 day, 7 days, and 28 days. Three specimens were tested at each age and the average value was used to represent the strength of the grout at that age. In addition, for grouts with very rapid setting and early strength development, three specimens were demolded and tested at approximately 6 hours to determine the compressive strength at the very early age.

3.2.5 Flexural bond test

During the passing of wheel loads, the deck is subjected to bending. Typically, the joint is located at or near the support, thus creating a negative moment or a tensile stress at the top of the joint. A composite action is required at the joint to provide satisfactory performance. To evaluate this composite action, a special beam specimen was prepared in this study to simulate the closure pour system. The mixture proportion for the substrate concrete was: cement: water: crushed limestone: natural sand = 1: 0.4: 2.43: 1.35. The cement was type I Portland cement manufactured by Holcim Inc. The crushed limestone was used as the coarse aggregate that had a nominal maximum size of 3/8" with the specific gravity of 2.7 and the absorption of 1.2%. The fine aggregate was the natural river sand that had the fineness modulus of 2.8, the specific gravity of 2.7, and the absorption of 1.0%. A water-reducing admixture (Glenium 7500) and an air-entraining admixture (Micro-air) both manufactured by BASF were used to achieve a slump of approximately 4 to 5 inches, a unit weight of 140 lbs/ft^3, and a fresh air content of approximately 6.5%. The 28-day compressive strength of this concrete using 4x8" cylindrical specimens was approximately 5600 psi.

After mixing, the fresh concrete was placed into a 6x6x21" plastic mold with a specially designed spacer positioned at each end of the mold, which helped to form an exposed surface of the key joint. The spacers were made of wood that was oil-saturated to avoid water absorption from fresh concrete during and after placement. The mold was filled with approximately two equal layers of fresh concrete and each layer was consolidated by external vibration for roughly 30 to 45 seconds. The specimen was then finished with a steel trowel, covered with plastic sheet, and stored at 73°F for 24 hours. After the initial curing, the specimen was demolded and cured in the lime-saturated water at 73°F for at least 28 days. After curing, the specimen was saw-cut from the middle section into two equal portions. The exposed surface of each portion was brushed, washed and cleaned, and pre-conditioned to the saturated surface dry condition (attained by removing the surface water film with wet cloth). Then, each portion of substrate was positioned at one end of the mold (6x6x21") with the exposed surface facing the center of the mold. This resulted in a key joint formed at the center of the mold with the top opening of approximately 1.5" and the bottom of about 1". After the substrate is adequately positioned, the fresh grout was immediately poured into the joint until it was slightly over-filled. For grouts with low flowability (typically less than 6" spread), the mold near the joint was slightly tapped with a mallet for approximately 5 times on each side to help achieve good contact between the fresh grout and the substrate concrete. After casting, the top surface of the joint was finished with a steel trowel and covered with plastic sheeting. Then, the composite specimen was stored in air at approximately 73°F for 24 hours, demolded, and subsequently cured in the lime-saturated water at 73°F until the time of testing.

The flexural bond test was conducted on the composite specimens following ASTM C78[42] and the test setup is shown in Figure 3.2[22]. The loading system used in this study was SATEC SYSTEMS Model 5500 supplied by INSTRON. Before loading, the composite specimen was slightly ground to remove any debris or roughness on the surface. The specimen was then centered on the support blocks with the top of the joint (1.5") facing up. A preload of approximately 100lbs was applied to achieve good contact between the load-applying blocks and the specimen. After the specimen was adequately setup, a continuous flexural load was applied at a rate of 1800lb/min until the specimen ruptured and the peak load was recorded by the testing system. The flexural bond strength (i.e. flexural strength or modulus of rupture) was calculated based on the following equation:

$$R = \frac{PL}{bd^2}$$

Where: R = flexural bond strength, psi; P = maximum applied load, lb; L = span length, inches (L=18 in this study); b = average width of specimen, inches (b=6 in this study); and d = average depth of specimen, inches (d=6 in this study). The failure section was examined and the failure patterns were recorded.

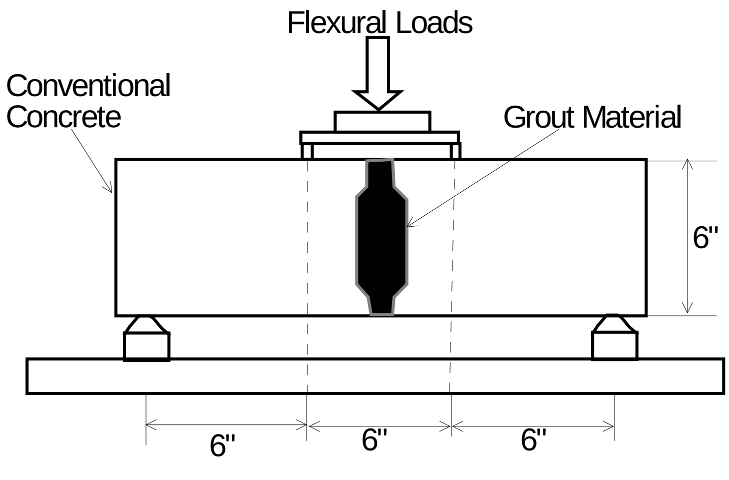


Figure 3.2 - Graphical view of flexural bond test setup

3.2.6 Slant shear bond test

The slant shear bond test was performed following the procedure similar to the one described in ASTM C882[43] to determine the slant shear bonding capacity of different grouts. The test setup is shown in Figure 3.3. A composite specimen, consisting of the conventional concrete substrate and the grout material, was prepared. The material and the proportion used for preparing the substrate was same as those used in the flexural bond test described above. After mixing, the fresh concrete was placed into a 4x8" cylindrical mold in approximately two equal layers and each layer was consolidated by external vibration for about 15 to 20 seconds. After casting, the specimen was finished with a steel trowel, capped, stored in air at 73°F. After the 24-hour initial curing, the specimen was demolded and cured in the lime-saturated water at 73°F for at least 28 days. Then, the specimen was saw-cut diagonally at an angle of 30º from the vertical plane into two equal sections. The bottom portion was used as the substrate concrete and its slant side was brushed with the wire and cleaned by the water spraying. After cleaning, the substrate was conditioned to saturated surface dry by removing the surface water film with wet cloth. Immediately after the SSD moisture surface was achieved, the substrate was positioned into the bottom of a 4x8" cylindrical mold with the slant side up and the fresh grout material was poured into the mold until it was full. The top of the composite specimen was finished with a trowel. For grouts with relatively low flowability, slightly tapping the side of the mold with a mallet for approximately 10 to 15 times was used to consolidate the specimen and to achieve better contact between the grout and the substrate. After finishing, the composite specimen was capped and initially cured in an environmental chamber with a temperature of 73ºF and relative humidity of 50% for 24 hours. It was then removed from the mold and cured in the lime-saturated water at the same temperature as the initial curing (73ºF) for 28 days or until the time of testing.

After curing, the unconfined compressive testing was followed based on the procedures described above in the compressive strength test section. A load control mode was employed with a loading rate of 35 psi/s. The peak load was recorded by the testing system and the failure plane was visually examined to assess the failure mode. The slant shear bond strength was calculated by dividing the peak load (lb.) by the slant surface area (25.13in^2 in this study). Two specimens were tested for each grout at each moisture and temperature condition and the average slant shear bond strength was used for the data analysis.

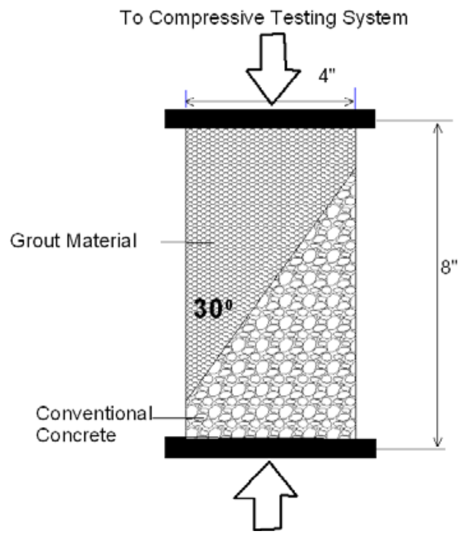


Figure 3.3- Illustration of slant shear bond test (Note: A 4x8"cylindrical mold for the slant shear bond test in lieu of the 3x6" mold specified by ASTM C882 because the concrete mixes were also involved in the test)

3.2.7 Free Dry Shrinkage Test

The free dry shrinkage of grout materials was examined following the procedures in ASTM C157[44]. The mortar (1x1x11 ¼") or concrete (3x3x11 ¼") prisms with a gage length of 10" were prepared using the molds similar to the ones described in ASTM C490[45]. After mixing, the fresh grout was poured into the molds and finished with a steel trowel. For less workable grout, consolidation was performed by rodding the fresh grout for approximately 25 times and then slightly tapping each side of the mold for approximately 10 to 15 times. The specimens were subsequently covered with plastic sheets and cured in air at approximately 73ºC for 24 hours. After the initial curing, the specimens were removed from the molds and their two opposite sides were sealed with duct tapes, thus allowing the dry to occur only from the top and the bottom of specimens. After the initial comparator reading was taken, each specimen was stored in an environmental chamber with the constant relative humidity of 50% and the constant temperature of 73ºF. For each specimen, the comparator reading was taken at 7 days and 28 days. The free dry shrinkage strain (i.e. the length change) at a specific age was calculated based on the equation provided in ASTM C157. For each material, 3 specimens were prepared and measured. The average value was used as the dry shrinkage of the material.

3.2.8 Rapid Chloride Permeability Test

The specimens were prepared using 4x8" single-use plastic molds. After mixing, the fresh grout was poured into the cylindrical mold until the mold was slightly overfilled. The specimen was consolidated by slightly tapping the outside of the mold with a mallet 10 to 15 times and finished with a steel trowel. For less workable grout, the mold was filled with approximately two equal layers. Besides tapping, rodding each layer 25 times was also performed to aide in compacting the specimen. The top of the mold was then sealed with a plastic cap and the mold together with the specimen were then transferred to the initial curing area with a constant temperature of 73ºF. After 24 hours initial curing, the specimen was demolded and then cured in the lime saturated water (73ºF) for 28 days. The specimen was taken out of the curing tank and a 2" slice was cut from the middle portion of each cylinder using the water cooled diamond saw. A total of 3 slices for each grout material were tested, using "PROOVE it" system manufactured by GERMANN INSTRUMENTS following ASTM C1202[46]. The total charge in Coulombs passed through each slice over a period of 6 hours was recorded. The average value of three slices was used to represent the permeability of each material.

3.2.9 Freeze and Thaw Test

The rapid freeze and thaw test was conducted in a chamber following the procedure described in ASTM C666[47]. After mixing, the fresh grout was placed into 3x4x16 in. metal forms, consolidated by tapping the side of the mold for approximately 10 to 15 times, and finished using a steel trowel. Again, for less workable grout, rodding and mallet tapping were used to compact the specimen. For each grout, two specimens were prepared. After finishing, the specimen was covered with plastic sheet and stored wet at the room temperature of 73ºF for 24 hours. The specimens were then de-molded and cured in the lime-saturated water at 73ºF for 14 days. After curing, each specimen was placed into a specimen holder. Water was added to the holder until the specimen was fully surrounded by 1/8" of water. The specimen together with the holder were positioned into the chamber and the test started. The weight of each specimen was measured and recorded regularly (at approximately 35 cycles) during the test. The Transverse Resonant Frequency of each specimen was also determined using the Impact Resonance Method. Before each measurement, the test was stopped to allow the specimen to thaw completely. The specimen was then moved out of the specimen holder and seated on a support to allow the free water on the surface to drain completely. Visual inspection was conducted on the specimen to note if there was cracking or severe deterioration. The durability factor (DF) and the weight loss as described in ASTM C666 were calculated. The specimen was defined as failure when the DF was below 60, or a substantial mass loss (more than 20%) was noticed, or the specimen became broken or crumbled during the measurement. The test for a specific specimen was stopped at 300 cycles or when the failure was noticed for that specimen.

4.0 RESULTS AND ANALYSIS

4.1 Flowability

A successful grout should be easy to mix and should have sufficient initial flowability to fill the gap. It should also be able to maintain this flowability until the entire length, particularly the hidden void, is filled. In this study, the flow time was measured. It was an indication of fluid viscosity, thus providing information on what may happen during mixing and placement. Shorter flow time indicated lower fluid viscosity, easy mixing and placing, and fast flowing. The flow time of 25 grout products was summarized in Table 4.1. It can be seen that some products, such as BASF Masterflow 928, SikaGrout 212, W.R Meadow SEALTIGHT 588-10K, CTS Rapid Set CEMENT ALL, Simpson StrongTie FX-229, NC grout, and NS grout, displayed relatively shorter flow time (less than 90 seconds). These materials were easier to mix, place, and rapidly flow to the site. Some products exhibited discontinuous flow or fully stopped flow during the test. These materials were more viscous and relatively more difficult to mix and place. It would take longer time for these materials to flow to the site under gravity. It should be noted that some products were dry after water was added. Obviously, these materials would have low workability at the recommended water content and the flow cone method was not applicable.

In addition, the mini slump of fresh grout was measured at approximately 5 minutes, 1 hour, and 3 hours after mixing. It described the ease of spreading of fresh grout, which was an indication of a grout material to advance into the cavities and hidden voids. While the spread measured immediately after mixing (5 minutes) indicated the initial filling capacity of a grout material; the measurement after 1 hour and 3 hours suggests the ability of a grout material to maintain its void-filling capacity. The mini slump test results are also given in Table 4.1. It can be seen that most products (15 out of 23 cementitious grouts) showed medium to high spread (7" or more when measured at 5 minutes), implying that they would have good void-filling capacity. 8 products displayed low to almost no spread (less than 6"). Undoubtedly, these products would have low flowability at the recommended water content and thus were not desirable for the closure pour.

It can also be seen that almost all products showed the reduced mini slump spread as the time elapsed. Some grout products, which had medium to high initial spread (>7"), displayed a rapid spread loss especially in the first hour after mixing. These products included BASF Masterflow 928, SikaGrout 328, SikaGrout 212, W.R Meadow SEALTIGHT 588-10K, CTS Rapid Set CEMENT ALL, Euclid TAMMS GROUT SUPREME, and Euclid NC Grout. The loss in workability with time was a normal phenomenon for all cementitious materials as a result of hydration reaction; however, a rapid spread loss was not desirable because it required rapid mixing, placing, and finishing. It was also not suitable for large volume placements. In contrast, some products had fairly slow spread loss with time. These products included Dayton Superior 1107 Advantage Grout, Dayton Superior Sure-Grip High Perofrmance Grout, Simpson StrongTie FX-229, Euclid Euco Pre-cast Grout, and Euclid Hi-Flow Grout. Interestingly, one product (Simpson StrongTie FX-229) even demonstrated a slight increase in spread during the first hour after mixing. Obviously, these materials had higher ability to maintain their flowability. They can be batched in a relatively large quantity and used where the construction required longer time.

It should be noted that for two epoxy grouts (Hilti Epoxy Grout CB-G EG and Euclid E3-DP Epoxy Grout), the flow time test and the mini slump test were not applicable and thus were not performed in this study. In addition, CeraTech Pavemend DOTLine (#11) was a concrete mix that contained 3/8" aggregate. The flow time test and the mini slump test were not applicable. Instead, the normal slump test (ASTM C 143[48]) was conducted in this study.

Table 4.1 Flow time and mini slump spread of grout products

Mix # and product name	Flow time (ASTM C939), s	Mini slump spread, inches		
		5 minutes	1 hour	3 hours
#1 - BASF Masterflow 928	66	8.75	5	set
#2 - SikaGrout 328	116	11.5	4.75	set
#3 - SikaGrout 212	82	10.75	6	4
#4 - Dayton Superior 1107 Advantage Grout	110	9.5	7.5	5
#5 - Dayton Superior Sure-Grip HP Grout	Stopped	12	10.75	8.25
#6 - W.R Meadow SEALTIGHT 588-10K	71	12.5	3.5	3.5
#7 - CTS Rapid Set CEMENT ALL	35	8.5	set	set
#8 - Hilti Epoxy Grout CB-G EG	N/A	N/A	N/A	N/A
#9 - Simpson StrongTie FX-228	150	10	6.5	4.25
#10 - Simpson StrongTie FX-229	49	8.5	9	7
#11 - CeraTech Pavemend DOTLine	N/A	3" slump*	set	set
#12 - CeraTech Pavemend SL	Dry mix	4	set	set
#13 - VEXCON CERTI-VEX Grout #1000	136	5.75	4	3.5
#14 - Quikrete Non-Shrink Precision Grout	150	7	set	set
#15 - ChemMasters Conset™ Grout	Stopped	4	3	set
#16 - Ash Grove No-shrink grout	Stopped	4	3.75	3.5
#17 - KAUFMAN Non-Shrinking Precision Grout	Stopped	3.75	3.5	3.25
#18 - Euclid E3-DP Epoxy Grout	N/A	N/A	N/A	N/A
#19 - Euclid TAMMS GROUT SUPREME	Stopped	10	4.5 (10 min)	set
#20 - Euclid Euco Pre-cast Grout	52	11	10	No material
#21 - Euclid NC Grout	87	7.5	3.5 (40 min)	set
#22 - Euclid NS Grout	77	10.5	7.5 (20 min)	3.75 (40 min)
#23 - Euclid Hi-Flow Grout	173	11.5	8.75	5.5
#24 - Phoscrete Four-Seasons	Dry mix	3.25	3	3
#25 - Phoscrete VO-Plus	Dry mix	Flash set	Flash set	Flash set

Note: * based on the slump test of concrete (ASTM C 143)

4.2 Bleeding and Expansion

The bleeding test results of 23 cementitious grout products are provided in Table 4.2. It can be seen that more than 78% of grout products (18 out of 23 cementitious grouts) did not have any bleeding in 3 hours after casting and four products showed slight bleeding (less than 1%). Only one product (Euclid Euco Precast Grout) exhibited comparatively high bleeding (4.8%) at the recommended water content for a flowable mixture. The excessive bleeding may be attributed to the inadequate aggregate gradation or the lack of fines in the mixture. Bleeding is a normal phenomenon of hydraulic cement-based materials. It describes the accumulation of water at the surface of freshly placed cementitious materials as a result of the settlement of solid particles and the simultaneous upward migration of water. Slight bleeding does not necessarily result in adverse effects on the closure pour, but it aided in controlling the plastic shrinkage cracking. However, excessive bleeding can lead to some performance problems such as the delay in finishing, and the reduction in the strength and durability of surface layer. In particular, as water migrates to the surface, evaporation will occur, causing the settlement of surface or the formation of voids. This may not be a big issue for the closure pour itself, however, it becomes a major concern for supporting members such as haunches where a complete fill is important to assure adequate load transfer. As a result, a desirable grout should have high resistance to bleeding. It is always preferred that a grout does not experience any volume reduction at any time.

The expansion of 23 cementitious grout products is also listed in Table 4.2. It can be seen that 9 products demonstrated zero expansion, implying that they had excellent volume stability during the first 3 hours after mixing. It can also be seen that 4 products showed negative expansion, meaning that the volume reduction took place in the fresh grout. Cautions should be taken when these products were applied for the closure pour where good bonding and load transfer were required. It was interesting to note that Dayton Superior Sure-Grip High Performance Grout did not show bleeding, but a significant volume reduction (-1.25%) occurred. This volume instability may be attributed to the entrapped air loss of fresh grout. Conversely, some products such as Simpson StrongTie FX-229 and KAUFMAN Non-Shrinking Precision Grout displayed bleeding, but no volume reduction was observed. This can be ascribed to the volume increase as a result of the use of expansive admixture that balanced the volume reduction.

Expansion of grout could occur in both fresh and hardened states as a result of using expansive or shrinkage-compensating admixtures. The expansion at the plastic state could offset the volume reduction due to bleeding of water and escape of entrapped air voids. The expansive admixture typically involves the gas release that increases the volume of fresh grout. For example, aluminum powder can react with the alkaline in cement and generates the hydrogen gas. However, after the hardening, the formation of gas is no longer able to produce expansion. Although expansion is not detrimental to the performance of fresh grout, excessive gas formation could negatively affect the long-term performance such as reduction in strength and durability. The shrinkage-compensating admixture may be used to create expansion that compensates for shrinkage in both fresh and hardened states. For instance, calcium sulfo-aluminate or lime-based materials when used together with Portland cement can create expansion that offsets the volume reduction due to the dry and autogenous shrinkage.

Table 4.2 Bleeding and expansion of grout products during early age (3 hours)

Mix # and product name	Bleeding at 3 hours, %	Expansion at 3 hours, %
#1 - BASF Masterflow 928	0	1.25
#2 - SikaGrout 328	0	0
#3 - SikaGrout 212	0.54	-0.125
#4 - Dayton Superior 1107 Advantage Grout	0	1.875
#5 - Dayton Superior Sure-Grip HP Grout	0	-1.25
#6 - W.R Meadow SEALTIGHT 588-10K	0	-0.625
#7 - CTS Rapid Set CEMENT ALL	Quick set	Quick set
#8 - Hilti Epoxy Grout CB-G EG	N/A	N/A
#9 - Simpson StrongTie FX-228	0	0
#10 - Simpson StrongTie FX-229	0.51	0
#11 - CeraTech Pavemend DOTLine	0	Dry mix
#12 - CeraTech Pavemend SL	0	Dry mix
#13 - VEXCON CERTI-VEX Grout #1000	0.125	0
#14 - Quikrete Non-Shrink Precision Grout	0	0
#15 - ChemMasters Conset™ Grout	0	0.625
#16 - Ash Grove No-shrink grout	0	Dry mix
#17 - KAUFMAN Non-Shrinking Precision Grout	0.44	0
#18 - Euclid E3-DP Epoxy Grout	N/A	N/A
#19 - Euclid TAMMSGROUT SUPREME	0	0
#20 - Euclid Euco Pre-cast Grout	4.8	-0.25
#21 - Euclid NC Grout	0	0
#22 - Euclid NS Grout	0	0
#23 - Euclid Hi-Flow Grout	0	0
#24 - Phoscrete Four-Seasons	0	Dry mix
#25 - Phoscrete VO-Plus	0	Dry mix

4.3 Time of Setting

Setting was used in this study to describe the change of grout from plastic to solid state, in which initial set described when the grout was unworkable; while final set indicated that the grout completely hardened and gained strength at a significant rate. As a result, adequate setting is essential to the success of closure pour. For example, relatively slow initial set is favored as it provides sufficient time for the grout materials to be mixed, transported, placed, and finished. However, once the placement is finished, fast final setting is desired since rapid hardening reduces the downtime and allows the rapid public access to the structure.

The time of setting of 23 cementitious grout products tested in this study is summarized in Table 4.3. As a comparison, Table 4.3 also listed the time of setting of each product provided in the material data sheet. Based on the setting criteria in conventional concrete, these products can be classified into normal-set, quick-set, flash-set, and slow-set. If a grout set in more than 180 minutes, it was categorized as slow-set. If a grout had an initial setting time of more than 45 minutes and a final setting time of 60 to 180 minutes after water was added, this grout can be generally characterized as normal-set. If a grout initially set in 10 to 45 minutes and finally set in 60 minutes after water addition, this grout can be classified as quick-set. If a grout set in less than 10 minutes, this grout was called flash-set. It can be seen that fourteen grouts exhibited an initial setting time of more than 60 minutes, indicating that they set slowly. In these products, nearly 50% showed more than 300 minutes of initial setting time. These products are not desirable for the fast-track construction under normal temperature because they may cause delay in public access. Three products displayed quick setting (less than 60 minutes of final setting time). These products should be chosen with cautions as there is limited time for the grout operation. Two products showed flash or very quick setting and were not applicable for closure pour as there was insufficient time for mixing, placing, and finishing. One product demonstrated quick initial setting, but slow final setting. This is an undesirable characteristic since it would require rapid mixing, placing and finishing, but also delay public access.

Table 4.3 Time of setting of grout products tested at normal temperature (73°F) in this study

Mix # and product name	Time of Setting, min.				
	Test results of this study			Results in product data sheet	
	Initial	Final	Classification	Initial	Final
#1 - BASF Masterflow 928	305	400	Slow	270	360
#2 - SikaGrout 328	300	460	Slow	>180	<720
#3 - SikaGrout 212	480	670	Slow	270 - 390	360 - 480
#4 - Dayton Superior 1107 Advantage Grout	540	570	Slow	Unavailable	Unavailable
#5 - Dayton Superior Sure-Grip HP Grout	300	780	Slow	Unavailable	Unavailable
#6 - W.R Meadow SEALTIGHT 588-10K	400	580	Slow	180	300
#7 - CTS Rapid Set CEMENT ALL	48.5	49	Quick	15	35
#8 - Hilti Epoxy Grout CB-G EG	N/A	N/A	N/A	N/A	N/A
#9 - Simpson StrongTie FX-228	770	860	Slow	240	Unavailable
#10 - Simpson StrongTie FX-229	205	500	Slow	120	Unavailable
#11 - CeraTech Pavemend DOTLine	22	27	Quick	20 - 25	30 - 40
#12 - CeraTech Pavemend SL	40	49	Quick	15 - 20	25 - 35
#13 - VEXCON CERTI-VEX Grout #1000	325	450	Slow	120	160
#14 - Quikrete Non-Shrink Precision Grout	90	180	Normal	25 (working time)	Unavailable
#15 - ChemMasters Conset™ Grout	280	366	Slow	132	210
#16 - Ash Grove No-shrink Grout	470	695	Slow	280	390
#17 - KAUFMAN Non-Shrinking Precision Grout	340	480	Slow	270	390
#18 - Euclid E3-DP Epoxy Grout	N/A	N/A	N/A	N/A	N/A
#19 - Euclid TAMMSGROUT SUPREME	39	470	Quick/Slow	27	37
#20 - Euclid Euco Pre-cast Grout	100	460	Slow	40	60
#21 - Euclid NC Grout	350	410	Slow	150 - 210	240 - 300
#22 - Euclid NS Grout	310	370	Slow	185	287
#23 - Euclid Hi-Flow Grout	360	480	Slow	230	290
#24 - Phoscrete Four-Seasons	12	13	Quick	13	13
#25 - Phoscrete VO-Plus	6.5	8.5	Flash	16	Unavailable

Figure 4.1 provides the evolution of penetration resistance with the elapsed time for all cementitious grout products in this study. The initial setting time was determined as the time at which the penetration resistance reached 500 psi; while the time when the penetration resistance approached 4000 psi was defined as the final setting time. It can be seen that some products (such as #4 Dayton Superior 1107 Advantage Grout, #9 Simpson StrongTie FX-228, #21 Euclid NC Grout, #22 Euclid NS Grout, and #23 Euclid Hi-flow Grout) showed a long dormant period, during which the penetration resistance was nearly zero. Once the initial set started, these materials would become fully hardened (final set) very quickly (in approximately 30 minutes). This characteristic is preferred because a long sleep period would provide sufficient time for the material to be transported and placed; while a rapid hardening process after the sleep period would enable the rapid strength gain and early public access. In contrast, some products exhibited a relatively gradual increase in the penetration resistance over time, particularly a rapid increase before initial setting and a relatively slow increase after initial setting such as #19 Euclid TAMMSGROUT Supreme. This is disadvantageous because it may not only cause rapid flowability/workability loss at the very beginning, but also result in a relatively slow strength gain after the placement.

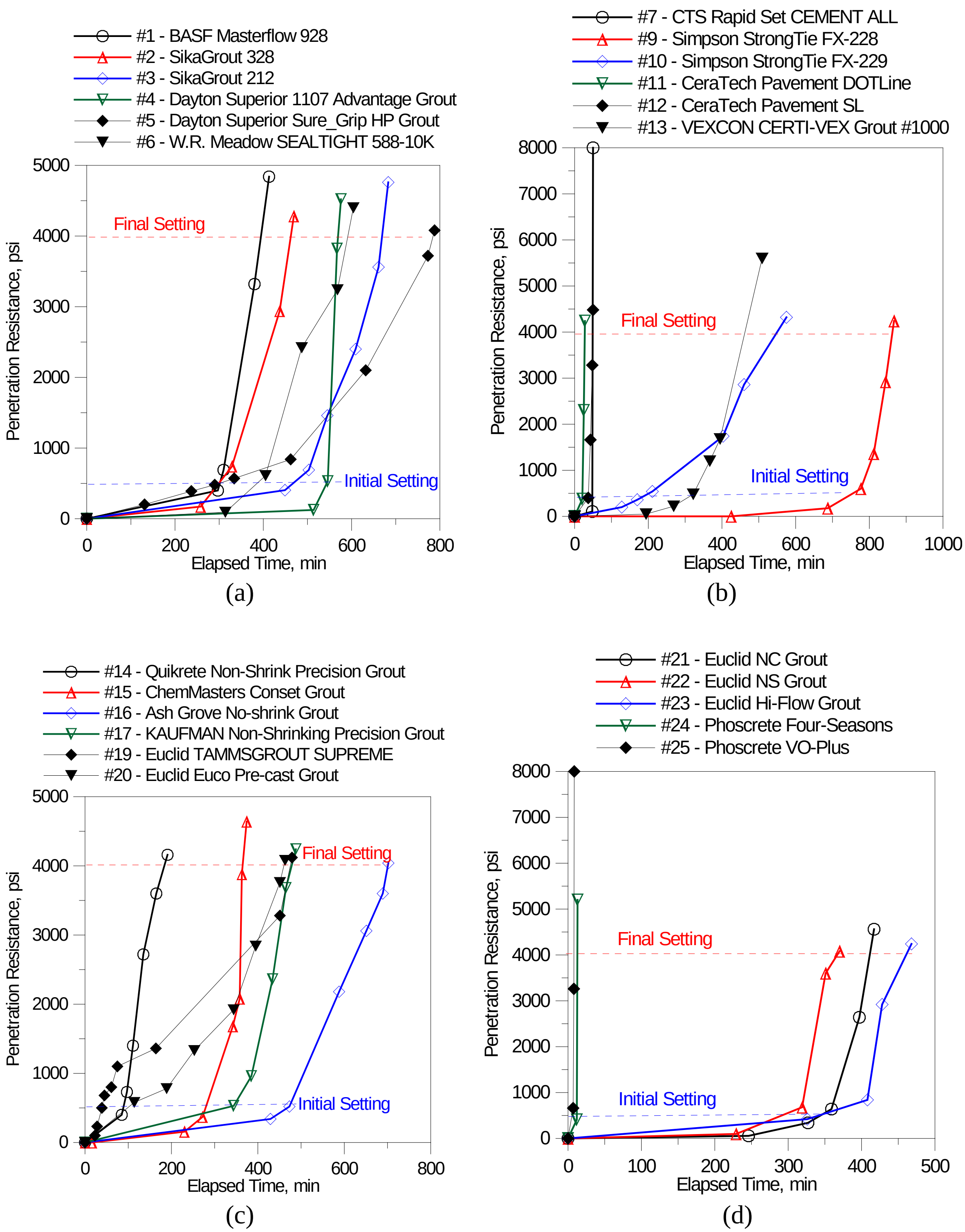


Figure 4.1 Penetration resistance vs. elapsed time for determining time of setting of cementitious grout products

4.4 Compressive Strength Development

The rapid strength development is always beneficial for transportation structures as it reduces the traffic disruption. This is particularly important for the accelerated bridge construction. A successful grout should have high early strength gain as well as adequate long-term strength because in service, the closure pour should continue to carry the wheel loads as well as to provide the load transfer between the panels. An early age (1-day) compressive strength of 1000 psi, 3-days compressive strength of 2500psi, 7-days compressive strength of 3500 psi, and 28-days compressive strength of 5000 psi are required for cement-based grouts based on the ASTM C1107[49] and PTI M55.1-12[50].

The unconfined compressive strength of different grout products at the age of 1 day, 7 days, and 28 days is summarized in Table 4.4. It can be seen that most products met the requirements specified in ASTM C1107 and PTI M55.1-12. Only two products (#10 and #13) did not meet the criteria. Simpson StrongTie FX-229 (#10) exhibited lower compressive strength at 1 and 7 days; while Vexcon Certi-Vex Grout #1000 (#13) displayed lower compressive strength at 7 and 28 days.

In addition, the National Cooperative Highway Research Program (NCHRP) of Transportation Research Board (TBR) proposed the performance criteria for cast-in-place concrete connections for precast concrete bridges, in which an overnight-cure material was required to have 6000 psi at 8 hours; while a compressive strength of 6000 psi at 7 days was needed for 7-day cure materials[28]. It can be noted that 10 cementitious grouts were 7-day-cure materials based on the NCHRP criteria. One cement-based product (#7) and 2 epoxy grouts (#8 and #18) met the criteria for overnight-cure materials. Twelve products demonstrated a compressive strength of less than 6000 psi at 7 days. As a result, nearly 50% of grouts tested in this study did not meet the criteria proposed by NCHRP.

Table 4.4 also lists the compressive strength of grout products at various ages in the product data sheet provided by the material supplier or manufacturer. Significant differences could be noted between the two results. For some products such as #6, #10, #16, #17, and #19, the compressive strength provided by the material supplier was considerably higher; while some products (for instances, #2 and #4) demonstrated higher compressive strength when tested in this study. This discrepancy may be caused by many factors such as material variations due to poor quality control as well as different specimen preparation practices such as specimen sizes, consolidation methods, and curing.

Table 4.4 Compressive strength of grout products at different ages

Mix # and product name	Unconfined Compressive Strength, psi					
	Test results in this study			Results in product data sheet		
	1 day	7 day	28 day	1 day	7 day	28 day
#1 - BASF Masterflow 928	4084	6375	8503	4000	6700	8000
#2 - SikaGrout 328	5730	8938	10345	4000	6200	8000
#3 - SikaGrout 212	1430	4944	7636	2700	5500	5800
#4 - Dayton Superior 1107 Advantage Grout	3093	6922	9004	2500	6000	8000
#5 - Dayton Superior Sure-Grip HP Grout	1998	8135	11040	3500	6500	8500
#6 - W.R Meadow SEALTIGHT 588-10K	2308	5032	6213	4500	6500	9200
#7 - CTS Rapid Set CEMENT ALL	8717	—	10921	6000	7000	9000
#8 - Hilti Epoxy Grout CB-G EG	10347	13411	16120	12500	15000	—
#9 - Simpson StrongTie FX-228	—	6331	7155	4000	8000	—
#10 - Simpson StrongTie FX-229	951	2984	5668	3500	5500	7000
#11 - CeraTech Pavemend DOTLine	4327	5730	9757	>5000	>7000	>9000
#12 - CeraTech Pavemend SL	3246	4115	7341	>5000	>6000	>7000
#13 - VEXCON CERTI-VEX Grout #1000	1286	2452	3443	4025*	7700*	10250*
#14 - Quikrete Non-Shrink Precision Grout	3827	7889	10415	3000	9500	12500
#15 - ChemMasters Conset™ Grout	—	5115	6849	2590	5260	6870
#16 - Ash Grove No-shrink grout	1006	4016	6829	3400	7800	9000
#17 - KAUFMAN Non-Shrinking Precision Grout	1801	4570	6353	4200	7400	8000
#18 - Euclid E3-DP Epoxy Grout	8739	12087	12740	11050	14100	15500
#19 - Euclid TAMMSGROUT SUPREME	3835	6572	8569	6510	9688	11510
#20 - Euclid Euco Pre-cast Grout	1389	3929	7028	4000	6800	8000
#21 - Euclid NC Grout	1519	4506	7481	4000 (3d)	6000	7500
#22 - Euclid NS Grout	3889	6467	8950	4500 (3d)	6000	8500
#23 - Euclid Hi-Flow Grout	2922	5913	9574	3000	5000	8500
#24 - Phoscrete Four-Seasons	5196	6059	8512	6034 (1hr)	—	—
#25 - Phoscrete VO-Plus	6770	6656	7033	6120 (1hr)	—	—

Note: *Only dry pack mix at low water content was available

The compressive strength development with time for the 25 grout products is also illustrated in Figure 4.2. It can be seen that most products gained strength at a relatively faster rate during the first 7 days and then the strength gain became relatively slow over time with only one exception (#25), in which the material showed very rapid strength development during the very early age; however, no significant strength gain was observed after 24 hours. It can also be seen that the epoxy grouts (#8 and #18) displayed the highest compressive strength development in this study.

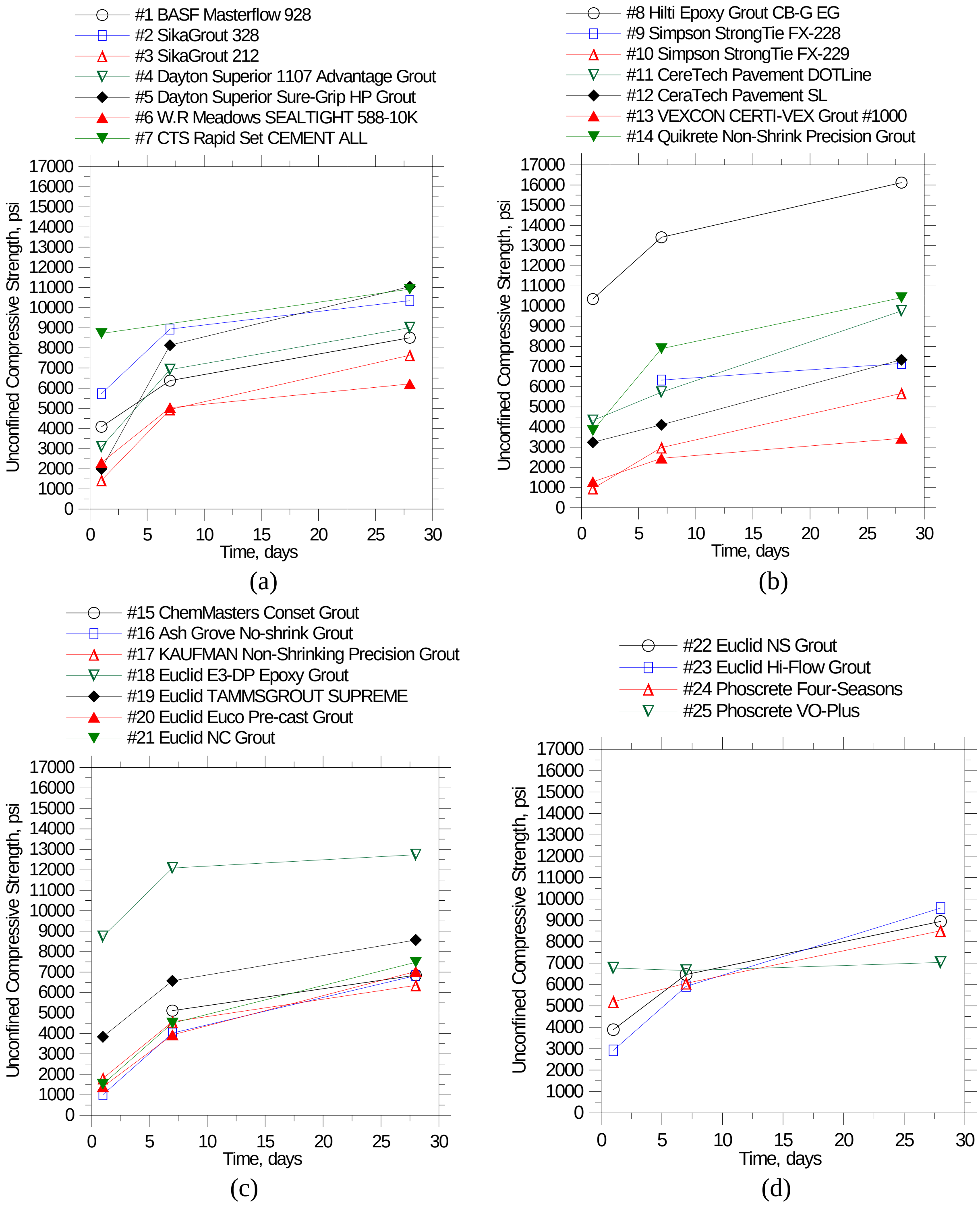


Figure 4.2 Compressive strength development with time for 25 grout products

4.5 Flexural Bond Strength and Failure Mode

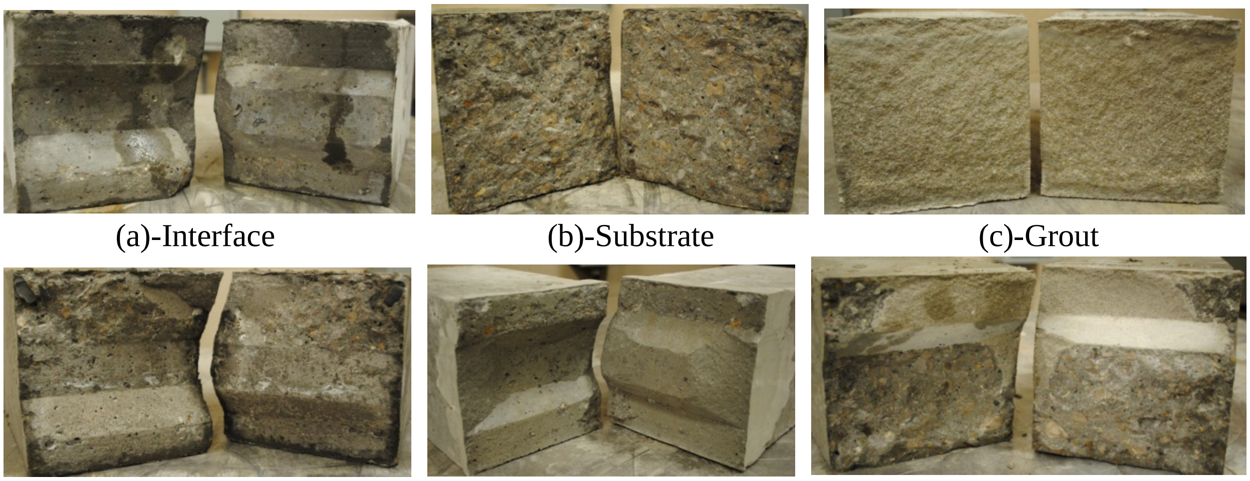
When vehicles pass across the transverse closure pour, vertical shear would develop at the interface. Tensile stresses may also be generated as a result of temperature and moisture variations. When the stresses exceed the bonding strength, debonding would occur, causing reduced load transfer between the adjacent panels. This is particularly troublesome when the post-tensioning is not applied in the longitudinal direction to help tighten the joints. As a result, strong adhesion to the deck panel is essential for the grout materials to achieve a monolithic behavior. Many factors may influence the bond capacity such as surface soundness, roughness, cleanness and moisture conditions, as well as the intimate contact and penetrability of grouts. Presently, there is no generally accepted criterion that specify the minimum bond strength requirement for grout materials. However, the NCHRP[28] proposed a minimum bond strength of 300 psi for closure pour materials for adequate performance based on a slant shear test (modified ASTM C882[43]); while the Virginia Department of Transportation specified a bond strength of at least 1000psi for acceptance[51].

The bond capacity of 25 grout products was evaluated through the flexural bond test and the slant shear bond test. The results are summarized in Table 4.5. It can be seen that the flexural bond strength of composite specimens varied widely, changing from 0 to 833psi with an average value of 422.5psi. Various failure modes were also observed as shown in Figure 4.3. In general, adequate flexural bonding was achieved when the failure took place away from the interface or the failure occurred at the interface, but at a high stress level. In this study, the quality of flexural bond was arbitrarily classified into high, medium, low, and very low based on the peak flexural stress level (i.e., the flexural bond strength) and the failure mode of composite specimens. High quality of flexural bond was defined when the flexural bond strength was 600psi or above; while medium quality referred to a peak stress level between 300psi and 600psi. When the flexural bond strength was between 100psi and 300psi, particularly when the failure plane was along the interface, the quality of flexural bond was categorized as low. When the flexural bond strength was below 100psi, the composite specimens typically failed along the interface and the quality of bond was characterized as very low.

Table 4.5 Flexural and slant shear bond strength and failure plane of 25 grout products

Mix # and product name	Flexural			Slant shear		
	Bond strength (SSD), psi	Failure plane	Quality of bond	Bond strength (SSD), psi	Failure plane	Quality of bond
#1 - BASF Masterflow 928	600	I+S	High	2765	S	High
#2 - SikaGrout 328	833	S	High	3235	S	High
#3 - SikaGrout 212	750	G+S+I	High	2937.5	I+G+S	High
#4 - Dayton Superior 1107 Advantage Grout	650	I	High	1512.5	I	Medium
#5 - Dayton Superior Sure-Grip HP Grout	667	S	High	3770	I+G+S	High
#6 - W.R Meadow SEALTIGHT 588-10K	560	G	Medium	3227.5	G+S	High
#7 - CTS Rapid Set CEMENT ALL	258	G+I	Low	1450	G+I	Medium
#8 - Hilti Epoxy Grout CB-G EG	379	I	Medium	1000	I+G	Medium
#9 - Simpson StrongTie FX-228	529	G	Medium	2705	S	High
#10 - Simpson StrongTie FX-229	600	G	High	2880	I+G	High
#11 - CeraTech Pavemend DOTLine	396	G	Medium	3025	S	High
#12 - CeraTech Pavemend SL	308	G	Medium	2922.5	S	High
#13 - VEXCON CERTI-VEX Grout #1000	92	I	Very low	1425	I+G	Medium
#14 - Quikrete Non-Shrink Precision Grout	333	I	Medium	2335	I+S	High
#15 - ChemMasters Conset™ Grout	425	G	Medium	2557.5	G+S	High
#16 - Ash Grove No-shrink grout	708	S+I	High	2877.5	I+S	High
#17 - KAUFMAN Non-Shrinking Precision Grout	633	I+G	High	2337.5	I+S	High
#18 - Euclid E^3-DP Epoxy Grout	363	I+S	Medium	1682.5	I+S	Medium
#19 - Euclid TAMMSGROUT SUPREME	267	G+S	Low	2895	I+S+G	High
#20 - Euclid Euco Pre-cast Grout	317	I	Medium	2800	I+G	High
#21 - Euclid NC Grout	417	I	Medium	2547.5	I	High
#22 - Euclid NS Grout	218	I	Low	3017.5	I+G+S	High
#23 - Euclid Hi-Flow Grout	142	I	Low	3375	I+G+S	High
#24 - Phoscrete Four-Seasons	117	I	Low	580	I	Low
#25 - Phoscrete VO-Plus	0	I	Very low	342.5	I	Low

Note: **Failure plane:** I –failure plane along interface; S – failure plane at substrate concrete; G – failure plane at grout materials. **Flexural bond strength:** High – flexural bond strength greater than 600psi; Medium – flexural bond strength between 300psi and 600psi; Low – flexural bond strength between 100psi and 300psi; Very low- flexural bond strength less than 100psi. **Slant shear bond strength:** High – slant shear bond strength greater than 2000psi; Medium – slant shear bond strength between1000 and 2000psi, low – slant shear bond strength between 300psi and 1000psi, Very low- slant shear bond strength less than 300psi



(a)-Interface (b)-Substrate (c)-Grout

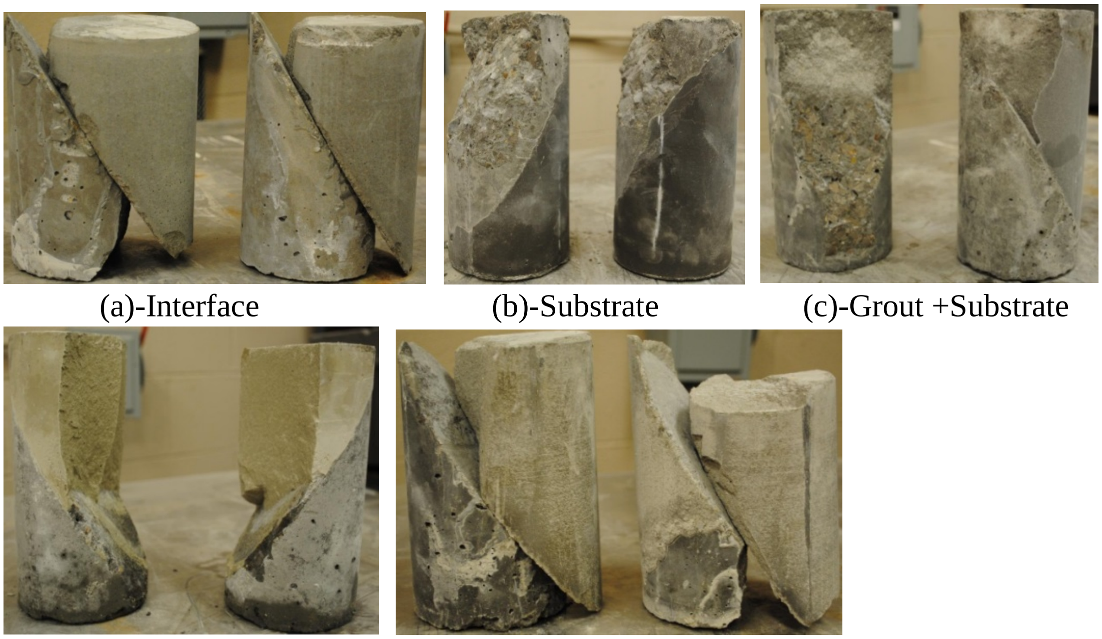
(d) Interface + Substrate (e) Interface + Grout (f) Interface +Substrate +Grout

Figure 4.3 Typical failure modes of composite specimens during flexural bond test

It can be seen that most products (approximately 72%) exhibited medium to high flexural bond strength. Obviously, these products would perform well under normal bending conditions as debonding was less likely to occur. Conversely, some materials (20%) displayed low quality of flexural bond. When in service, these materials would be susceptible to debonding. This low bonding capacity may be partially due to the lack of flowability and penetrability of grout because the fresh grout was dry and quick-setting (e.g., CTS Rapid Set CEMENT ALL and Euclid TAMMSGROUT SUPREME). In particular, two products (8%) demonstrated very low flexural bond strength. This was because the Phoscrete VO-Plus was very dry and set extremely fast (flash set), which resulted in poor contact and deficient interlock at the interface; while VEXCON CERTI-VEX Grout #1000 itself was a low strength material with an average 28-day compressive strength of 3443 psi, leading to a low flexural bond strength.

4.6 Slant Shear Bond Strength and Failure Mode

The grout products also displayed a wide variety of slant shear bond capacity. It can be seen from Table 4.5 that the slant shear bond strength changed from 342.5psi to 3770psi with an average value of 2408psi. Again, different failure modes were observed as illustrated in Figure 4.4. The quality of slant shear bond was subjectively grouped into high, medium, low, and very low in this study based on the slant shear bond strength and the failure mode. If the slant shear bond strength was high (>2000 psi), the quality of slant shear bond was classified as "high". This was due to the fact that whatever the failure mode was, the high bond strength would assure good bonding performance. A medium quality of bond was defined as the one that exhibited the slant shear bond strength of 1000 to 2000psi. The performance of these materials was fairly satisfactory based on both the NCHRP[28] or VDOT[24] criteria. A low quality of bond was defined when the slant shear bond strength was between 300psi and 1000psi especially when the failure occurred along the interface. The performance of these materials would be unacceptable when the VDOT criterion was considered; however, it was still acceptable based on the NCHRP criterion. It can be noted that no materials displayed very low slant shear bond strength (less than 300psi), indicating that all materials met the bonding requirement recommended by NCHRP.



(a)-Interface (b)-Substrate (c)-Grout +Substrate

(d)-Grout +Interface (e)-Interface +Substrate +Grout

Figure 4.4 Typical failure modes of composite specimens during slant shear bond test

It is interesting to note that for most products (approximately 80%), the failure planes or modes of flexural bond specimens were similar to those of slant shear bond specimens. However, it can also be noted that the flexural bond specimens were more susceptible to fail at the interface; while a combined failure mode (interface plus grout or substrate) was more likely to occur during the slant shear bond test.

4.7 Dry Shrinkage

The dry shrinkage would take place in the closure pour when exposed to a dry environment as a result of moisture loss from the cementitious grouts. This typically happens at the early age before the deck is overlaid. When the shrinkage movement is restrained, tensile stress may develop in the grout material. When the stress exceeds the bond strength, debonding will occur. The overstress may also cause cracking when it exceeds the tensile strength of grout. As a result, a non-shrink grout is advantageous in the closure pour. Very often, a non-shrink grout contains an expansive admixture. When hydrated, it creates a slight expansion that helps to compensate for the dry shrinkage.

The free dry shrinkage of 19 cementitious products measured at 7 days and 28 days after casting is provided in Table 4.6. The free dry shrinkage was classified into three groups (high, medium, and low) based on the criteria that were commonly accepted in conventional concrete[52]. If the free dry shrinkage at 28 days was more than 0.1%, it was defined as high. Between 0.05% and 0.1% was considered as medium; while less than 0.05% was classified as low. It can be seen that out of 19 cementitious grouts measured in this study, 12 products (approximately 63%) had high free dry shrinkage. Consequently, these products were more susceptible to debond or develop shrinkage cracking as compared with the conventional concrete. Only 3 products (nearly 16%) demonstrated low free dry shrinkage. These products would have better shrinkage performance as compared with the conventional concrete.

In addition, Tepke and Tikalsky developed a guide for performance-based concrete design, in which the high performance concrete can be classified into three grades based upon the free dry shrinkage at 56 days following ASTM C157[53]. Grade 1 referred to a group that showed the free dry shrinkage of 600 με (i.e. 0.06%) or less; while the free dry shrinkage of 400 με (0.04%) or less was classified as grade 2, and the free dry shrinkage of 200 με (0.02%) or less was categorized as grade 3. Obviously, most grout products (approximately 84%) were far beyond the specified limit (0.06%) and thus did not meet this specification. Only three products may satisfy the requirements assuming that the free dry shrinkage of these products did not change significantly from 28 days to 56 days. For examples, CTS Rapid Set CEMENT ALL can be classified as grade 2, and CeraTech Pavemend DOTLine and CeraTech Pavemend SL as grade 1.

It became evident that most grout products collected in this study exhibited excessively high dry shrinkage. This can be primarily attributed to the excessive cementitious materials used in these products. This unnecessarily high content of cementitious materials would possibly aide in the flow behavior and strength development, but would adversely increase the dry shrinkage due to the fact that the dry shrinkage only occurred in the paste.

It should be noted that for the two epoxy grouts, the dry shrinkage was negligible and thus not measured in this study. Some products such as Phoscrete Four-Seasons and VO-Plus exhibited extremely fast setting (flash-set), there was insufficient time to adequately prepare the shrinkage specimens. Consequently, the free dry shrinkage of these products could not be measured in this study. In addition, some products such as Kaufman Non-shrinking Precision grout and Vexcon Certi-Vex Grout #1000 were very dry and difficult to consolidate, causing poor bonding between the steel studs and the prism. The loose steel studs made it impossible to accurately measure the length change of the shrinkage specimen. As a result, the dry shrinkage of these products was not measured in this study.

Table 4.6. Free dry shrinkage of 19 cementitious grout products at 7 and 28 days

Mix # and product name	Free dry shrinkage (ASTM C157)		
	7 days, %	28 days, %	Classification
#1 - BASF Masterflow 928	0.088	0.153	High
#2 - SikaGrout 328	0.0755	0.12	High
#3 - SikaGrout 212	0.0695	0.1185	High
#4 - Dayton Superior 1107 Advantage Grout	0.091	0.1425	High
#5 - Dayton Superior Sure-Grip HP Grout	0.0635	0.102	High
#6 - W.R Meadow SEALTIGHT 588-10K	0.0845	0.134	High
#7 - CTS Rapid Set CEMENT ALL	0.0275	0.0395	Low
#9 - Simpson StrongTie FX-228	0.114	0.206	High
#10 - Simpson StrongTie FX-229	—	0.096	Medium
#11 - CeraTech Pavemend DOTLine	0.025	0.044	Low
#12 - CeraTech Pavemend SL	0.012	0.022	Low
#14 - Quikrete Non-Shrink Precision Grout	—	0.2065	High
#15 - ChemMasters Conset™ Grout	—	0.1285	High
#16 - Ash Grove No-shrink grout	—	0.1225	High
#19 - Euclid TAMMSGROUT SUPREME	0.037	0.09	Medium
#20 - Euclid Euco Pre-cast Grout	0.0555	0.075	Medium
#21 - Euclid NC Grout	0.0555	0.085	Medium
#22 - Euclid NS Grout	0.0815	0.137	High
#23 - Euclid Hi-Flow Grout	0.0855	0.144	High

4.8 Permeability

The permeability of grout materials is not a major concern when a preservative overlay is applied to seal the precast deck system. However, cracks or deterioration often occur in the overlay due to wearing and high seasonal temperature variations, thus providing access of water and aggressive chemicals to the underneath deck system. Accumulation of water and salts along the joints is likely to result in corrosion and freeze/thaw deteriorations when a highly permeable grout is used. As a result, a low permeable grout is favored to assure good long-term performance of deck system. In this study, the rapid chloride ion penetrability test (ASTM C1202) was conducted on the 13 selected grout products to evaluate their permeability. These products were chosen because they showed acceptable performance in the flow, setting, and compressive strength testing.

The rapid chloride ion penetrability of 13 grout products was summarized in Table 4.7. Based on the criteria described in ASTM C1202, the result was classified into four groups: high, moderate, low, and very low. Very low penetrability was defined when the total charge passed over a period of 6 hours was below 1000 coulombs; while the total charge between 1000 and 2000 coulombs was classified as low; between 2000 and 4000 coulombs as moderate; and in excess of 4000 coulombs as high. It can be seen that the grout products exhibited a wide variety of rapid chloride ion penetrability. Out of thirteen products, seven (nearly 54%) showed low to very low chloride ion penetrability. Undoubtedly, these products would have high resistance to the penetration of water and aggressive chemicals. Three products displayed moderate chloride ion penetrability, indicating that their performance would still be acceptable. However, three products (23%) were found to have high chloride ion penetrability. Obviously, these products would provide an easy pathway for the penetration of water and aggressive chemicals, leading to high risk of deterioration.

Table 4.7. Results of rapid chloride ion penetrability test for 13 selected grout products

Mix # and product name	Charge passed (coulombs)	Chloride ion penetrability
#1 - BASF Masterflow 928	3119	Moderate
#2 - SikaGrout 328	2867	Moderate
#3 - SikaGrout 212	124	Very low
#4 - Dayton Superior 1107 Advantage Grout	3832	Moderate
#5 - Dayton Superior Sure-Grip HP Grout	1857	Low
#6 - W.R Meadow SEALTIGHT 588-10K	1064	Low
#7 - CTS Rapid Set CEMENT ALL	4659	High
#9 - Simpson StrongTie FX-228	1532	Low
#19 - Euclid TAMMSGROUT SUPREME	1327	Low
#20 - Euclid Euco Pre-cast Grout	8886	High
#21 - Euclid NC Grout	6767	High
#22 - Euclid NS Grout	1610	Low
#23 - Euclid Hi-Flow Grout	1287	Low

4.9 Freeze and Thaw Durability

The resistance of 13 grout materials to cyclic freezing and thawing was examined following ASTM C666 procedures and the results are summarized in Table 4.8. The failure was defined when the relative dynamic modulus of elasticity fell below 60%. The freeze and thaw durability in this study was classified into three groups: low, medium, and high. If the relative dynamic modulus after 300 cycles was less than 60%, the freeze and thaw durability was defined as low. Between 60 and 95% was considered as medium and above 95% was categorized as high. It can be seen that 12 grout products (approximately 92.3%) showed a relative dynamic modulus of more than 95% after 300 cycles. This indicated that these products had excellent resistance to freezing and thawing with essentially no internal deterioration through 300 cycles although most materials exhibited surface scaling and some of them even showed significant scaling. It should be noted that the weight loss of specimens after 300 cycles was different from the scaling due to water uptake during freezing and thawing test. That was why some specimens even showed severe scaling, but had low weight loss. Only 1 product (CTS Rapid Set CEMENT ALL) performed rather poorly with the relative dynamic modulus of 49 (less than 60). Visual examination showed that severe longitudinal cracking occurred at approximately 300 cycles. This poor performance may be associated with its high permeability (as can be seen from Table 4.7) and the lack of entrained air void system.

In addition, the freeze and thaw durability of grout products can be evaluated based on the proposed performance criteria by NCHRP[28]. When the relative dynamic modulus after 300 cycles was equal to or greater than 70%, the material was classified as grade 1, above 80% as grade 2, and equal to or higher than 90% as grade 3. Clearly, 12 products (92.3%) can be categorized into the highest grade (i.e. grade 3). Again, only one product (CTS Rapid Set Cement All) did not meet this criterion.

Table 4.8. Freeze and thaw test results for 13 selected grout products

Mix # and product name	Relative dynamic modulus after 300 cycles, %	Weight loss after 300 cycles, %	Visual examination after 300 cycles	Freeze/thaw durability
#1 - BASF Masterflow 928	98.6	1.1	Medium scaling	High
#2 - SikaGrout 328	100	1.0	Slight scaling	High
#3 - SikaGrout 212	100	3.5	Slight scaling	High
#4 - Dayton Superior 1107 Advantage Grout	100	0.75	No visible deterioration	High
#5 - Dayton Superior Sure-Grip HP Grout	100	0.25	No visible deterioration	High
#6 - W.R Meadow SEALTIGHT 588-10K	100	2.6	Slight scaling	High
#7 - CTS Rapid Set CEMENT ALL	49	0.85	Severe cracking	Low
#9 - Simpson StrongTie FX-228	100	2.3	Severe scaling	High
#19 - Euclid TAMMSGROUT SUPREME	100	0.1	Slight scaling	High
#20 - Euclid Euco Pre-cast Grout	100	1.2	No visible deterioration	High
#21 - Euclid NC Grout	100	1.8	Severe scaling	High
#22 - Euclid NS Grout	100	3.4	Slight scaling	High
#23 - Euclid Hi-Flow Grout	100	1.2	Slight scaling	High

5.0 EFFECTS OF WEATHER CONDITIONS ON PERFORMANCE OF GROUT PRODUCTS

5.1 Effects of Substrate Surface Moisture on Bond Capacity of Grout Products

This study investigated the influence of surface moisture conditions of substrate concrete on the performance of grout products. The specimen preparation was similar to what was described above in the Experimental Program section except that the different surface moisture conditions of substrate concrete (dry, saturated-surface-dry (SSD), and wet) were prepared. A wet substrate surface was achieved by spraying the water on the exposed surface immediately after the substrate concrete was cured in the lime saturated water; while a SSD condition was attained by removing the surface water film of a wet substrate with wet cloth or through slight air blowing. A dry substrate surface was obtained by drying the wet substrate in the air at approximately 73°F and 50% relative humidity for at least a week.

5.1.1 Effects of Substrate Surface Moisture on Flexural Bond Strength

The effects of substrate surface moisture on the flexural bond strength and the failure plane were summarized in Table 5.1 and also illustrated in Figure 5.1. It can be seen that the flexural bond strength (i.e. the flexural peak stress or modulus of rupture) varied widely with the substrate surface moisture conditions and no general trends can be concluded. Some grouts exhibited high flexural bond strength under all substrate surface moisture conditions; while some grouts including epoxy grouts, preferred dry substrate surface and some grouts favored wet or SSD substrate surface.

When the substrate surface moisture changed from SSD to wet, 6 products (25%) displayed a noticeable decrease (more than 50psi) in the flexural bond strength. 13 products (approximately 54%) showed essentially insignificant changes (less than 50psi) in the flexural bond strength and 5 products (nearly 21%) surprisingly demonstrated a substantial increase (more than 50psi) in the flexural bond strength. Also, for most products (at least 19 out of 25 products), the failure plane did not change as the substrate surface moisture varied from SSD to wet. These results indicated that a wet substrate surface did not necessarily reduce the flexural bond strength. This was surprising because it is commonly recognized that the wet substrate surface would reduce the bond strength due to the fact that the free surface moisture would prevent the grout materials from absorbing into the open pores of substrate, resulting in poor interlocking and weak bonding. Although the exact reason for this discrepancy was unclear, a review of test results indicated that these products typically had high flowability (e.g. Dayton Superior Sure-Grip, W.R. Meadows SEALTIGHT 588-10K, Euclid NS, and Euclid Hi-flow). A highly flowable grout was more penetrative, which might be able to penetrate into the open pores of wet substrate.

When the substrate surface moisture changed from SSD to dry, 12 grout products (approximately 48%) exhibited a reduced flexural bond strength (by more than 50psi), 6 products (24%) showed roughly equal flexural bond strength (less than 50psi difference), and 7 products (28%) even demonstrated a significant increase in the flexural bond strength. In addition, the substrate surface moisture change (from SSD to dry) caused a slight increase in the interfacial failure although most products exhibited a similar failure plane. A comparison of all these results suggested that a dry substrate would be more likely to reduce the flexural bond strength and cause a higher risk of debonding than a wet substrate. One explanation was that a very dry substrate would absorb the free water from the fresh grout at the interface, leading to insufficient hydration. At low W/C, which was true for most grout products, any water loss due to absorption would be more detrimental to the strength development.

The effect of substrate surface moisture on the flexural bond strength also depended on the nature of the product. For examples, some products such as SikaGrout 328 normally failed at the substrate at all substrate surface moisture conditions. These grouts typically had high compressive strength and flowability. For low-strength grouts such as Simpson StrongTie FX-229 and ChemMasters Conset Grout, failure normally occurred at the grout regardless of the substrate surface moisture condition. This was easy to understand because failure always started at the weakest location. For some grouts (e.g., Euclid Euco pre-cast, NC, NS, Hi-flow, and Phoscrete Four-Seasons and VO-Plus), the specimens normally failed along the interface despite the substrate surface moisture condition, indicating that these materials may be less penetrative.

For the two epoxy grouts, dry substrate typically showed better bonding and failure normally occurred at the substrate, whereas, wet or SSD substrates generally led to reduced bond capacity and resulted in the interfacial failure.

Table 5.1 Flexural bond strength and failure plane of composite specimens prepared with different substrate surface moisture conditions

Mix # and product name	Dry		SSD		Wet	
	Flexural bond strength, psi	Failure plane	Flexural bond strength, psi	Failure plane	Flexural bond strength, psi	Failure plane
#1 - BASF Masterflow 928	408	I	600	I+S	600	I
#2 - SikaGrout 328	812	S	833	S	700	S
#3 - SikaGrout 212	575	G+S+I	750	I+G+S	**	**
#4 - Dayton Superior 1107 Advantage Grout	375	I	650	I	633	G
#5 - Dayton Superior Sure-Grip HP Grout	483	G+S	667	S	754	S
#6 - W.R Meadow SEALTIGHT 588-10K	708	G	560	G	713	G
#7 - CTS Rapid Set CEMENT ALL	34	I	258	G+I	139	G+I
#8 - Hilti Epoxy Grout CB-G EG	538	S	379	I	413	I
#9 - Simpson StrongTie FX-228	175	I	529	G	558	G
#10 - Simpson StrongTie FX-229	596	G	600	G	599	G
#11 - CeraTech Pavemend DOTLine	450	G+S	396	S	408	G
#12 - CeraTech Pavemend SL	192	I	308	S	300	G
#13 - VEXCON CERTI-VEX Grout #1000	250	I	92	I	126	G
#14 - Quikrete Non-Shrink Precision Grout	354	G+I	333	I	233	**
#15 - ChemMasters Conset™ Grout	671	G	425	G	558	G
#16 - Ash Grove No-shrink grout	633	I+S	708	S+I	525	G+I
#17 - KAUFMAN Non-Shrinking Precision Grout	450	G+I	633	I+G	600	S
#18 - Euclid E^3-DP Epoxy Grout	508	S	363	I+S	317	I
#19 - Euclid TAMMSGROUT SUPREME	119	I	267	G+S	263	G
#20 - Euclid Euco Pre-cast Grout	0*	I	317	I	0*	I
#21 - Euclid NC Grout	554	I	417	I	288	I
#22 - Euclid NS Grout	183	I	218	I	400	I
#23 - Euclid Hi-Flow Grout	92	I	142	I	254	I
#24 - Phoscrete Four-Seasons	94	I	117	I	78	I
#25 - Phoscrete VO-Plus	0*	I	0*	I	0*	I

Note: *-specimens were broken along the interface during demolding. **-the data was not recorded. I-failure occurred along interface; G-failure occurred at the grout; and S-failure occurred at the substrate concrete.

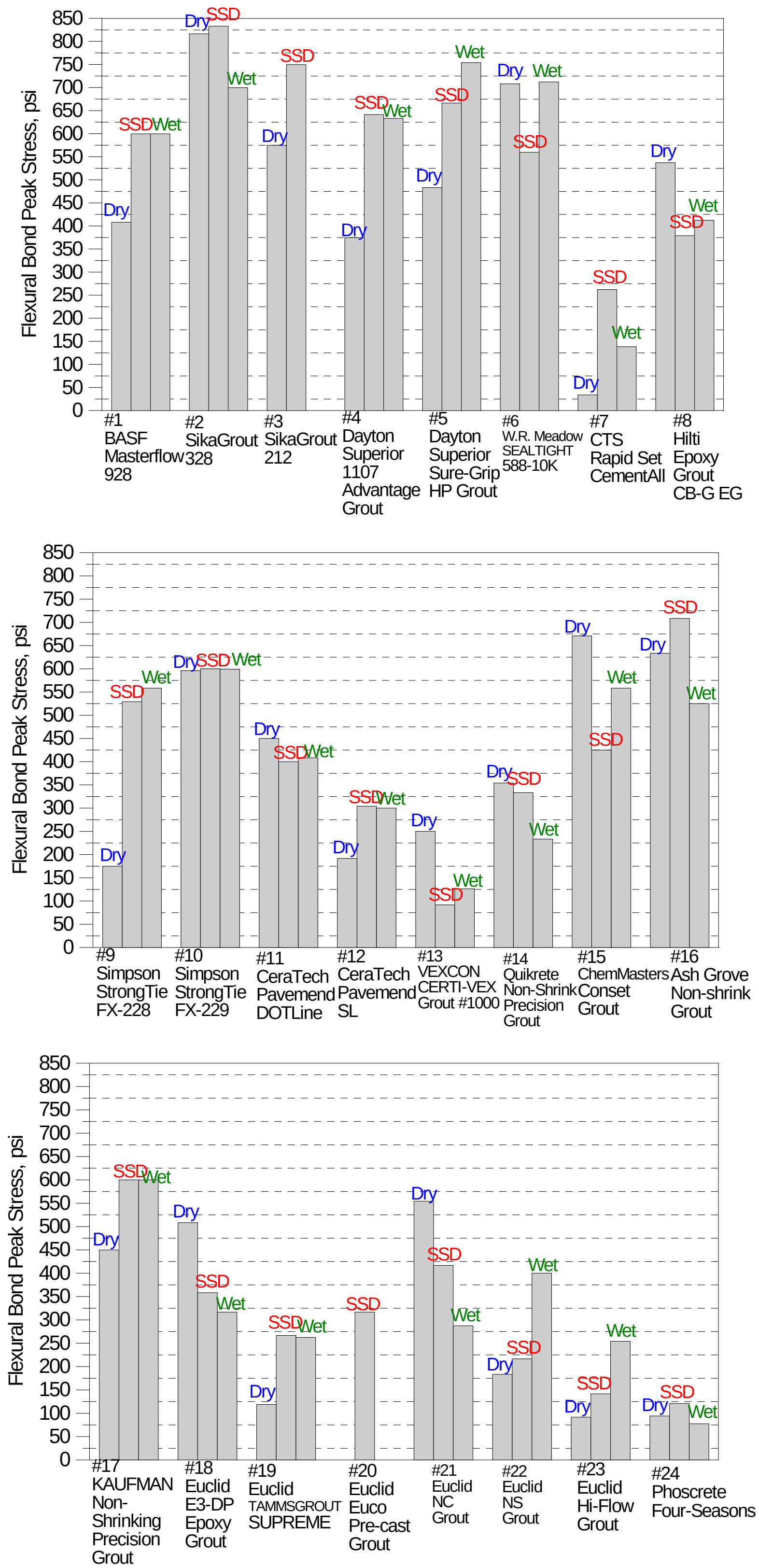


Figure 5.1 Illustration of flexural bond strength of composite specimens with different substrate surface moisture conditions

5.1.2 Effects of Substrate Surface Moisture on Slant Shear Bond Strength

The slant shear bond capacity was also evaluated in this study. The results are summarized in Table 5.2 and also illustrated in Figure 5.2. Again, there was no clear trend regarding which substrate surface moisture condition exhibited a better performance during the slant shear bond test. For examples, some products such as CeraTech Pavemend SL and VEXCON CERTI-VEX grout #1000 displayed almost equal slant shear bond strength at different substrate surface moisture conditions, indicating that the substrate surface moisture had insignificant influences on the bond capacity of these products. However, some products such as Dayton Superior Sure-Grip and W.R Meadows SEALTIGHT 588-10K preferred the SSD condition, under which the highest slant shear bond strength was achieved. Conversely, some products such as Dayton Superior 1107 and CeraTech Pavemend DOTLine, showed the best slant shear bond strength when the wet substrate surface was used. For some products especially two epoxy grouts, the dry substrate surface was desirable.

In general, 10 out of 24 products (nearly 42%) showed a noticeable reduction (by more than 100psi) in the slant shear bond strength as the substrate surface moisture changed from SSD to wet. This reduction was understandable because the pores in the wet substrate were saturated with water, thus preventing the grout penetration and leading to poor bonding. However, 6 products (25%) demonstrated approximately the equal slant shear bond strength and 8 products (approximately 33%) even displayed a significant increase (by more than 100psi) in the slant shear bond strength when the substrate surface moisture altered from SSD to wet. These two observations indicated that a wet substrate surface did not always reduce the slant shear bond strength. This again did not agree with the commonly recognized principle that the wet substrate surface generally resulted in poor bonding.

Similarly, a dry substrate surface did not always reduce the slant shear bond strength. This was particularly true for the epoxy grouts such as Hilti Epoxy Grout CB-G EG and Euclid E3-DP Epoxy Grout. Out of 25 products, 10 (approximately 42%) demonstrated a substantial increase (by more than 100 psi) when the substrate surface moisture changed from SSD to dry. 4 products (nearly 17%) showed insignificant variation in the slant shear bond strength (less than 50psi difference). Only 10 grout products (nearly 42%) exhibited a reduced slant shear bond strength (by more than 100psi) when the substrate surface moisture changed from SSD to dry.

The diverse results in this study further indicated that factors affecting the slant shear bond strength of grout materials were complicated. For examples, SikaGrout 328 typically failed at the substrate, implying that the substrate concrete afftected the slant shear bond strength. Some grouts always failed at the interface, suggesting that the characteristics of grout materials also affected the slant shear bond strength.

Table 5.2. Slant shear bond strength and failure plane of composite specimens prepared with different substrate surface moisture conditions

Mix # and product name	Dry		SSD		Wet	
	Slant shear bond strength, psi	Failure plane	Slant shear bond strength, psi	Failure plane	Slant shear bond strength, psi	Failure plane
#1 - BASF Masterflow 928	2389.0	I	2765	S	3011.3	S
#2 - SikaGrout 328	2843.9	S	3235	S	3386.2	S
#3 - SikaGrout 212	2429.0	I+G+S	2937.5	I+G+S	2916.3	I+S+G
#4 - Dayton Superior 1107 Advantage Grout	1671.8	I	1512.5	I	2581.5	I
#5 - Dayton Superior Sure-Grip HP Grout	3056.3	G+I	3770	I+G+S	2594.0	S+I
#6 - W.R Meadow SEALTIGHT 588-10K	2783.9	G	3227.5	G+S	2676.4	G
#7 - CTS Rapid Set CEMENT ALL	2194.1	G+I+S	1450	G+I	1017.1	I+G+S
#8 - Hilti Epoxy Grout CB-G EG	3038.8	S	1000	I+G	2471.5	I+S
#9 - Simpson StrongTie FX-228	2696.4	S+I	2705	S	3036.3	S
#10 - Simpson StrongTie FX-229	2426.5	I+S	2880	I+G	2906.3	S+I
#11 - CeraTech Pavemend DOTLine	2611.5	G+I+S	3025	S	3751.0	S+G
#12 - CeraTech Pavemend SL	2823.9	I+S	2922.5	S	2921.3	S+G+I
#13 - VEXCON CERTI-VEX Grout #1000	1344.5	I	1425	I+G	1441.9	I+G
#14 - Quikrete Non-Shrink Precision Grout	2721.4	I+G	2335	I+S	2426.5	**
#15 - ChemMasters Conset™ Grout	2094.2	S+I+G	2557.5	G+S	2511.5	S
#16 - Ash Grove No-shrink grout	2743.9	I+S	2877.5	I+S	2279.1	G+I
#17 - KAUFMAN Non-Shrinking Precision Grout	2753.9	S	2337.5	I+S	2459.0	S+I
#18 - Euclid E^3-DP Epoxy Grout	2521.5	S	1682.5	I+S	1059.6	I
#19 - Euclid TAMMSGROUT SUPREME	982.1	I	2895	I+S+G	2753.9	G+I+S
#20 - Euclid Euco Pre-cast Grout	*	I	2800	I+G	*	I
#21 - Euclid NC Grout	3023.8	I+S+G	2547.5	I	2324.1	I
#22 - Euclid NS Grout	3286.2	S	3017.5	I+G+S	2743.9	I+S+G
#23 - Euclid Hi-Flow Grout	3126.3	I	3375	I+G+S	2833.9	I+S+G
#24 - Phoscrete Four-Seasons	1369.5	I	580	I	219.9	I
#25 - Phoscrete VO-Plus	399.8	I	342.5	I	764.7	I

Note: * Specimens failed during demolding; ** Failure plane was not recorded; I-failure occurred along the slant interface; G-failure occurred at the grout portion of specimen; and S-failure occurred at the substrate concrete.

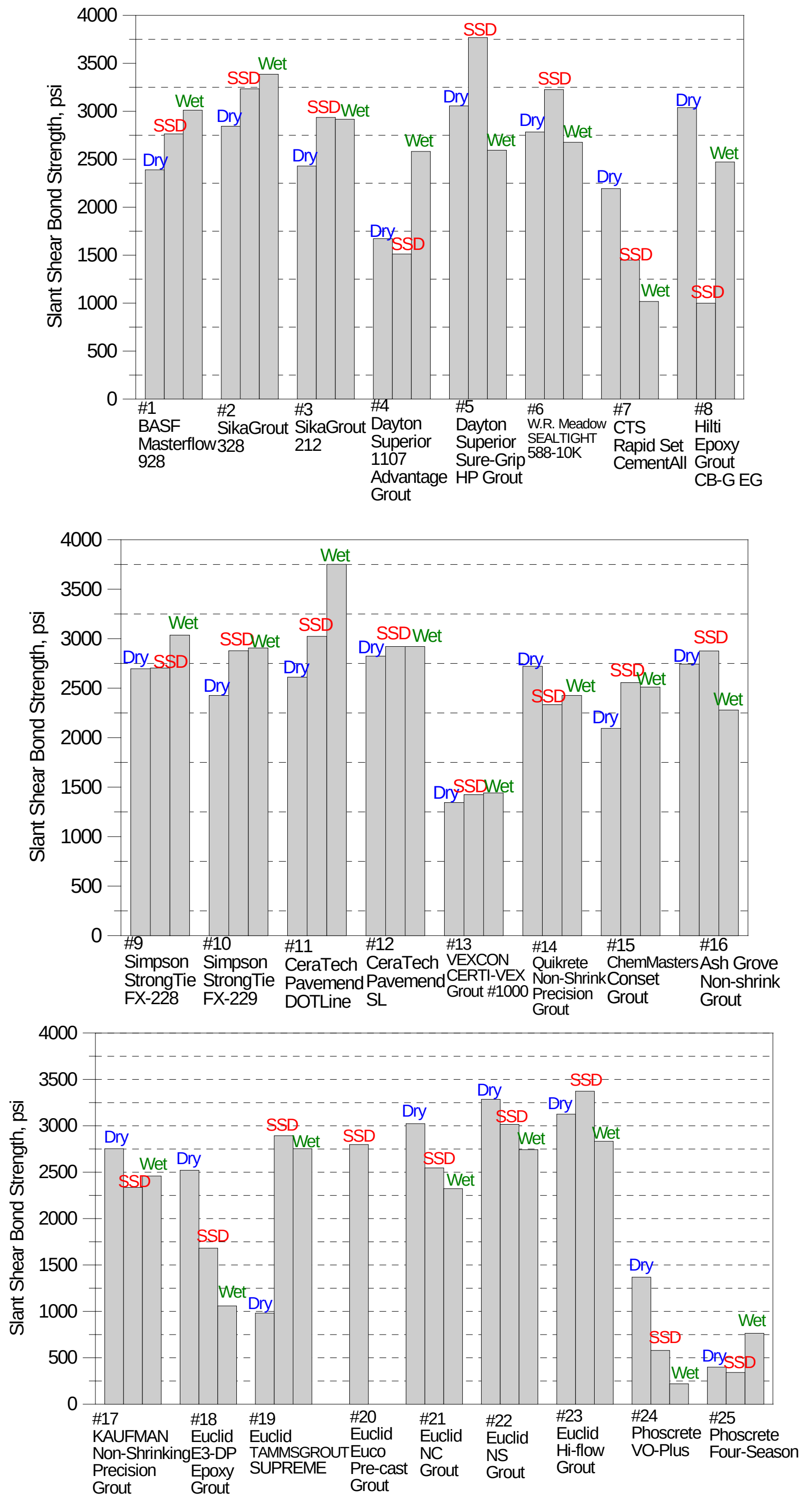


Figure 5.2 Illustration of slant shear bond strength of composite specimens with different substrate surface moisture conditions

It should be noted that the test method also affected the bonding capacity of grout materials. For examples, some grouts performed better when evaluated by the flexural test; while some grouts exhibited improved performance when tested by the slant shear test. In fact, almost all products showed different bonding behaviors when tested by different test methods (the flexure and the slant shear).

5.2 Effects of Temperature Variations on Performance of Grout Products

The elevated temperature is likely to be encountered during the closure pour in precast concrete bridge construction. The elevated temperature accelerates the hardening of cementitious grouts, thereby reducing their flow time. In particular, high temperature may increase the moisture evaporation from cement-based grouts, which further leads to a decrease in flowability. As a result, it is essential to fully understand how temperature variations affect the properties of grouts so that successful construction procedures can be developed. In this study, three levels of temperature were tested (73°F, 85°F and 95°F) on 13 selected products. The effects of temperature variations on the flowability, setting, compressive strength development, and bond strength are investigated.

5.2.1 Specimen Preparation

The specimen preparation was similar to what was described in the Experimental Program section except that the temperature for mixing and curing was different. Before mixing, all the ingredient materials were preconditioned to the designated degree of temperature (i.e. 73°F, 85°F, or 95°F). They were then mixed in a bucket using a paddle mixer. Immediately after mixing, the fresh mixture was stored in an environmental chamber at the same designated temperature (i.e. 73°F, 85°F, or 95°F) at 50% relative humidity. The mini slump spread was tested at different time intervals typically 5 minutes, 1 hour, and 3 hours after mixing. The time of setting was measured with the elapsed time until the final set occurred. Meanwhile, the specimens for the compressive strength development were prepared, sealed, and initially cured for 24 hours at the same designated temperature (i.e. 73°F, 85°F, or 95°F). They were then demolded and cured in the lime-saturated water at the same designated temperature (i.e. 73°F, 85°F, or 95°F) until the time of testing.

For the composite specimens prepared for the flexural bond test and the slant shear bond test, the substrate concrete was preconditioned to a designated temperature level (i.e. 73°F, 85°F, or 95°F) and the SSD moisture condition before pouring the fresh grout into the joint. After casting and finishing, the composite specimen together with the mold was sealed by wrapping the plastic sheet around the mold and kept in an environmental chamber at the same designated temperature level (i.e. 73°F, 85°F, or 95°F) and 50% relative humidity for 24 hours. After the initial curing, the composite specimen was demolded and then cured in the lime-saturated water at the same designated temperature level (i.e. 73°F, 85°F, or 95°F) until the time of testing.

5.2.2 Effects of Temperature Variations on Flowability of Grout Products

Table 5.3 summarizes the mini slump spread measured at different time and temperature. In general, it can be seen that at each temperature level, the mini slump spread decreased with time; however, at a higher temperature level, the mini slump spread decreased more rapidly with time. These observations agreed with the general principles that any cementitious materials set as a function of time and temperature due to the cement hydration. This also explained why some cementitious grouts were still fresh in 1 or 3 hours when tested at 73°F, but they became set when tested at 85°F or 95°F as shown in Table 5.3. It can also be seen that some products (such as #1 BASF Masterflow 928, #4 Dayton Superior 1107 Advantage Grout, and #5 Dayton Superior Sure Grip HP Grout) displayed an opposite behavior. Their mini slump spread at 85°F was higher than that at 73°F. It also reduced faster with the elapsed time at a lower temperature (73°F). In particular, the #4 Dayton Superior 1107 advantage Grout had not only a higher mini-slump spread at 95°F, but also a slower rate of reduction in the mini-slump spread at this high temperature. This meant that these products would flow better and longer at a high temperature level. As a result, they were more suitable for hot weather applications.

Table 5.3. Effects of temperature on mini-slump spread of grout products tested at different time

Mix # and product name	73°F			85°F			95°F		
	5 min.	1 hour	3 hour	5 min.	1 hour	3 hour	5 min.	1 hour	3 hour
#1 - BASF Masterflow 928	8.75	5	Set	11	10	6.5	7.5	6	3.5
#2 - SikaGrout 328	11.5	4.75	Set	9.5	4.5 *	Set	7	Set	Set
#3 - SikaGrout 212	10.75	6	4	7.5	3 *	Set	7.375	4.25	Set
#4 - Dayton Superior 1107 Advantage Grout	9.5	7.5	5	11.5	11	10	9.75	9.5	6.25
#5 - Dayton Superior Sure-Grip HP Grout	12	10.75	8.25	12.5	12.25	11.5	4.25	3.5	Set
#6 - W.R Meadow SEALTIGHT 588-10K	12.5	3.5	3.5	11	Set *	Set	6	Set	Set
#7 - CTS Rapid Set CEMENT ALL	8.5	Set	Set	5.75	Set *	Set	7.25	3.5 *	Set
#9 - Simpson StrongTie FX-228	10	6.5	4.25	7.5	7	5.5	5.5	5	3.25
#10 - Simpson StrongTie FX-229	8.5	9	7	6	7.5	3.5	5.5	5.5	3.5
#14 - Quikrete Non-Shrink Precision Grout	7	Set	Set	5.5	5.5 *	Set	7.5	3.5 **	Set
#19 - Euclid TAMMSGROUT SUPREME	10	4.5 *	Set	7	Set	Set	Set	Set	Set
#20 - Euclid Euco Pre-cast Grout	11	10.5	3.75	10.5	8.5	3.5	9	Set	Set
#21 - Euclid NC Grout	7.5	3.25	Set	6.5	4	Set	7	5.25 *	3.5 **
#22 - Euclid NS Grout	10.5	3.5	Set	9	3.25	Set	7.75	3.5 *	Set
#23 - Euclid Hi-Flow Grout	11.5	8.75	5.5	9.75	6.75 **	5.5 (2 h)	9	7.5 **	3.5

Note: * measured at 15 minutes, and ** measured at 30 minutes.

The change of initial mini slump spread measured 5 minutes after water was added as a function of temperature is also illustrated in Figure 5.3. Clearly, increasing temperature would generally reduce the initial flowability of grout products. While this trend was true for most products, some opposite behaviors were noted. For instances, some products (#1 BASF Masterflow 928, #4 Dayton Superior 1107 Advantage Grout, and #5 Dayton Superior Sure Grip HP Grout) showed better initial flowability at the medium temperature (85°F) and #14 Quikrete Non-shrink precision grout even showed the highest flowability at the high temperature (95°F).

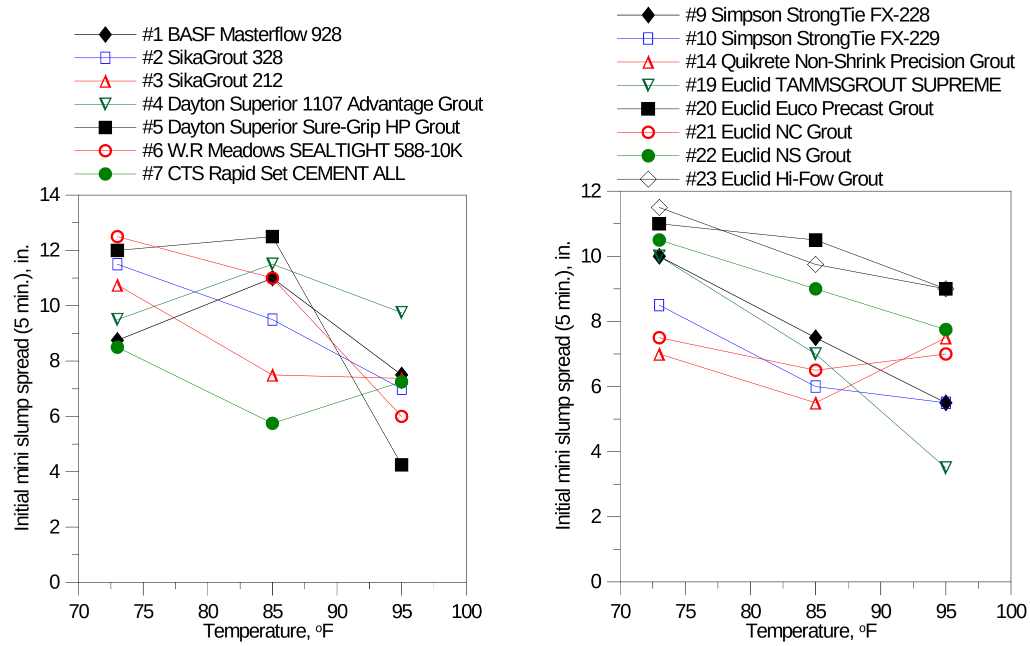


Figure 5.3 Effects of temperature variations on initial mini-slump spread of grout products

The flow cone test was also performed in this study. However, the flow time was only measured at 5 minutes after mixing because for most products, the flow became either discontinuous or fully stopped at a later time (e.g. 1 hour). Table 5.4 summarizes the flow time of 15 grout products tested at different temperature levels. Obviously, the flow time increased with the increasing temperature. This again meant that a high temperature would reduce flowability of fresh grouts. It should be noted that at the medium to high temperature levels (85°F and 95°F), the flow cone test was actually not applicable for most products due to the quick setting.

Table 5.4. Effects of temperature on flow time of grout products tested in 5 minutes

Mix # and product name	73°F	85°F	95°F
#1 - BASF Masterflow 928	66	NA*	NA*
#2 - SikaGrout 328	116	NA*	NA*
#3 - SikaGrout 212	82	NA*	NA*
#4 - Dayton Superior 1107 Advantage Grout	110	141	NA*
#5 - Dayton Superior Sure-Grip HP Grout	NA*	NA*	NA*
#6 - W.R Meadow SEALTIGHT 588-10K	71	92	NA*
#7 - CTS Rapid Set CEMENT ALL	35	NA*	NA*
#9 - Simpson StrongTie FX-228	150	NA*	NA*
#10 - Simpson StrongTie FX-229	49	NA*	NA*
#14 - Quikrete Non-Shrink Precision Grout	150	NA*	85
#19 - Euclid TAMMSGROUT SUPREME	NA*	NA*	NA*
#20 - Euclid Euco Pre-cast Grout	52	85	86
#21 - Euclid NC Grout	87	129	170
#22 - Euclid NS Grout	77	102	NA*
#23 - Euclid Hi-Flow Grout	170	NA*	NA*

Note: * NA-not applicable due to discontinuous flow, or flow stop, or fast set during the flow test.

5.2.3 Effects of Temperature Variations on Time of Setting of Grout Products

The elevated temperature had great impacts on the time of setting of 15 cementitious grout products. The results are summarized in Table 5.5. Generally, an increase in temperature accelerated both the initial and the final setting of most cementitious grouts. This was again because a high temperature would speed up the hydration reaction of cement.

Table 5.5. Effects of temperature on time of setting of grout products

Trade Name	Time of setting at 73°F, min.		Time of setting at 85°F, min.		Time of setting at 95°F, min.	
	Initial	Final	Initial	Final	Initial	Final
#1 - BASF Masterflow 928	305	400	420	490	295	380
#2 - SikaGrout 328	300	460	280	400	275	340
#3 - SikaGrout 212	480	670	325	425	150	290
#4 - Dayton Superior 1107 Advantage Grout	540	570	450	530	425	465
#5 - Dayton Superior Sure-Grip HP Grout	300	780	370	500	296	325
#6 - W.R Meadow SEALTIGHT 588-10K	400	580	420	510	360	490
#7 - CTS Rapid Set CEMENT ALL	48.5	49	19	21	8	9
#9 - Simpson StrongTie FX-228	770	860	420	510	340	415
#10 - Simpson StrongTie FX-229	205	500	430	510	390	470
#14 - Quikrete Non-Shrink Precision Grout	90	180	60	90	30	35
#19 - Euclid TAMMSGROUT SUPREME	39	470	21	340	20	260
#20 - Euclid Euco Pre-cast Grout	100	460	77	122	60	85
#21 - Euclid NC Grout	350	410	309	450	240	360
#22 - Euclid NS Grout	310	370	180	260	110	190
#23 - Euclid Hi-Flow Grout	360	480	510	591	416	480

The effects of temperature on the setting of 15 grout products are also illustrated in Figure 5.4 (initial setting) and Figure 5.5 (final setting). It can be seen that the temperature effects on setting varied with product. For examples, some products showed the accelerated setting as the temperature increased. These products included #3 SikaGrout 212, #4 Dayton Superior 1107 Advantage Grout, #9 Simpson StreongTie FX-229, #20 Euclid Euco Precast Grout and #21 Euclid NS Grout. However, some products displayed the decelerated setting as the temperature increased especially from 73°F to 85°F. These products included #1 BASF Masterflow 928, #5 Dayton Superior Sure-Grip HP Grout, #10 Simpson StrongTie FX-229, and #23 Euclid Hi-Flow Grout. This was contradictory to what was observed in conventional cement-based materials possibly due to special admixtures that were incorporated into these products that interacted with the cement hydration.

It should be noted that the temperature variation within the normal range (73°F-95°F) in this study did not cause big concerns. This was because most grout products in this study belonged to slow-setting materials. An increase in temperature enabled these products to set normally, which was in fact beneficial for the construction as it helped to avoid the construction delay. However, for some quick-set grouts such as #7 CTS Rapid Set CEMNTALL, #14 Quikrete Non-

Shrink Precision Grout, and #19 Euclid TAMMSGROUT SUPREME, the temperature rise would lead to serious problems because these products would become flash-set and could no longer be adequately mixed, placed, and finished.

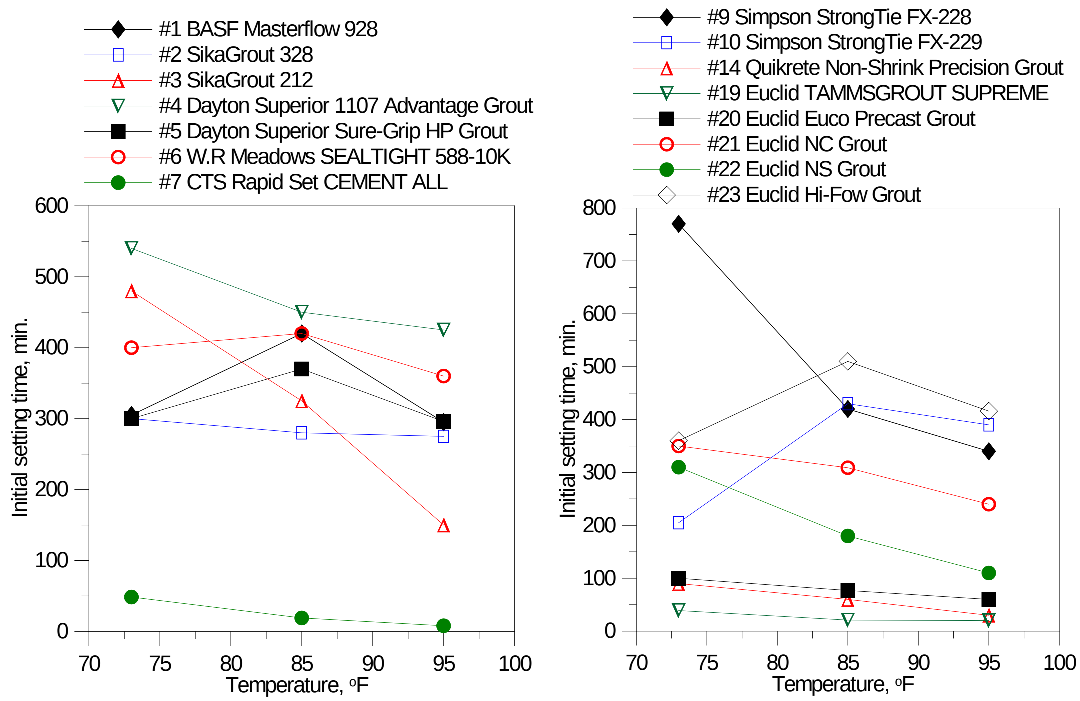


Figure 5.4 Effects of temperature on initial setting time of 15 grout products

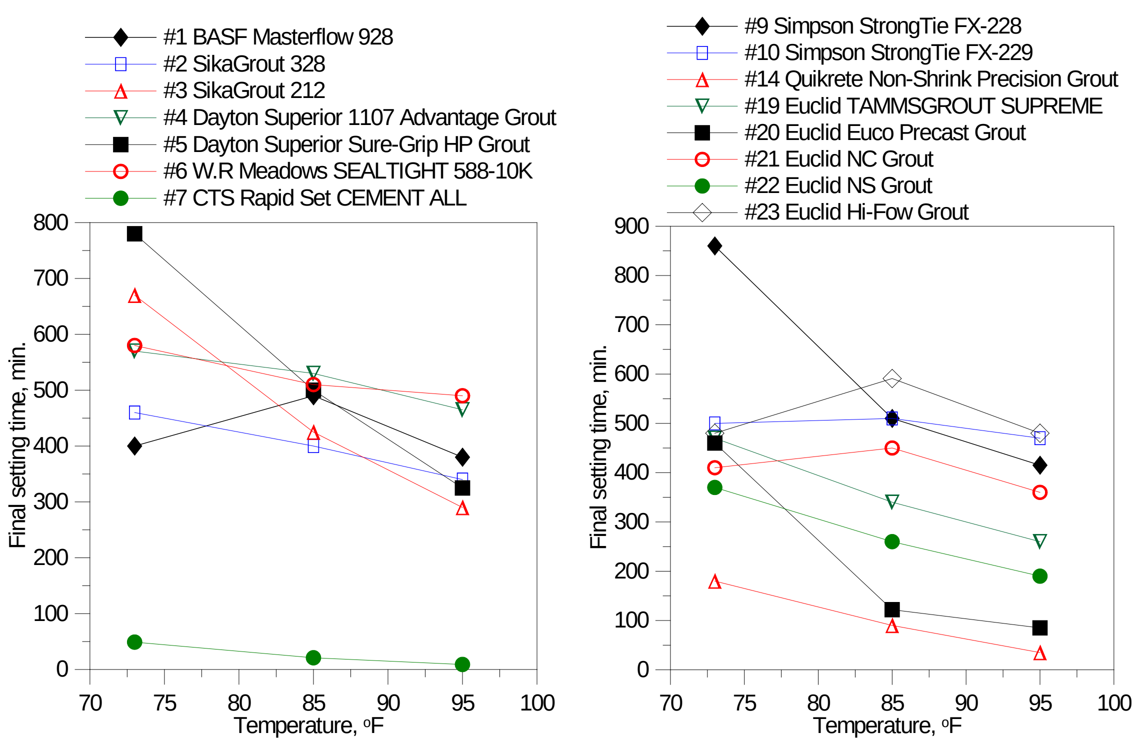


Figure 5.5 Effects of temperature on final setting time of 15 grout products

5.2.4 Effects of Temperature Variations on Compressive Strength of Grout Products

Table 5.5 listed the detailed test results of compressive strength development for 15 grout products selected in this study. Largely, specimens that were mixed, placed and cured at a higher temperature level displayed faster compressive strength development. It can also be seen that at the low temperature level (73°F), no 8-hour compressive strength was measured because almost all grout products did not gain significant compressive strength at that age; however, at high temperature levels (e.g. 95°F), most products developed substantial amount of compressive strength at 8 hours. This was again because the high temperature accelerated the hydration reactions of cement. High strength development especially at the early age was important to the closure pour of precast deck panels as it may promote early public access to the structure. As a result, some products such as SikaGrout 328, Dayton Superior 1107 Advantage Grout, and Sure-Grip HP Grout, would be able to provide early opening when the construction took place during hot weather.

The 28-day compressive strength displayed a different trend. Some products showed a reduced 28-day compressive strength at 95°F as compared with 85°F or 73°F. This was not surprising because the high temperature promoted the early-age compressive strength development, but compromised the long-term compressive strength.

Table 5.5. Effects of temperature on compressive strength of grout products at different ages

Trade Name	73°F, psi			85°F, psi				95°F, psi			
	1 day	7 day	28 day	8 hour	1 day	7 day	28 day	8 hour	1 day	7 day	28 day
#1 - BASF Masterflow 928	4084	6375	8503	*	5014	8007	9540	555	5291	7623	8884
#2 - SikaGrout 328	5730	8938	10345	*	2869	4095	5851	3036	4477	6182	7036
#3 - SikaGrout 212	1430	4944	7636	*	2527	4360	5141	597	3567	4616	5766
#4 - Dayton Superior 1107 Advantage Grout	3093	6922	9004	*	6751	9720	10959	4124	5971	8618	10174
#5 - Dayton Superior Sure-Grip HP Grout	1998	8135	11040	*	5602	8941	11259	4493	5941	7833	8771
#6 - W.R Meadow SEALTIGHT 588-10K	2308	5032	6213	*	4434	7741	9293	1160	3800	6248	7136
#7 - CTS Rapid Set CEMENT ALL	8717	**	10921	8267	9207	11418	9829	8059	8804	8777	9511
#9 - Simpson StrongTie FX-228	860	6331	7155	*	5159	6595	8652	420	4733	7618	8613
#10 - Simpson StrongTie FX-229	951	2984	5668	*	2259	5165	5881	138	2553	5132	5677
#14 - Quikrete Non-Shrink Precision Grout	3827	7889	10415	1028	5287	9521	11869	1025	784	8946	9101
#19 - Euclid TAMMSGROUT SUPREME	3835	6572	8569	479	7345	10832	12423	N/A	N/A	NA	N/A
#20 - Euclid Euco Pre-cast Grout	1389	3929	7028	1283	1271	8471	10699	1268	1927	6637	7510
#21 - Euclid NC Grout	1519	4506	7481	304	2299	6134	8077	279	2773	6506	7479
#22 - Euclid NS Grout	3889	6467	8950	1974	5392	7827	10170	1971	5080	8680	9782
#23 - Euclid Hi-Flow Grout	2922	5913	9574	*	3899	7391	9530	*	4391	8449	10733

Note: * Specimens were not fully hardened or the strength was very low. N/A-not applicable because the mixture set too fast to prepare the specimens. ** the results were not recorded.

The effects of temperature on the compressive strength development are also illustrated in Figures 5.5 to 5.7. Obviously, increasing temperature improved the 1-day compressive strength (Figure 5.5) although different products showed different trends especially for quick-set grouts. For instance, an increase in temperature only slightly increased the 1-day compressive strength for the #7 CTS Rapid Set Cement All. One reason was that this product consisted of the calcium sulfoaluminate cement, which hydrated with water very quickly even at the normal temperature level. Therefore, the effect of temperature on the hydration reaction was limited. Conversely, a significant reduction was observed for #14 Quikrete Non-Shrink Precision Grout when the temperature varied from 85°F to 95°F. This was mainly because at 95°F, the fresh grout set extremely fast. There was insufficient time to adequately place and consolidate the specimens, resulting in poor specimen preparation that adversely affected the compressive strength.

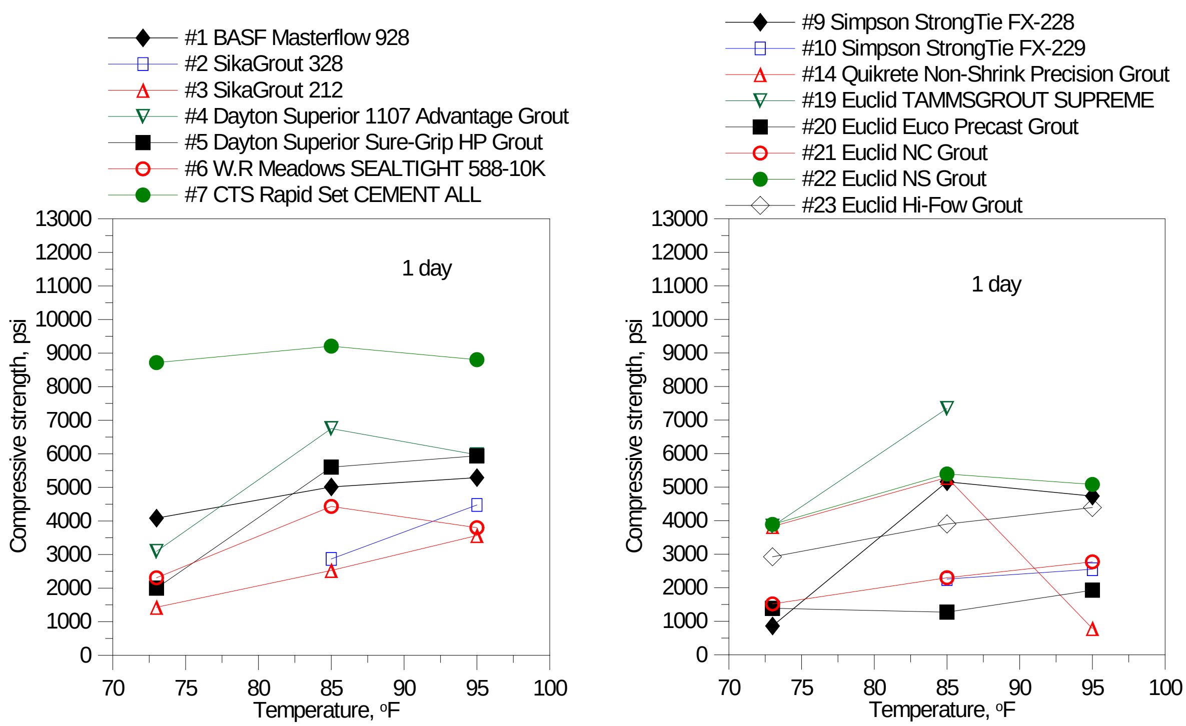
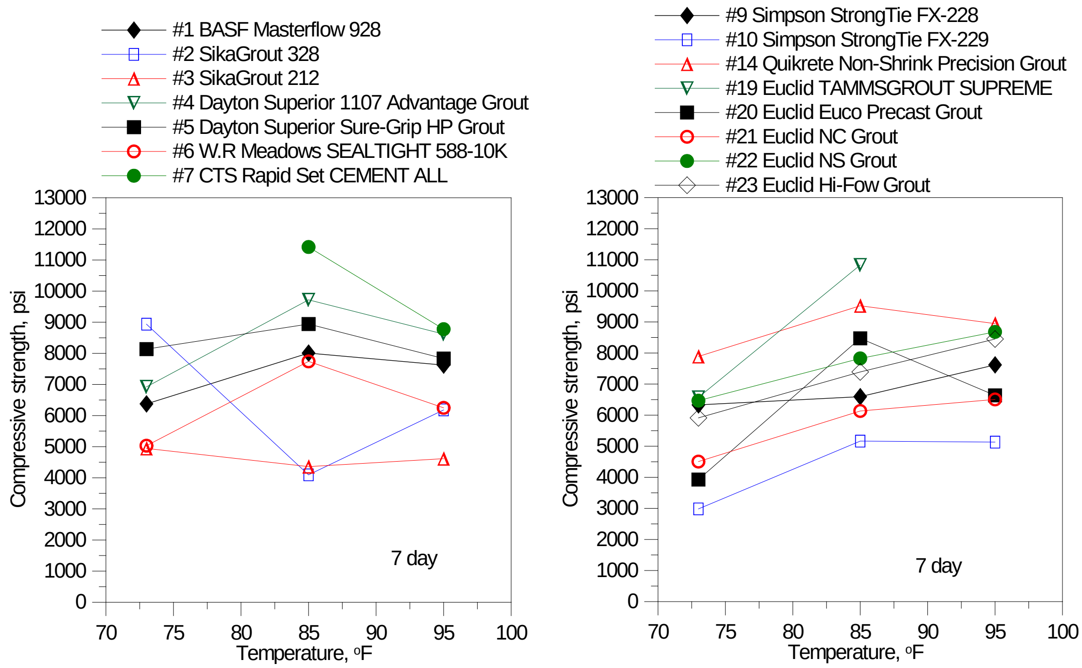


Figure 5.6 Effects of temperature on 1-day compressive strength of 15 grout products

The elevated temperature had a mixed effect on the 7-day compressive strength as shown in Figure 5.7. For some products (mainly in Figure 5.7a), an increase in temperature led to a reduced 7-day compressive strength especially when the temperature increased from 85°F to 95°F. However, most products in Figure 5.7b demonstrated an improved 7-day compressive strength as temperature increased with only one exception (#20 Euclid Euco Precast Grout), in which a significant reduction was noticed as the temperature increased from 85°F to 95°F.



(a) (b)

Figure 5.7 Effects of temperature on 7-day compressive strength of 15 grout products

Similarly, various relations between the temperature variation and the 28-day compressive strength were observed as shown in Figure 5.8. Out of fifteen grout products, four products (#2, #3, #5, and #7) showed the decreasing 28-day compressive strength with the increasing temperature. Seven products (#1, #4, #9, #10, #21, #22, and #23) demonstrated either a slight increase or almost no variation as the temperature increased. Interestingly, three products (#6, #14, and #20) exhibited the highest 28-day strength at the medium temperature (i.e. 85°F).

It became evident that the effects of temperature on the compressive strength development of grout products were complicated. It was certain that an increase in temperature would undoubtedly improve the early-age compressive strength of grout products. However, no single relation could truly describe how the compressive strength varied with the temperature. This was because many factors would affect the compressive strength development. One main reason was that different products used different materials and proportions as well as different quality control procedures.

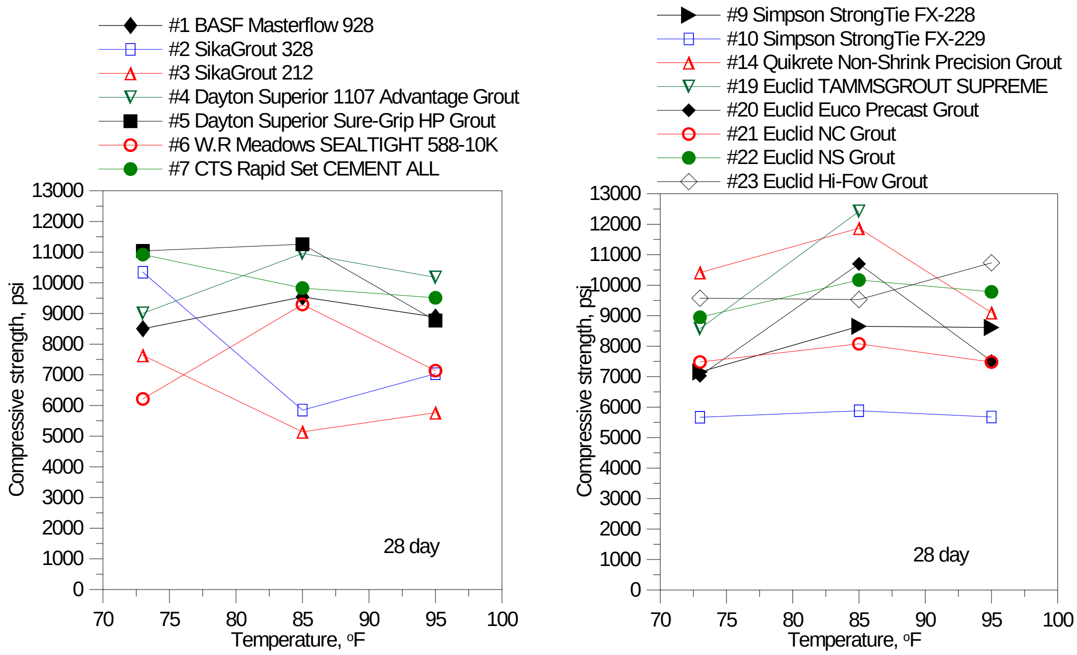


Figure 5.8 Effects of temperature on 28-day compressive strength of 15 grout products

5.2.5 Effects of Temperature Variations on Flexural Bond Strength of Grout Products

The flexural bond test was performed on 15 selected grout products. Three temperature levels (73°F, 85°F, and 95°F) and three ages (1 day, 3 days, and 28 days) were examined. Table 5.6 summarizes all test results. The temperature change was found to have substantial impacts on the flexural bond strength of grout products. At the same age, the flexural bond strength was reduced with increasing temperature. This was again due to the fact that the high temperature accelerated setting, which in turn reduced flowability of fresh grouts. The reduction in flowability limited the grout penetration and contact, thus resulting in poor mechanical interlocking. Another reason was that the high temperature typically generated low-quality hydration products. A review of results in Table 5.6 further confirmed this assumption. For examples, at 73°F, only two products (#22 Euclid NS and #23 Euclid Hi-flow) showed both low flexural bond strength and interfacial failure, meaning that they had deficient mechanical interlocking. However, at 85°F at same age, six products demonstrated this pattern, and at 95°F, nine products including two quick-set products (i.e. #7 and #19) showed this behavior. It should be noted that for the two quick-set products, the fresh grout set extremely fast at 95°F, causing poor contact between the grout and the substrate. They broke at the interface during demolding.

Interestingly, a few products such as Euclid NS (#22) and Hi-flow (#23) grouts exhibited some improvements in the flexural bond strength when the temperature increased. The exact reason was unclear in this study. More research may be needed to verify this trend.

Table 5.6. Effects of temperature on flexural bond strength of grout products

Mix # and product name	73°F		85°F						95°F					
	28 day		1 day		7 day		28 day		1 day		7 day		28 day	
	FBS psi	FP	FBS psi	FP	FBS psi	FP	FBS psi	FP	FBS psi	FP	FBS psi	FP	FBS psi	FP
#1 - BASF Masterflow 928	600	I+S	333	I	238	I	217	I	192	I	442	I	292	I
#2 - SikaGrout 328	833	S	263	I	258	I	375	I	35	I	131	I	129	I
#3 - SikaGrout 212	750	I+ G+ S	217	I	192	I	483	G	325	I	*	*	279	G
#4 - Dayton Superior 1107 Advantage Grout	650	I	54	I	48	I	104	I	48	I	49	I	92	I
#5 - Dayton Superior Sure-Grip HP Grout	667	S	258	I	483	I	558	**	26	I	165	I	375	I
#6 - W.R Meadow SEALTIGHT 588-10K	560	G	446	I	667	I	658	S	52	I	0	I	88	I
#7 - CTS Rapid Set CEMENT ALL	258	G+ I	25	I	233	I	200	I	N/A	N/ A	N/A	N/ A	N/A	N/A
#9 - Simpson StrongTie FX-228	529	G	283	I	345	I	500	**	283	I	217	I	238	I
#10 - Simpson StrongTie FX-229	600	G	212	G	500	G	471	G	167	I	188	I	400	G
#14 - Quikrete Non-Shrink Precision Grout	333	I	135	I	275	I	188	I	22	I	60	I	25	I
#19 - Euclid TAMMSGROUT SUPREME	267	G+ S	146	G	375	G	650	S	N/A	N/ A	N/A	N/ A	N/A	N/A
#20 - Euclid Euco Pre-cast Grout	317	I	154	G	121	I	87.5	I	90	G	333	I	183	G
#21 - Euclid NC Grout	417	I	146	I	400	I	254	I	213	I	500	I	321	I
#22 - Euclid NS Grout	218	I	221	I+S	600	I	600	S	296	I	388	S	513	I
#23 - Euclid Hi-Flow Grout	142	I	279	I	183	I	333	I	217	I	417	S	192	I

Note: FBS-Flexural bond strength, FP-Failure plane, I-Failed at interface, S-failed at substrate, G-failed at grout material, NA-not applicable because the fresh mixture set so fast and there was not enough time to prepare the composite specimens. *Specimen failed at interface during demolding due to misalignment. ** Failure plane was not recorded.

The effect of temperature variations on the 28-day flexural bond strength of 15 grout products is also illustrated in Figure 5.9. It is clearly shown that an increase in temperature mostly had negative influences on the 28-day flexural bond strength. For some products, a dramatic decrease in the 28-day flexural bond strength was noted as the temperature increased. Again, some products (e.g., #22 and #23) showed an opposite trend, in which high temperature helped to improve the 28-day flexural bond strength and the highest bond strength occurred at 85°F.

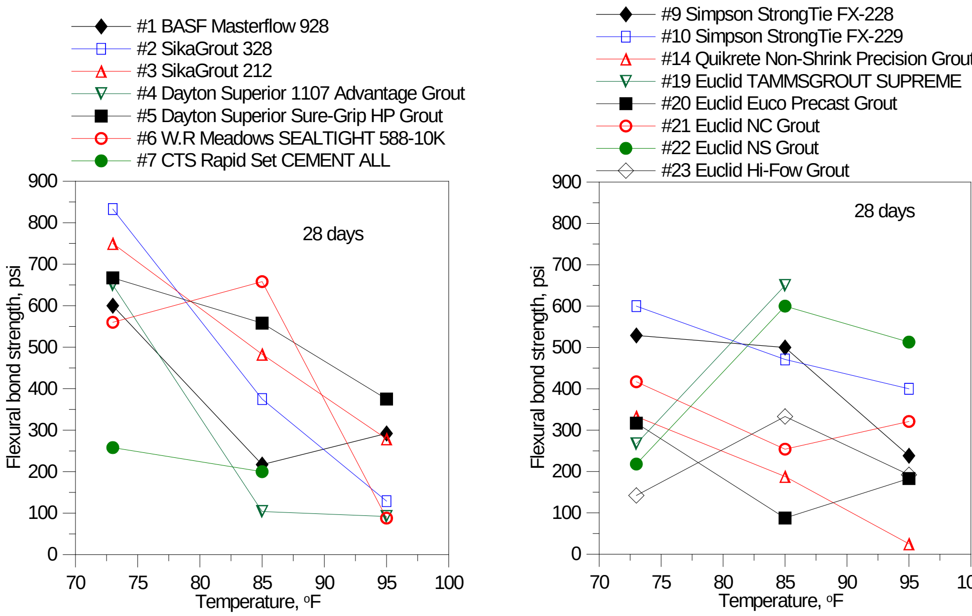


Figure 5.9 Effects of temperature on 28-day flexural bond strength of 15 grout products

In addition, the flexural bond strength development as a function of time is shown in Figure 5.10 for 85°F and Figure 5.11 for 95°F. At 85°F, most products showed the enhanced flexural bond strength with the longer curing time. However, two products (#1 BASF Masterflow 928 and #20 Euclid Euco Precast) demonstrated different behaviors, in which the flexural bond strength slightly reduced with the increasing curing time. This reverse trend was not understandable, which may be associated with the deviations in specimen preparation and testing.

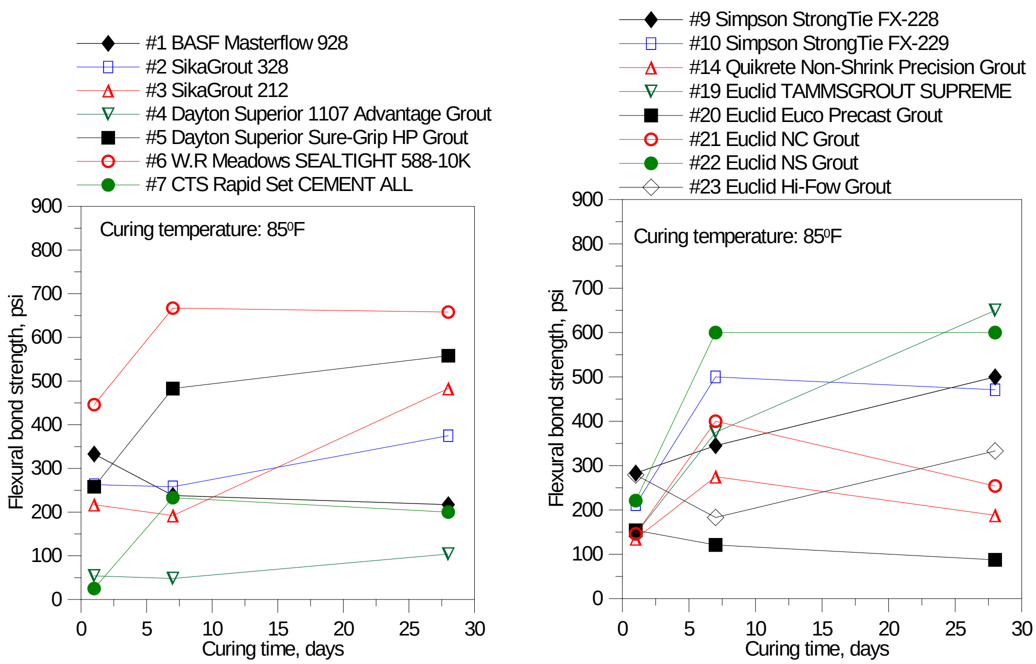


Figure 5.10 Flexural bond strength development with curing time at 85°F

Similarly, at 95°F, the flexural bond strength also increased with the curing time. However, this increase was very limited for most products. The main reason was that at the high temperature, the strength developed relatively faster at the early age, leaving limited room for the improvement at a late age. In addition, a comparison of Figure 5.10 with Figure 5.11 indicated that most products developed higher flexural bond strength at 85°F than that at 95°F. This was again due to the reduced flowability that led to poor bonding at high temperature.

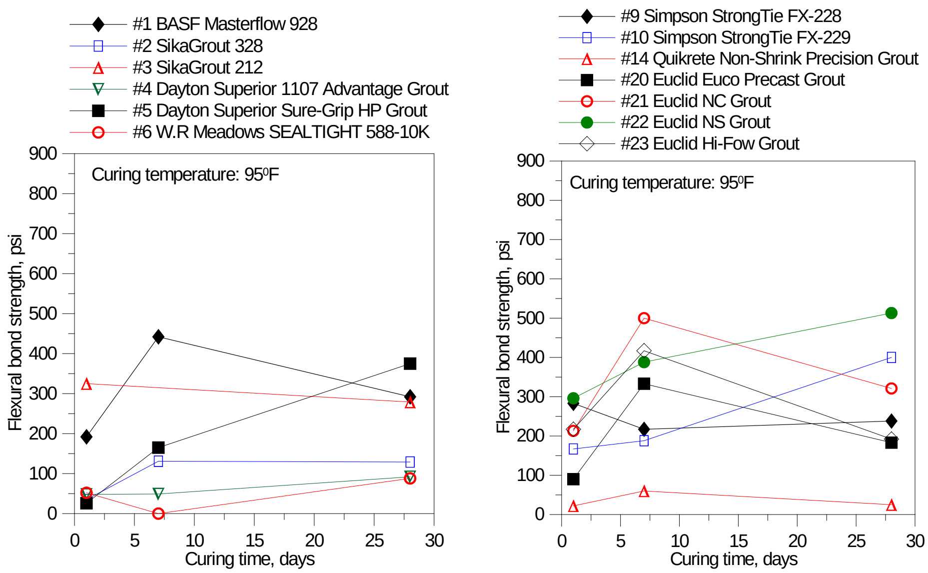


Figure 5.11 Flexural bond strength development with curing time at 95°F

5.2.6 Effects of Temperature Variations on Slant Shear Bond Strength of Grout Products

The slant shear bond test was also performed in this study to further evaluate the effects of temperature on the bonding capacity of grout products. The results are summarized in Table 5.7. Similar to what was observed in the flexural bond test, a high temperature generally resulted in a reduced slant shear bond strength at a specific age. This reduction can be again attributed to the combined effect of the lowered flowability and a reduced quality of hydration products as the temperature became higher. This also explain why the composite specimens were more likely to fail at the interface at a high temperature level.

Table 5.7. Effects of temperature on slant shear bond strength of grout products

Mix # and product name	73°F		85°F						95°F					
	28 days		1 day		7 days		28 days		1 day		7 days		28 days	
	SSBS, psi	FP	SSBS, psi	FP	SSBS, psi	FP	SSBS, psi	FP	SSBS, psi	FP	SSBS, psi	FP	SSBS, psi	FP
#1 - BASF Masterflow 928	2765	S	827	I	1447	I+G	2149	—	682	I	1454	I	1544	I+G
#2 - SikaGrout 328	3235	S	875	I	1407	I + S+G	1662	I+S	697	I+G	1247	I+G	1122	I
#3 - SikaGrout 212	2938	I + G + S	1027	G + I	1282	I	1709	I	1112	I+G	1384	I	2079	I+G
#4 - Dayton Superior 1107 Advantage Grout	1513	I	2314	I+G	2651	I + G	2876	I + S	1944	I	2429	I+G	2394	I+G
#5 - Dayton Superior Sure-Grip HP Grout	3770	I + G+S	1759	I + G	2204	I + G	3041	—	1732	I	2559	I	2522	I+G
#6 - W.R Meadow SEALTIGHT 588-10K	3228	G + S	1157	I	2342	I	2502	I+G+S	1258	I	2157	I+G	1419	I
#7 - CTS Rapid Set CEMENT ALL	1450	G + I	1082	I + G	1135	I + G	1285	G+I+S	NA	NA	NA	NA	NA	NA
#9 - Simpson StrongTie FX-228	2705	S	1120	I	1952	I+G	2219	—	1125	I	2134	I	2304	I+G
#10 - Simpson StrongTie FX-229	2880	I + G	1040	I	1762	I	2679	I+G	605	I	1307	I	1689	I
#14 - Quikrete Non-Shrink Precision Grout	2335	I + S	1205	I+G	2199	I	2209	I+S	800	I+G	1539	I+G	2222	I+G
#19 - Euclid TAMMSGROUT SUPREME	2895	I+G+S	1719	I + G	2367	I+G	2736	I + S+G	NA	NA	NA	NA	NA	NA
#20 - Euclid Euco Pre-cast Grout	2800	I + G	597	I	2574	I	2527	I+G	622	I+G	2484	I+G	2866	I+G
#21 - Euclid NC Grout	2548	I	621	I	1602	I+G	1370	I	1177	I	1622	I+G	2417	I+G
#22 - Euclid NS Grout	3018	I + G+S	1432	I+G	2102	I+G	2312	I+G+S	1862	I+G	2779	I+G	2669	I+G
#23 - Euclid Hi-Flow Grout	3375	I + G+S	235	I	2074	I+G	2252	I+G	1085	I	2577	I+G	2592	I+G

Note: SSBS-Slant shear bond strength, FP-Failure plane, I-Failed at interface, S-failed at substrate, G-failed at grout material, NA-not applicable because the fresh mixture set too fast to prepare the composite specimens.

The slant shear bond strength vs. temperature relationship was also plotted as shown in Figure 5.12. Obviously, the 28-day slant shear bond strength reduced with the increasing temperature. Only one product (#4 Dayton Superior 1107 Advantage Grout) showed an increased slant shear bond strength at the medium or high temperature level.

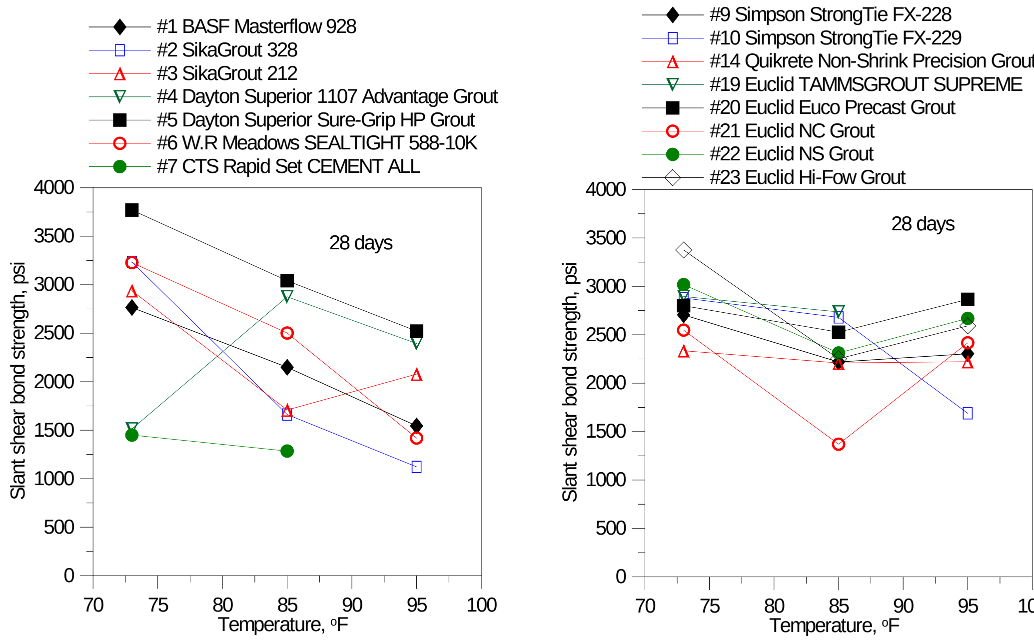


Figure 5.12 Effects of temperature on 28-day slant shear bond strength of 15 grout products

The slant shear bond strength increased with the curing time and the results are shown in Figure 5.13 for 85°F and Figure 5.14 for 95°F. It can be seen that most products gained the slant shear bond strength very rapidly at the early age (a week); while there was very limited growth or even slight reduction in the strength after that. This was again because the high temperature (85°F or 95°F) accelerated the hydration reactions and the strength gain primarily took place at early age. Unlike the flexural bond strength development, the slant shear bond strength development at 85°F did not differ significantly from that at 95°F (Figure 5.13 vs. Figure 5.14). This implied that high temperature had less negative impacts on the slant shear bond strength as compared with the flexural bond strength.

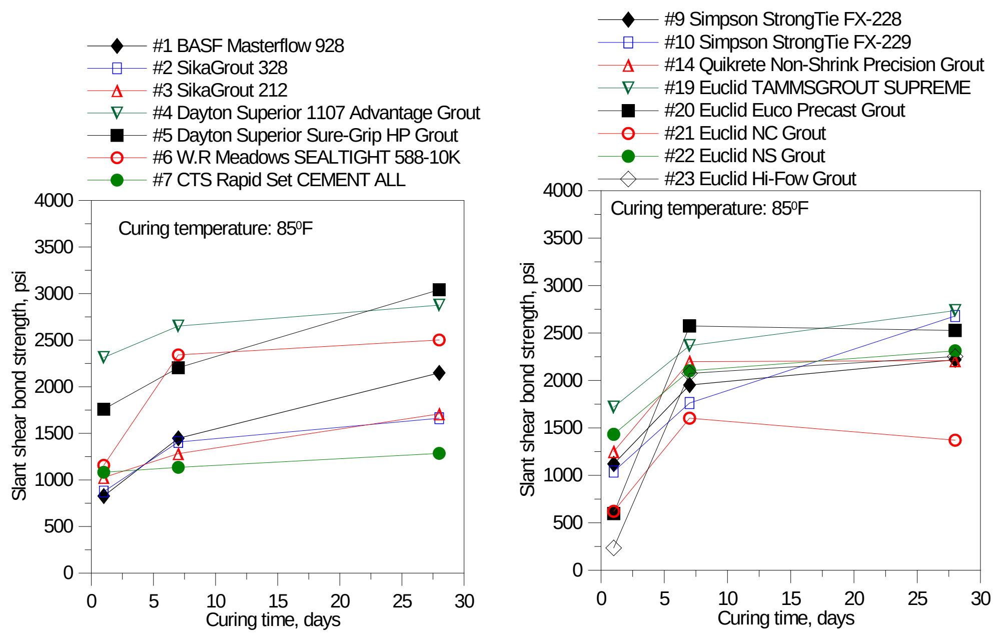


Figure 5.13 Slant shear bond strength development with curing time at 85°F

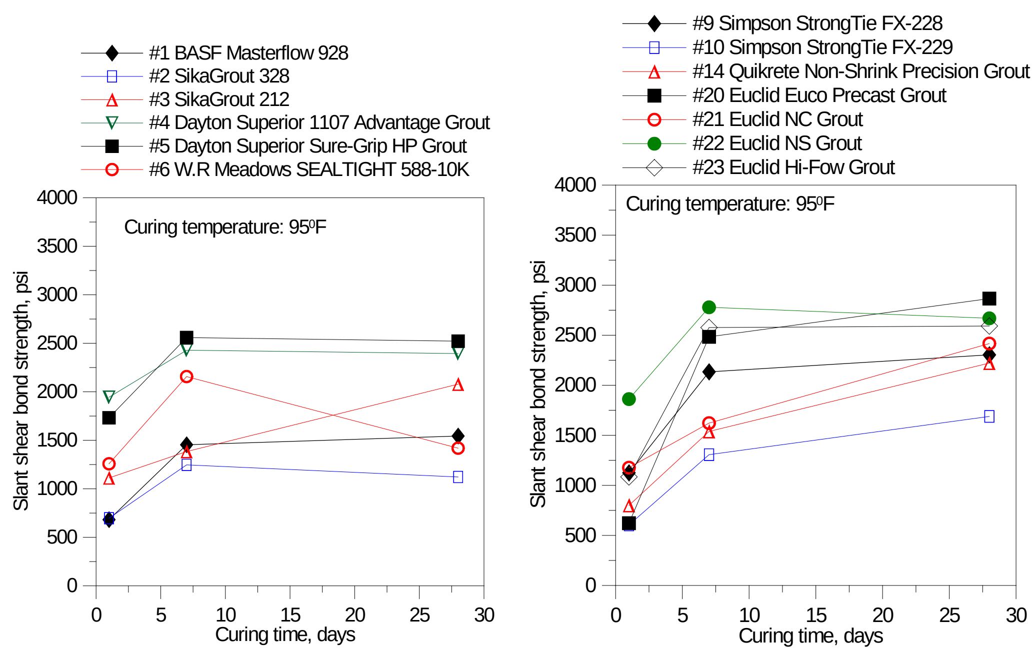


Figure 5.14 Slant shear bond strength development with curing time at 95°F

6.0 MODIFY EXISTING PRODUCTS AND DEVELOP NEW GROUT MATERIALS

6.1 Modifying Grout Products with Steel Fibers

One goal of this project was to investigate how to improve the properties of grout products through modifying the materials and proportions of these products. In this study, steel fibers were added into the plain grouts to see how they influenced the flowability, compressive strength development, and bonding capacity of grouts. Again, 15 products were chosen for these tests.

6.1.1. Effects of Steel Fibers on Flowability of Grout Products

The mini slump spread was measured before and after the steel fiber addition. The results are summarized in Table 6.1. It can be seen that adding steel fibers greatly impacted the mini-slump spread of grout products. A 3% (by the batch weight) steel fiber addition averagely reduced the min slump spread by 1 to 2 inches for most products. As described above, the mini slump spread measured the free deformability of a fresh grout in the absence of obstruction. It was an indication of materials' ability to advance into open spaces and even hidden voids. As a result, the decrease in the mini slump spread suggested that the steel fiber addition played a negative role in the void-filling capacity of grouts. This agreed with what was observed in conventional concrete, in which adding steel fibers into concrete would cause the loss of workability. The main reason is that steel fibers enhanced the stability of fresh grout due to the intermingling of fibers, thus reducing the free deformation of fresh mix. It can also be seen that two products (#1 BASF Masterflow 928 and #20 Euclid Euco Precast) exhibited a slight increase (0.5 inches) in the mini-slump spread after the fiber addition. This was opposite to the general trend. One possible explanation was that steel fibers increased the unit weight of fresh grout. Heavy weight may facilitate the deformation, which outweighed the intermingling effects of fibers. In addition, two products (#6 W.R. Meadow SEALTIGHT 588-10K and #14 Quikrete Non-shrink Precision Grout) showed no variations after the fiber addition.

Besides the mini slump test, the flow cone test was also performed in this study. As previously stated, it measured the time it took for the fresh grout to flow out of a cone. The test seemed to indicate the passing ability of a grout through the small opening; but it was actually related to the viscosity of fresh grout. High viscosity generally increased the friction between the particles as well as between the grout and the cone, thus leading to slow or even discontinuous flow. Conversely, very low viscosity and the lack of adhesion may cause flow to stop due to the blockage resulting from the segregation of sand particles. In addition, the flow time may be associated with the deformability (i.e. mini slump spread) of fresh grout. At a given viscosity, more deformable grout with a larger mini-slump spread would typically flow faster. Table 6.1gives the flow time of 15 grout products before and after fiber addition. It can be seen that six products had a reduced flow time after the steel fiber was added. This meant that the steel fibers assisted in facilitating the flow and improving the passing ability of fresh grout. One explanation was that small smooth steel fibers helped to lubricate the mix and reduce the friction. Another reason may be due to the increased unit weight of fresh grout after incorporating heavy steel fibers, which increased the potential of flow. A review of test results in Table 6.1 indicated that these products generally had relatively lower flow time meaning that they had adequate viscosity. In other words, steel fibers aided in increasing the flowability of grouts with adequate viscosity. For grouts with high viscosity (e.g. Sika Grout 328, Dayton Superior Sure Grip HP Grout), adding steel fibers were found to negatively affect the flow.

It seemed that there were some correlation between the flow time and the mini slump spread. Apparently, a grout showing small mini slump spread such as CTS Rapid Set CEMENT ALL was not flowable during the flow cone test; while a highly deformable grout with a larger mini slump spread (e.g. SikaGrout 212 or Simpson StrongTie FX-228) was more likely to flow rapidly and resulted in less flow time. However, this was not true for a viscous mix. For examples, some products having high mini slump spreads such as Dayton Superior 1107 Advantage and Sure-Grip HP Grout, showed long flow time or discontinuous flow. The primary reason was that these products typically had high viscosity that increased flow resistance, but did not affect the deformability of mix.

Table 6.1 Comparison of flowability with and without steel fiber additions at 73°F

Mix # and product name	Flow Time, Seconds		Mini Slump Spread, in.	
	Before adding fibers	After adding fibers	Before adding fibers	After adding fibers
#1 - BASF Masterflow 928	178	115	12	12.5
#2 - SikaGrout 328	258 (Discontinuous)	Stopped	10.5	9
#3 - SikaGrout 212	71	68	11.5	10
#4 - Dayton Superior 1107 Advantage Grout	209	115	12.5	11.5
#5 - Dayton Superior Sure-Grip HP Grout	769 (Discontinuous)	Stopped	10.25	10
#6 - W.R Meadow SEALTIGHT 588-10K	120	Stopped	12	12
#7 - CTS Rapid Set CEMENT ALL	Stopped	Stopped	5.25	4.75
#9 - Simpson StrongTie FX-228	210	Stopped	9	8.5
#10 - Simpson StrongTie FX-229	49	46	10	6.5
#14 - Quikrete Non-Shrink Precision Grout	189	Stopped	7	7
#19 - Euclid TAMMSGROUT SUPREME	Dry	*	Dry	*
#20 - Euclid Euco Pre-cast Grout	129	116	11	11.5
#21 - Euclid NC Grout	90	Stopped	11	8
#22 - Euclid NS Grout	137	110	10.5	9
#23 - Euclid Hi-Flow Grout	200	Stopped	11.5	10.5

*The fresh mixture was very dry and not suitable for fiber addition.

6.1.2. Effects of Steel Fibers on Compressive Strength of Grout Products

Adding steel fibers into the plain grouts had considerable influences on the compressive strength development. The compressive strength development with and without steel fibers are compared in Table 6.2. It can be seen that the effect of steel fibers on the early-age compressive strength was unclear because approximately 58% products showed a decreased 1-day compressive strength, but nearly 42% products displayed an increased 1-day compressive strength after 3% steel fibers were added. It can also be seen that the majority of products (approximately 80%) exhibited an increased compressive strength at both 7 and 28 days when 3% steel fibers were added. The increase in compressive strength may be attributed to the toughening effects of steel fibers on the matrix. Under the increasing load, crack would initiate in the matrix when the local stress exceeded the strength. In a plain grout, this crack would propagate and cause immediate break of material. However, the presence of steel fibers bridged the crack and transferred an additional load to the matrix through bonding. This caused new cracks to form in the matrix and increased the work of fracture. The toughening process would continue until the fibers were fully pulled out.

It should be noted that no consolidation was applied during specimen preparation. As a result, another effect of steel fibers on the compressive strength may be associated with the change in flowability that in turn affected the self-compaction of fresh grout. For some products, the use of steel fibers may reduce their self-compacting ability leading to a decrease in compressive strength.

Table 6.2 Comparison of compressive strength development with and without steel fiber additions at 73°F

Source Trade Name	Compressive strength without steel fibers, psi			Compressive strength with 3% steel fibers, psi		
	1 day	7 day	28 day	1 day	7 day	28 day
#1 - BASF Masterflow 928	4084	6375	8503	2966	8978	11700
#2 - SikaGrout 328		8938	10345	4071	7555	9238
#3 - SikaGrout 212	1430	4944	7636	1793	5644	6889
#4 - Dayton Superior 1107 Advantage Grout	3093	6922	9004	3770	8776	10567
#5 - Dayton Superior Sure-Grip HP Grout	1998	8135	11040	5578	9501	12064
#6 - W.R Meadow SEALTIGHT 588-10K	2308	5032	6213	876	8428	10689
#7 - CTS Rapid Set CEMENT ALL	8717		10921	6781	9784	10899
#9 - Simpson StrongTie FX-228	860	6331	6331	2071	6487	8029
#10 - Simpson StrongTie FX-229		2984	2984	888	4575	6654
#14 - Quikrete Non-Shrink Precision Grout	3827	7889	10415	1111	7125	11033
#19 - Euclid TAMMSGROUT SUPREME	3835	6572	8569	*	*	*
#20 - Euclid Euco Pre-cast Grout	1389	3929	7028	1269	5900	9881
#21 - Euclid NC Grout	1519	4506	7481	351	4181	8003
#22 - Euclid NS Grout	3889	6467	8950	4313	7265	9629
#23 - Euclid Hi-Flow Grout	2922	5913	9574	2524	7284	10277

Note: *the fresh mixture was very dry and not suitable for fiber addition

In addition, two grout products were selected in this study to investigate how the fiber dosage affected the compressive strength development. The results are shown in Figure 6.1. It can be seen that two products showed two different trends. For Dayton Superior Sure-Grip, with an increase in the steel fiber dosage from 1% to 6%, the compressive strength at all ages was noticeably improved. However, the StrongTie FX-229 showed an opposite trend. An increase in the fiber dosage resulted in a decrease in the compressive strength at all ages. This suggested that increasing the fiber dosage may be beneficial or detrimental to the compressive strength development of grout products. Again, this may be due to the effects of steel fibers on the flow behavior of the mix. If the fiber helped to facilitate the self compaction of fresh grout during the specimen preparation, the beneficial effect may occur; otherwise, a negative result would take place.

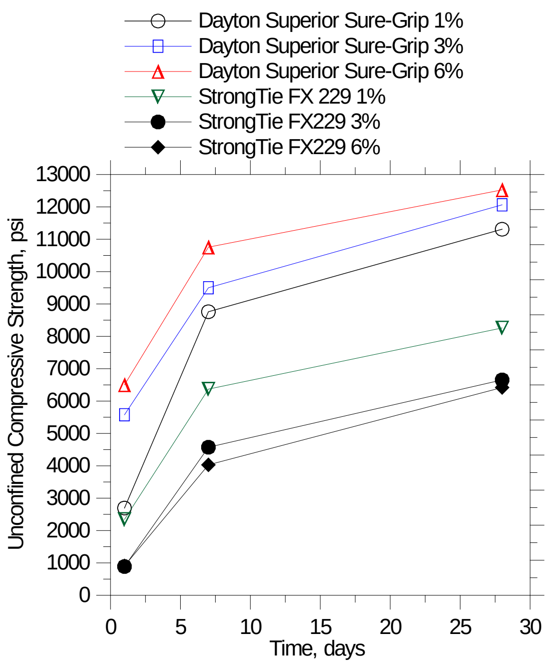


Figure 6.1 Compressive strength development of two selected grout products with different steel fiber dosage at normal temperature (73°C)

6.1.3. Effects of Steel Fibers on Flexural and Slant Shear Bond Strength of Grout Products

Steel fibers had distinct influences on the flexural and the slant shear bond behaviors of composite specimens. Table 6.3 summarized the bond strength and the failure plane of composite specimens with and without the steel fibers. It can be seen that eight products showed a reduced flexural bond strength as a result of 3% steel fiber additions. A review of the test data indicated that these products mostly had high flexural bond strength (above 600 psi). This suggested that for grout products already having high flexural bond strength, steel fiber addition would have negative impacts on the bond strength and thus would not be recommended. In opposition, six products showed an improved flexural bond strength as a result of 3% steel fiber additions. These products typically had relatively low flexural bond strength (less than 600 psi), implying that adding steel fibers was beneficial in improving the flexural bond strength of these products. The benefit of steel fiber addition was also reflected by the failure plane. For examples, before adding fibers, some composite specimens failed at interface (e.g. #20, #21, #22, and #23); however, they failed at grout after 3% steel fiber addition. Also, without steel fibers, brittle failure typically occurred. However, when steel fibers were added, they typically bridged the cracks, leading to tougher and more ductile failure. These bridged failure planes are also shown in the Figures in Appendix A4.

Similar to the flexural bond strength, the use of steel fibers may also improve or reduce the slant shear bond strength of grout products (shown in Table 6.3). For grouts with a high slant shear bond strength (e.g. #2, #3, #5, #6, #22, and #23), adding steel fibers typically reduced their slant shear bond strength and thus not recommended. Conversely, for grouts with a relatively low slant shear bond strength (e.g. #4 and #7), introducing steel fibers substantially improved their slant shear bond capacity and thus were beneficial. For these products, the use of steel fibers may also positively modify the failure plane. For example, the #4 Dayton Superior 1107 Advantage Grout failed at interface without steel fibers; however, after steel fiber addition, the composite specimens failed at substrate.

Table 6.3 Comparison of flexural and slant shear bond strength with and without steel fiber additions

Source Trade Name	Flexural bond (28 days, SSD, 73°F)				Slant shear bond (28 days, SSD, 73°F)			
	Without steel fiber		With 3% steel fiber		Without steel fiber		With 3% steel fiber	
	Strength, psi	Failure plane	Strength, psi	Failure plane	Strength, psi	Failure plane	Strength, psi	Failure plane
#1 - BASF Masterflow 928	600	I+S	567	I	2765	S	3201	S
#2 - SikaGrout 328	833	S	717	S	3235	S	3066	S
#3 - SikaGrout 212	750	I+G+S	708	G	2938	I + G + S	2561	G
#4 - Dayton Superior 1107 Advantage Grout	650	I	467	I	1513	I	3076	S
#5 - Dayton Superior Sure-Grip HP Grout	667	S	542	S	3770	I + G+S	2369	I+G
#6 - W.R Meadow SEALTIGHT 588-10K	560	G	604	I+S	3228	G + S	2746	I+G
#7 - CTS Rapid Set CEMENT ALL	258	G+I	113	I	1450	G + I	2569	I+S
#9 - Simpson StrongTie FX-228	529	G	775	S	2705	S	3144	I
#10 - Simpson StrongTie FX-229	600	G	533	G	2880	I + G	2332	I
#14 - Quikrete Non-Shrink Precision Grout	333	I	458	I	2335	I + S	2594	I
#19 - Euclid TAMMSGROUT SUPREME	267	G+S			2895	I+ G+S		
#20 - Euclid Euco Pre-cast Grout	317	I	288	G	2800	I + G	2969	I+G
#21 - Euclid NC Grout	417	I	617	G	2548	I	2769	I+G
#22 - Euclid NS Grout	218	I	533	G	3018	I + G+S	3006	I
#23 - Euclid Hi-Flow Grout	142	I	458	G	3375	I + G+S	3241	S

The steel fiber dosage also affected the bond strength of grout products. In this study, two products were investigated with the fiber dosage varying from 1% to 6% by weight. The results were illustrated in Figure 6.2. Clearly, increasing the fiber dosage from 1% to 6% would reduce both the flexural and the slant shear bond strength of grout products. This reflected that a low percentage of steel fibers was more advantageous for improving the bonding capacity. This may be associated with the change in flow behaviors as a result of increasing steel fiber dosage. As can be seen from Table 6.4, introducing 1% steel fiber into the grout increased the mini slump spread, implying that a small dosage of steel fibers helped to facilitate the flow, which in turn aided in achieving intimate contact. However, adding a high percentage of steel fibers especially 6% drastically reduced the mini slump spread, which would negatively affect the bonding due to the reduced flowability that may cause poor contact at the interface.

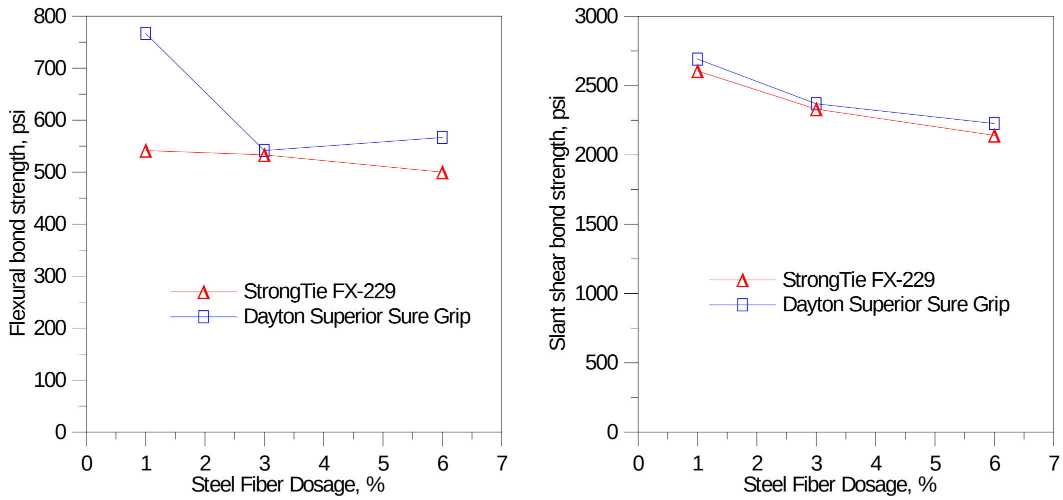


Figure 6.2 Flexural and slant shear bond strength of two grout products with different steel fiber dosage and SSD substrate moisture condition at normal temperature (73°C)

Table 6.4 Effects of steel fiber dosage on mini slump spread of grout products

Source	Mini slump spread measured 5 minutes after water was added, inches			
	0% steel fiber	1% steel fiber	3% steel fiber	6% steel fiber
#5 Dayton superior Sure-Grip HP grout	10.5	11.5	10	7.25
#10 Simpson StrongTie FX-229	8	9.5	6.5	6.5

6.2 Develop New Closure Pour Materials

One objective of this project was to develop cementitious grouts using local materials. Three types of mixes were designed: conventional cementitious mortars, high performance cementitious mortars, and ultra-high performance concrete.

6.2.1 Selection of Superplasticizers and Accelerators for Type III Cement-Based Mortars

The research work began with trying the conventional mortars using different types of accelerators and superplasticizers with the goal of achieving mortar mixes that showed good flowability, adequate setting, and rapid strength development. The results are summarized in Table 6.5. It should be noted that all mixes listed in Table 6.5 used the same materials and proportions except the accelerator and the superplasticizer. The detailed information on the materials and proportions is given in Table 3.3. As a result, the different results in the mini-slump spread, the time of setting, and the compressive strength development were due to the use of different chemical admixtures at the recommended dosage by the manufacturer.

The use of BASF admixtures (Glenium 7500-superplasticizer and AC 534-accelerator) would greatly enhance the flowability as well as the compressive strength; however, the main limitation was the relatively slow setting and the slow strength development at the very early age (e.g., 6 hours). In contrast, the W.R. Grace Adva-Cast 575 (superplasticizer) and Polarset (accelerator) were able to produce adequate flowability, setting and compressive strength development. The main advantage was the fast strength development at the very early age. The admixtures from Sika (Viscocrete 2100, NC, and Rapid 1) were unable to significantly increase the mini slump spread, while causing quick to flash set at the high temperature.

A comparison of these results indicated that the W.R Grace admixtures (Adva-Cast 575 and Polarset) provided better performance because the compressive strength development at the very early age is very critical for the closure pour where early public access is preferred. As a result, the W.R. Grace accelerator (Polarset) and superplasticizer (Adva-Cast 575) were chosen for the further testing.

Table 6.5 Effects of different superplasticizers and accelerators on basic properties of type III cement-based mortars

Mix # and Characteristics	Mini slump spread, in.	Time of Setting, min.		Compressive Strength Development, psi			
		Initial	Final	6 hours	1 day	7 day	28 day
#26 BASF Glenium 7500+AC534 (73°F)	11.5	240	280	*	8510	11666.7	13747
#27 W.R. Grace Adva-Cast 575+Polarset (73°F)	8.25	110	140	*	7167	8803.7	10708
#28 Sika Viscocrete 2100+NC (73°F)	6.5	140	195	*	9608	10972.7	13411
#29 Sika Viscocrete 2100 +Rapid 1 (73°F)	7	120	280	*	7286	8578.3	10615
#30 BASF Glenium 7500+AC534 (85°F)	11	170	200	1528	8208	11770.3	13157
#31 W.R. Grace Adva-Cast 575+Polarset (85°F)	8.25	140	170	3768	8402	10552	10969
#32 Sika Viscocrete 2100+NC (85°F)	9	150	250	988	10099	12826.7	12268
#33 Sika Viscocrete 2100 +Rapid 1 (85°F)	6.5	180	310	3401	7365	8310	10890
#34 BASF Glenium 7500+AC534 (95°F)	10	115	160	1167 (4hrs) 3534 (6hrs)	9378	11282	11711
#35 W.R. Grace Adva-Cast 575+Polarset (95°F)	4	70	100	3129 (4hrs) 4579 (6hrs)	7695	8854	9717
#36 Sika Viscocrete 2100+NC (95°F)	Quick set	40	130	**	**	**	**
#37 Sika Viscocrete 2100 +Rapid 1 (95°F)	Flash set	6	150	1316	4525	—	5353

Note: * Specimens were too weak; ** No specimens were made due to quick set.

6.2.2 Effects of Sand, W/C, and Quartz Flour on Basic Properties of Type III Cement-Based UHPC

In addition, the Ultra-High Performance Concrete (UHPC) was investigated in this study. The commercial UHPC is very costly and may not be suitable for applications under local weather. This project was attempted to develop UHPC using local materials under local weather conditions. Detailed information on materials and proportions is provided in the materials and proportions section (Table 3.4). The test results are summarized in Table 6.6. It can be seen that reducing W/C from 0.3 to 0.2 (#38, #39, and #40) noticeably accelerated setting, increased the compressive strength, and reduced the mini-slump spread. In particular, when the W/C was very low (e.g. 0.2), the mixture became so sticky that the min slump spread could not be adequately measured. Consequently, this mix would be difficult to place and finish, and was not be suitable for the closure pour. The accelerated setting may be associated with the high stickiness of mixture when the W/C became very low. A high sticky mix would create high friction during paddle mixing, which would generate high heat that accelerated the hydration reaction and setting. This was also confirmed by the temperature measurement, in which the temperature could averagely increase by 5 to 10°F during mixing.

The use of quartz flour (median diameter 3.1 µm) in UHPC with the sieved sand (#40 vs. #41) was observed to further increase the stickiness of mix, which in turn accelerated the setting. Again, the acceleration was possibly due to the heat generated during the paddle mixing. Also, adding quartz flour slightly increased the compressive strength. One explanation was that the quartz flour particles would readily fill the gap between the cement and the silica fume particles, which improved the particle gradation and thus the packing density of mix.

Using the natural river sand without sieving (#42 vs. #38) was noted to slightly reduce the flowability (e.g. the mini-slump spread) and the compressive strength. One reason was that the natural river sand contained coarse particles (retained on No 30 sieve, greater than 0.6mm), particularly some large particles (retained on No.4 sieve, greater than 4.75mm), which could negatively affect the gradation. Another reason could be the size effect of particles on strength. Large sand particles would have high potentials to develop weaker interfacial transition zones between the sand particle and the paste, thus weakening the material.

Similarly, incorporating the quartz flour into the natural river sand-based UHPC (#42 vs. #43) slightly increased the flow, accelerated the setting, and improved the compressive strength. This was again associated with the increased cohesiveness as well as the improved gradation between the silica fume and the cement after the quartz flour was added. Higher cohesiveness induced more heat during mixing and caused quick setting. Better gradation resulted in better workability as well as denser packing.

The use of fine masonry sand to replace the natural river sand (#44 vs. #42) also increased the flowability, accelerated the setting, and enhanced the compressive strength. This again may be ascribed to the improved gradation and the increased cohesiveness of the mix.

Table 6.6. Effects of sand, W/C, and quartz flour on basic properties of UHPC

Mix # and characteristics	Spread in.	Time of setting, min.		Compressive strength development, psi			
		Initial	Final	5 hours	1 day	7 day	28 day
#38 sieved river sand +0.3 W/C+ 0.043 HRWR+ 0.12 accelerator	8.75	180	220	1209	8000	12266	15866
#39 sieved river sand +0.25 W/C+ 0.043 HRWR+ 0.12 accelerator	4.5	150	200	1718	8819	13147	16895
#40 sieved river sand +0.2 W/C+ 0.043 HRWR+ 0.12 accelerator	Sticky	76	110	1292	9828	13745	17133
#41 sieved river sand +0.2 W/C+ 0.043 HRWR+ 0.12 accelerator + quartz flour	Sticky	60	80	1372	9044	14797	17184
#42 natural river sand+ 0.3 W/C+ 0.043 HRWR+ 0.12 accelerator	8.5	180	220	1149	7713	11583	15379
#43 natural river sand+ 0.3 W/C+ 0.043 HRWR+ 0.12 accelerator + quartz flour	8.75	165	200	1191	8030	12509	17669
#44 fine masonry sand +0.3 W/C+ 0.043 HRWR+ 0.12 accelerator	9.75	175	210	1322	8330	12289	16705

6.2.3 Flowability, Time of Setting, and Compressive Strength of Cementitious Mortars and UHPC

Based on the results in Table 6.5 and Table 6.6, seven mixes (#45 through #51) including normal mortar, high performance mortar, and UHPC were developed for full-scale testing including the bonding strength test, dry shrinkage test, rapid chloride permeability test, and freeze and thaw durability test. Air-entraining and shrinkage-reducing admixtures were also added to some mixtures to see whether or not these admixtures could improve the durability and reduce the shrinkage. In addition, two conventional concretes (Mixes #52 and #53) and two special rapid-set cement-based mortars (Mixes #54 and #55) were designed and tested, which were used as baselines to compare the performance of various cementitious materials.

Table 6.7 summarized the mini slump spread, the time of setting, and the compressive strength development of these mixes. It should be noted that mixes (#45 through #51) used similar materials and proportions as those in Table 6.6. However, noticeable reduction in flow and compressive strength was observed. This may be associated with the different mixing methods used in this study. All batches in Table 6.6 were mixed with a paddle mixer using a small batch size (0.5 ft^3). The intensive mixing by the paddle would lead to well-dispersed particles, which would result in more workable and denser mixture. In contrast, all batches in Table 6.7 were mixed in a rotating drum mixer with relatively large batch sizes (3.0 ft^3). These mixes typically consisted of low water-to-cement ratios, high percentages of fines especially silica fume, and high dosages of superplasticizer, which led to a very cohesive mixture. The lack of intensive mixing would result in an unvenly distributed system. This would have negative impacts on the flowability and the compressive strength.

The use of natural river sand to design the normal mortar (Mixes #45 and #47) successfully provided adequate flowability, setting, and compressive strength development. Adding the air-entraining admixture (Mix #47) further facilitated the flow, but slightly reduced the compressive strength. Replacing the normal river sand with the sieved river sand (Mix #45 vs. Mix #46) substantially reduced the flowability, but slightly increased the compressive strength. Besides the decrease in flowability, the sieved river sand was noted to cause excessive bleeding (as shown in the mini slump measurement in Figure E7 in the Appendix). As a result, the sieved sand was not recommended for proportioning the normal mortar. One reason was that the finer sieved sand required more paste for better workability. Without the use of silica fume, the mixture would become lean, easy to bleed, and less flowable.

The high performace mortar (#48), proportioned by incorporating a high percentage of silica fume into the normal mortar (#45), was observed to show the reduced flowability and the decelerated setting. It also exhibited a slight decrease in the compressive strength at early ages, but a significant increase in the compressive strength at 7 and 28 days. Adding the air-entraining admixture (AEA) and the shrinkage-reducing admixture (SRA) into the high performance mortar (#49 vs. #48) was found to increase the flowability and the 28-day compressive strength. The improved flowability may be ascribed to the reduced cohesiveness of mix as a result of air entrainment. It should be noted that air entrainment may increase the stickiness of mix when the mixture is lean and does not have sufficient fines. The increase in the 28-days compressive strength may be due to the dual effects of air entrainment. Although the entrained air voids typically reduced the compressive strength; they helped to reduce the stickiness of the mix. The reduction in stickiness helped to reduce the air entrapment as well as improved the self compaction, which was beneficial to the compressive strength particularly at the late age. It can also be seen that the use of AEA and SRA slowed down the setting and reduced the earl-age compressive strength. This may be due to the interaction between the chemical admixtures as a result of adding SRA that caused delays in setting and strength development.

Replacing the natural river sand with the fine masonry sand (#50 vs. #48) significantly improved the flowability and the compressive strength at all ages. As a result, the fine masonry sand would perform better when proportioning with silica fume in the high performance mortar.

The ultra high performance concrete (#51), proportioned in this study by adding the quartz flour and the steel fiber into the high performance mortar (#48), displayed adequate flowability, setting, and excellent compressive strength development. However, the mixture became extremely sticky and very difficult to mix and place due to the addition of extra fines (quartz flour). That was why the UHPC showed the lower compressive strength than the high performance mortar with the fine masonry sand (#50). For a very sticky mix, it was very hard to distribute the particles during the lab mixing, which would influence the packing density and the strength of UHPC.

The conventional concrete (#52) with accelerating admixture, designed in this study as a baseline for comparison, demonstrated good flowability, adequate setting, and acceptable compressive strength development. Without using accelerator (#53), the concrete showed relatively slower setting and compressive strength development at the early age, however, its 28-days compressive strength was high.

The CTS rapid-set cement-based mortar (#54) with the set-control admixture had good flowability and very high compressive strength development. Its main advantage was the rapid gain of compressive strength at the very early age (1-2 hours) and the main limitation was the relatively rapid setting even with the use of set control admixture. Similarly, the CTS DOT cement-based mortar (#55) showed acceptable flowability, very quick setting, and very rapid compressive strength development. However, its performance was not as good as that of CTS rapid-set cement-based mortar in this study.

Table 6.7. Mini slump spread, setting, and compressive strength development of different cementitious mortar and concrete

Mix # and characteristics	Spread, in.	Time of setting, min.		Compressive strength development at 73°F, psi			
		Initial	Final	6 hours	1 day	7 day	28 day
#45 Normal mortar (natural river sand)	7.5	150	210	440	5852	9140	10515
#46 Normal mortar (sieved river sand)	4.5	250	330	**	5042	9314	11053
#47 Normal mortar (natural river sand) + AEA	8.5	170	230	773 (5hrs)	6162	8144.7	9051
#48 High performance mortar (natural river sand)	6	175	225	**	5562	10613	12416
#49 High performance mortar +AEA+SRA (natural river sand)	10.5	270	340	**	3988	9449.7	13222
#50 High performance mortar (fine masonry sand)	8.5	180	200	976 (5hrs)	7670	11613	14721
#51 UHPC	6.5	130	180	617 (5hrs)	6715	9990	13826
#52 Normal concrete+accelerator***	23*	150	230	820	6485	8226.7	9570
#53 Normal concrete, no accelerator	25*	310	500	**	6075	8960	9877
#54 CTS rapid-set cement mortar	9.25	80	88	4623	8105	9271	10130
#55 CTS DOT cement mortar	7.25	58	72	3681	5668	7006.7	7984

Note: *measured using regular slump cone. ** the strength was too low to be measured. ***This concrete reached 4000psi in approximately 16 hours.

6.2.4 Flexural and Slant Shear Bond Strength of Cementitious Mortar and Concrete Developed in This Study

The bonding capacity of various cementitious materials developed in this study was investigated and the results are summarized in Table 6.8. It can be seen that the materials demonstrated a wide variety of flexural and slant shear bond strength when the substrate surface moisture changed. In general, all mortar mixes showed good to excellent flexural bond strength at the SSD moisture condition with values ranging from 421.9 to 853.7 psi. However, these mortar mixes particularly the high performance mortar and UHPC performed rather poorly with the lowest value of 63.5 psi when the substrate was dry. One reason was that the high performance mortar and UHPC comprised of high percentage of silica fume and very low water-to cement ratios (0.2 to 0.3). Any water loss from the fresh mixture would be significant. Consequently, water absorption by the dry substrate would cause insufficient hydration at the interface, leading to a weak bond. In contrast, the wet substrate would slightly supply water to the mixture. Under extremely low W/C, this limited water supply was less detrimental. As a result, the wet substrate is preferred over the dry substrate for mixes with a very low W/C and a high silica fume content.

Conversely, two concrete mixes (Mixes #52 and #53) exhibited relatively higher flexural bond strength at the dry substrate (734.3 and 847.5 psi), but they demonstrated relatively lower flexural bond strength at the wet substrate (433.6 and 635.8 psi). This was because two concrete mixes contained no or a small dosage of silica fume and a relatively high water-to-cement ratio (0.37). A small water loss due to the dry substrate absorption was less harmful to the strength gain. However, any water supply from the wet substrate would be unfavorable as it may increase the local W/C and prevent the grout penetration, thus reducing the bond strength.

For two CTS cement-based mortars, the highest flexural bond strength was observed when the substrate was SSD. However, the CTS cement-based mortars averagely had much lower flexural bond strength as compared with the type III Portland cement-based materials.

For most mortar and concrete mixes, the substrate moisture appeared to slightly affect the slant shear bond strength with typical values varying from 3000 to 3600 psi. This suggested that the slant shear bond test could be less sensitive to the substrate moisture condition as compared with the flexural bond test. However, the dry substrate substantially reduced the slant shear bond strength for UHPC or the high performance mortar with the fine masonry sand; while the wet substrate caused a noticeable reduction for the CTS DOT cement-based mortars.

Table 6.8. Flexural and slant shear bond strength of different cementitious mortar and concrete

Mix # and characteristics	Flexural bond strength (28 days), psi			Slant shear bond strength (28 days), psi		
	Dry	SSD	Wet	Dry	SSD	Wet
#45 Normal mortar (natural river sand)	736	853.7	688.6	3673.5	3658.5	3573.6
#46 Normal mortar (sieved river sand)	569.9	553.5	725.7	3581.1	3596.1	2953.8
#47 Normal mortar (natural river sand) + AEA	483.3	589	675	3673.5	3298.7	3383.7
#48 High Performance (HP) mortar (natural river sand)	349	733	715.3	3503.6	3596.1	3313.7
#49 HP mortar +AEA+SRA (natural river sand)	453.6	722.7	791.7	3668.5	3296.2	3208.7
#50 HP mortar (fine masonry sand)	100.8	738.5	623.8	2271.6	3381.2	3381.2
#51 UHPC	63.5	657.5	604.3	1399.4	3296.2	3383.7
#52 Normal concrete+accelerator	734.3	562.6	433.6	3183.7	3341.2	3406.1
#53 Normal concrete, no accelerator	847.5	693.3	635.8	3201.2	3408.6	3326.2
#54 CTS rapid-set cement mortar	241.5	421.9	308.3	2781.4	3086.3	2696.4
#55 CTS DOT cement mortar	259.9	593.8	506.1	2658.9	2953.8	1804.3

For easy comparison, the effect of substrate surface moisture condition on the flexural bond strength is also illustrated in Figure 6.3. Clearly, all mortar mixes especially high performance mortars and UHPC again displayed better performance at the SSD substrate surface, followed by wet and then dry substrate surfaces. However, for two concrete mixes, the dry substrate surface performed well, but the wet substrate surface performed poorly.

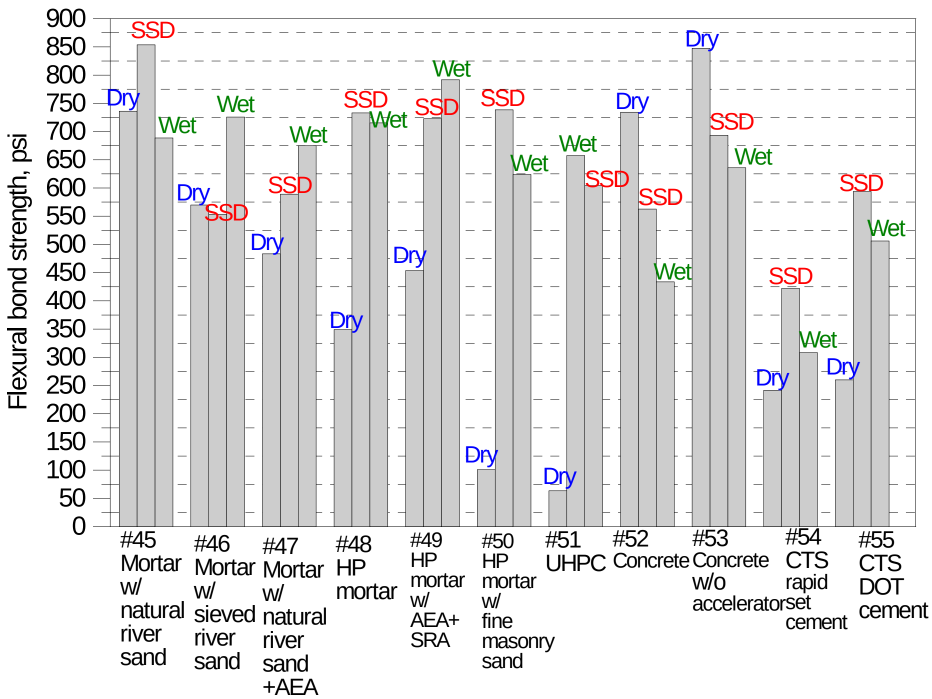


Figure 6.3 Flexural bond strength of cementitious mortar and concrete developed in this study

Similarly, the variation of slant shear bond strength with the substrate surface moisture conditions is illustrated in Figure 6.4. As compared with the flexural bond strength (Figure 6.3), the slant shear bond strength evidently showed less variation when the substrate moisture changed. Also, it became more obvious that the UHPC and the high performance mortar with the fine masonry sand exhibited the lowest bond strength (both flexural and slant shear) in the presence of dry substrate.

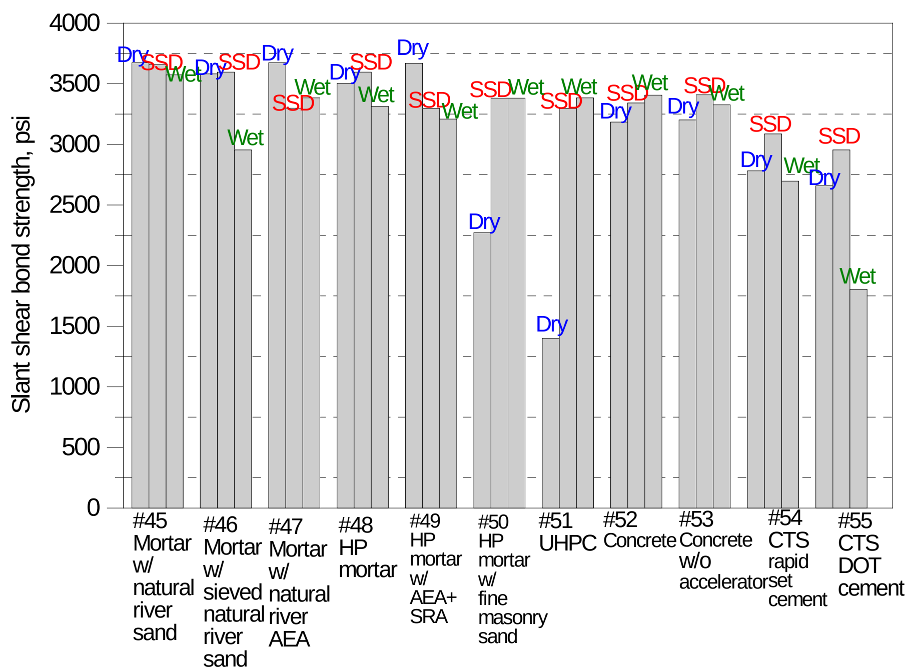


Figure 6.4 Slant shear bond strength of cementitious mortar and concrete developed in this study

6.2.5 Dry Shrinkage, Rapid Chloride Permeability, and Freeze and Thaw Durability of Cementitious Mortar and Concrete

The dry shrinkage, the rapid chloride permeability, and the freeze and thaw durability were evaluated in this study and the results are provided in Table 6.9. Almost all mortar mixes and the UHPC mix showed medium (0.05% to 0.1% at 28 days) to high (> 0.1% at 28 days) free dry shrinkage based on the criteria that were commonly accepted in conventional concrete[52]. This implied that these materials had high risks of debonding or developing shrinkage cracking. Conversely, the two normal concrete mixes and two CTS cement-based mortars demonstrated low free dry shrinkage (<0.05% at 28 days), meaning that they would have low potentials to dry shrinkage debonding or cracking. In addition, all mortar mixes did not meet the criteria specified by Tepke and Tikalsky[53]. Only the two concrete mixes and the two CTS cement-based mortars met the requirement and can be classified as Grade 1.

The normal mortar without the silica fume and the air entrainment (#45) showed very high rapid chloride permeability, but good resistance to cyclic freezing and thawing. The high permeability may be due to the use of high early strength cement (Type III) and the absence of silica fume because the rapid hydration reaction is more susceptible to create more porous hydration products. Without the refinement of pozzolanic reaction by silica fume, these porous pastes would result in high permeability. The good freeze and thaw durability may be associated with the presence of entrapped air voids in the mix (3.3%). In contrast, the normal mortar with AEA and a small dosage of silica fume (8% by weight of cement) (#46) exhibited a slight decrease in the rapid chloride permeability and the excellent resistance to the freeze and thaw cycles with essentially no deterioration after 300 cycles. This further confirmed that the use of silica fume was able to reduce the permeability; while the entrained air voids helped to increase the freeze and thaw durability.

The high performance mortar (#48), designed by adding a high percentage of silica fume (27.5% by weight of cement) and a high dosage of superplasticizer, demonstrated low rapid chloride permeability and acceptable freeze and thaw durability. The high percentage of silica fume and the high dosage of superplasticizer created a very cohesive mix, which caused a high entrapped air content (5%). This high level of entrapped air voids may aide in improving the freeze and thaw resistance of the mix. Interestingly, adding the AEA and the shrinkage-reducing admixture (SRA) into the high performance mortar (#49) was found to increase the rapid chloride permeability and to reduce the freeze and thaw durability. The addition of air-entraining admixture (AEA) was supposed to increase the fresh air content in the mix; however, the use of the shrinkage-reducing admixture (SRA) together with AEA surprisingly caused the air loss. The lack of air void protection led to the reduction in the freeze and thaw resistance. The air loss may be possibly due to the incompatibility of AEA with SRA in the mix.

The UHPC displayed high rapid chloride permeability and high freeze and thaw durability. The high rapid chloride permeability may be caused by the high percentage of steel fibers present in the specimen, which increased the electric conductivity of cementitious materials. As a result, it was not a direct reflection of porosity of the material. In fact, the rapid chloride permeability test was not applicable to the steel fiber reinforced cementitious materials such as UHPC. The high freeze and thaw durability may be associated with the dense paste as well as the presence of high entrapped air content.

As a comparison, the normal concrete mixture with 8% silica fume and air entrainment (#53) performed very well, which showed low rapid chloride permeability and high freeze and thaw durability. The silica fume addition helped to reduce the rapid chloride permeability; while the high entrained air content assisted in enhancing the freeze and thaw resistance. It can also be seen that adding accelerator into the normal concrete mixture (#52) was noted to increase the rapid chloride permeability and reduced the entrained air content. The increased permeability can be again ascribed to the accelerated hydration reaction that led to porous microstructure of paste; while the reduced air entrainment can be due to the interaction and incompatibility of admixtures between the accelerator and the air entraining agent.

The two CTS cement-based mortars performed very poorly. They showed high rapid chloride permeability and very low freeze and thaw resistance. The high permeability was an indication of high porosity of paste resulting from the rapid hydration reaction of CTS rapid-set cement. The very low freeze and thaw durability may be due to the lack of entrained air void system and the porous paste.

Table 6.9. Permeability, freeze and thaw durability, and dry shrinkage of different cementitious mortar and concrete

Mix # and characteristics	RCPT		FT durability			Dry shrinkage, %	
	Charge passed (coulombs)	Chloride ion penetrability	Fresh air, %	Relative dynamic Modulus after 300 cycles, %	Weight loss after 300 cycles, %	7 days	28 days
#45 Normal mortar (natural river sand)	8461	High	3.3	97.5	-0.3	0.035	0.1065
#46 Normal mortar (sieved river sand)	*	*	*	*	*	0.0415	0.1255
#47 Normal mortar (natural river sand) + AEA	7929.7	High	9	100	-0.15	0.073	0.101
#48 High Performance (HP) mortar	1563.7	Low	5	70	-0.15	0.066	0.119
#49 HP mortar +AEA+SRA	3804	Moderate	2.9	39	-0.15	0.049	0.093
#50 HP mortar (fine masonry sand)	*	*	*	*	*	0.0875	0.1175
#51 UHPC	6730.7**	High	4.7	100	-0.1	0.0755	0.099
#52 Normal concrete + accelerator	2781	Moderate	4.9	100	0.1	0.0295	0.048
#53 Normal concrete, no accelerator	1066	Low	7.2	100	0.05	0.028	0.046
#54 CTS RS cement + set control+ BASF Superplasticizer	5812	High	2.2	0	10.1	0.0345	0.037
#55 CTS DOT cement + set control + BASF Superplasticizer	6241	High	2.6	37	14	0.041	0.048

Note: *The tests were not performed. ** High value was due to steel fibers used in the mixtures.

7.0 SUMMARY AND CONCLUSIONS

The grout products collected in this study exhibited a wide variety of performance under the room temperature (73°F) and the SSD substrate moisture condition as shown in Table 7.1. In general, most grouts showed good flowability (medium to high), adequate early-age compressive strength (medium to high), high 28-day compressive strength, and acceptable bond strength (medium to high). While these properties were essential for the closure pour, the high dry shrinkage and the slow setting would be the major concerns for these products. This was because the excessive dry shrinkage would be likely to cause debonding or cracking; whereas slow-setting would slow down the construction.

Table 7.1 Result summary of basic properties for 25 grout products

Trade Name	Flowability	Setting	Compressive strength		Flexural bond strength	Slant shear bond strength	Dry shrinkage
			Early age	28 d			
#1 - BASF Masterflow 928	Medium	Slow	High	High	High	High	High
#2 - SikaGrout 328	High	Slow	High	High	High	High	High
#3 - SikaGrout 212	High	Slow	Low	High	High	High	High
#4 - Dayton Superior 1107 Advantage Grout	Medium	Slow	Medium	High	High	Medium	High
#5 - Dayton Superior Sure-Grip HP Grout	High	Slow	Medium	High	High	High	High
#6 - W.R Meadow SEALTIGHT 588-10K	High	Slow	Medium	High	Medium	High	High
#7 - CTS Rapid Set CEMENT ALL	Medium	Quick	High	High	Low	Medium	Low
#8 - Hilti Epoxy Grout CB-G EG	N/A*	N/A*	High	High	Medium	Medium	***
#9 - Simpson StrongTie FX-228	High	Slow	**	High	Medium	High	High
#10 - Simpson StrongTie FX-229	Medium	Slow	Low	Medium	High	High	Medium
#11 - CeraTech Pavemend DOTLine	Dry	Quick	High	High	Medium	High	Low
#12 - CeraTech Pavemend SL	Dry	Quick	Medium	High	Medium	High	Low
#13 - VEXCON CERTI-VEX Grout #1000	Low	Slow	Low	Low	Very low	Medium	***
#14 - Quikrete Non-Shrink Precision Grout	Low	Normal	Medium	High	Medium	High	High
#15 - ChemMasters Conset™ Grout	Dry	Slow	**	High	Medium	High	High
#16 - Ash Grove No-shrink grout	Dry	Slow	Low	High	High	High	High
#17 - KAUFMAN Non-Shrinking Precision Grout	Dry	Slow	Low	High	High	High	***
#18 - Euclid E^3-DP Epoxy Grout	N/A*	N/A*	High	High	Medium	Medium	***
#19 - Euclid TAMMSGROUT SUPREME	High	Quick/ Slow	Medium	High	Low	High	Medium
#20 - Euclid Euco Pre-cast Grout	High	Slow	Low	High	Medium	High	Medium
#21 - Euclid NC Grout	Low	Slow	Low	High	Medium	High	Medium
#22 - Euclid NS Grout	High	Slow	Medium/ High	High	Low	High	High
#23 - Euclid Hi-Flow Grout	High	Slow	Medium	High	Low	High	High
#24 - Phoscrete Four-Seasons	Dry	Quick	High	High	Low	Low	***
#25 - Phoscrete VO-Plus	N/A	Flash	High	High	Very low	Low	***

Notes: *N/A: Not Applicable; **Early compressive strength was very low and could not be measured; *** shrinkage could not be measured due to poor specimen preparation as a result of flash set or very dry mix.

Criteria for property classifications: **Flowability:** High-Mini slump spread greater than 10" measured 5 minutes after water was added; Medium – 8" to 10"; Low- 4" to 8"; Dry-less than 4". **Setting:** Flash-Initial set less than 10 minutes; Quick–Initial set less than 1 hour; Normal–Initial set 1 to 3 hours; Slow-Initial set more than 3 hours. **Early compressive strength**: High – 4000psi or above in 1 day; Medium–2000 to 4000 psi in 1 day, low – less than 2000psi in 1 day. **28 days Compressive Strength**: High – 6000psi or above; Medium–4000 to 6000 psi, low – less than 4000psi. **Flexural bond strength**: High – failure peak stress 600psi or above; Medium–300 to 600 psi, low – 100 to 300psi, Very low-less than 100psi. **Slant shear bond strength**: High – bond strength 2000psi or above; Medium–bond strength 1000 to 2000 psi, low – 300 to 1000psi, and very low-less than 300psi.

Most of the 13 selected grout products showed medium to low permeability and nearly all 13 grouts demonstrated very high freeze and thaw durability as shown in Table 7.2. Surprisingly, some grouts with high permeability showed high resistance to freeze and thaw attack.

Table 7.2 Result summary of permeability and durability for 13 selected grout products

Mix # and product name	Permeability	Freeze/thaw durability
#1 - BASF Masterflow 928	Moderate	High
#2 - SikaGrout 328	Moderate	High
#3 - SikaGrout 212	Very low	High
#4 - Dayton Superior 1107 Advantage Grout	Moderate	High
#5 - Dayton Superior Sure-Grip HP Grout	Low	High
#6 - W.R Meadow SEALTIGHT 588-10K	Low	High
#7 - CTS Rapid Set CEMENT ALL	High	Low
#9 - Simpson StrongTie FX-228	Low	High
#19 - Euclid TAMMSGROUT SUPREME	Low	High
#20 - Euclid Euco Pre-cast Grout	High	High
#21 - Euclid NC Grout	High	High
#22 - Euclid NS Grout	Low	High
#23 - Euclid Hi-Flow Grout	Low	High

Criteria for property classifications: **Permeability**: Very low-total chloride ion charge passed over a period of 6 hours below 1000 coulombs; Low-between 1000 and 2000 coulombs Moderate- between 2000 and 4000 coulombs; and High-greater than 4000 coulombs. Freeze/thaw durability

It can be concluded that the grout from BASF (Masterflow 928) generally performed well with acceptable flowability, high compressive strength, excellent bonding capacity, fair permeability, and good freeze and thaw durability. The main concerns were the slow setting and high dry shrinkage.

Similarly, the two Sika grout products (Sika grout 328 and 212) exhibited good performance in flowability, compressive strength, bonding capacity, permeability, as well as freeze and thaw durability with the same concerns of slow setting and high dry shrinkage.

The two Dayton Superior grouts (1107 advantage and Sure-Grip High Performance) showed medium to high flowability, medium early-age compressive strength and high 28-day compressive strength, medium to high bonding capacity, moderate to low permeability, and high freeze and thaw durability. Again, the main concerns were the slow setting and the high dry shrinkage.

The majority of grouts from Euclid (TAMMSGROUT SUPREME, Euco Pre-cast, NC, NS, and Hi-flow) showed high performance in flow, 28-day compressive strength, slant shear bonding capacity, and freeze and thaw durability. The main disadvantages included slow setting, medium to low early-age compressive strength and flexural bonding capacity, and medium to high levels of dry shrinkage. In addition, the NC grout had low flowability and high permeability. The NS grout displayed high permeability.

The Simpson StrongTie FX-228 demonstrated excellent performance in flow, 28-day compressive strength, slant shear bonding, permeability, and freeze and thaw durability. Its main disadvantages were slow setting, very low early-age compressive strength, and high free shrinkage. In contrast, the Simpson StrongTie FX-229 showed high bonding capacity. The main limitations were the slow setting and low early-age compressive strength. Its medium flow and 28-day compressive strength were also discouraging. Due to its relatively poor performance, the permeability and freeze and thaw durability were not evaluated in this study.

The two products from CeraTech (Pavemend DOTLine and SL) were basically not workable (dry) when the average dosage of water recommended in the product data sheet was added. This made them unsuitable for the closure pour application. They also set quickly, gained medium to high compressive strength and bonding strength, as well as shrunk less as compared with conventional concrete.

Likewise, the two products from Phoscrete (Four-Seasons and VO-Plus) set quickly and the VO-Plus grout even showed flash set, which caused poor contact between the grout and the substrate leading to low bonding capacity. However, they developed the compressive strength extremely fast.

The VEXCON CERTI-VEX Grout #1000 performed poorly in this study and was inadequate for the closure pour application.

The Quikrete Non-Shrink Precision Grout showed normal to high performance in setting, compressive strength, and bonding. However, its flowability was low and dry shrinkage was high.

The remaining cementitious grout products (ChemMasters ConsetTM Grout, Ash Grove No-shrink grout, and KAUFMAN Non-Shrinking Precision Grout) all had low flowability at the average water content recommended. They set slowly and developed strength slowly. Clearly, these limitations made them inappropriate for the closure pour. However, these products had high 28-day compressive strength and bonding capacity.

The two epoxy grouts (Hilti Epoxy Grout CB-G EG and Euclid E^3-DP) showed very high compressive strength both at the early age and at 28 days. They also had medium levels of bonding capacity.

The substrate surface moisture condition had noticeable effects on the bond capacity of grout products, especially on the flexural bond strength. However, there was no clear trend showing which substrate surface moisture condition performed best because different products showed different results. For the flexural bond capacity, approximately 44% of the products performed rather poorly at the dry substrate surface, 24% of the products showed relatively poor performance at the wet substrate surface, 16% of the products exhibited the lowest bond strength at the SSD substrate surface, and 16% of the products did not show significant differences when the substrate surface moisture condition changed. In comparison, the substrate surface moisture had less effects on the slant shear bond capacity. For more than 40% of the products, the substrate surface moisture did not significantly affect the slant shear bond strength. Only 20% of the products performed relatively poorly at the dry substrate and 24% of the products displayed the lowest slant shear bond strength at the wet substrate surface.

The temperature change had great impacts on the flowability, time of setting, compressive strength development, and bond capacity. Increasing temperature generally reduced the flowability of fresh grout. At a higher temperature level, the flowability of fresh grout decreased more rapidly with time. However, for some grouts such as Dayton Superior 1107 Advantage Grout, the flowability was noted to increase with the increasing temperature. High temperature typically accelerated the setting of fresh grouts; but some grouts showed the decelerated setting when the temperature increased from 73°F to 85°F. In addition, increasing temperature generally increased the compressive strength of grouts at all ages; however, some grouts showed a slightly reduced 28-day compressive strength. In a rare case, the grout showed a reduced compressive strength at both early-age and 28 days. Conversely, an increase in temperature mostly reduced the flexural and the slant shear bond strength. Only a few products showed an increased bond strength when the temperature increased from 73°F to 85°F, and then a decreased bond strength as the temperature increased from 85°F to 95°F.

The use of steel fibers to modify the grout products significantly affected the grout properties. For most grout products, adding 3% steel fibers into the fresh grout significantly reduced its flowability. Some grouts (e.g. W.R. Meadow SEALTIGHT 588-10K and Quikrete Non-shrink Precision Grout) showed no changes in flowability after the fiber addition and some grouts (e.g. BASF Masterflow 928 and Euclid Euco Precast Grout) showed a slightly increased flowability. For most grout products, the steel fiber addition had positive effects on the compressive strength particularly at late ages; however, some products showed a reduced compressive strength especially at the early age. For grout products with high bond strength, adding 3% steel fibers normally caused a reduced bond strength (both the flexural and the slant shear). For grout products with low bond strength, the steel fiber addition significantly improved the bond strength (both the flexural and the slant shear). It seemed that a low fiber dosage (less than 3%) was more effective in enhancing the bond strength than a high fiber dosage (6%).

The normal mortar, high performance mortar, and ultra-high performance concrete developed in this study using local materials can be a successful substitute for the commercial grout products. The conventional mortar without accelerating admixture provided good flowability, adequate setting, high compressive strength at both 1 day and 28 days (4000psi in approximately 17 hours), high flexural and slant shear bond strength at all substrate surface moisture conditions, as well as excellent freeze and thaw durability. The main limitations included high dry shrinkage and relatively high permeability.

The high performance mortar showed better compressive strength particularly at 28 days as compared with the normal mortar. It also had acceptable flowability, normal setting, excellent bonding capacity at wet and SSD substrate, as well as low permeability. The main disadvantages were low freeze and thaw durability, low bond strength at dry substrate, and high dry shrinkage.

The UHPC demonstrated similar behaviors as the high performance mortar except that the UHPC exhibited high freeze and thaw durability.

In addition, the conventional concrete (similar to TDOT class D mix) with accelerating admixture displayed acceptable performance in all the tests in this study. It had good flowability, normal setting, good compressive strength development (4000psi in approximately 16 hours), excellent bond strength at all substrate surface moisture conditions, low permeability, low dry shrinkage, as well as excellent freeze and thaw durability.

The CTS rapid-set cement-based mortars showed relatively low bond strength, high permeability, as well as poor freeze and thaw durability; although they had low free dry shrinkage, high compressive strength, and gained the strength extremely fast at the very early age.

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APPENDIX A – FAILURE MODE OF FLEXURAL BOND TEST FOR GROUT PRODUCTS

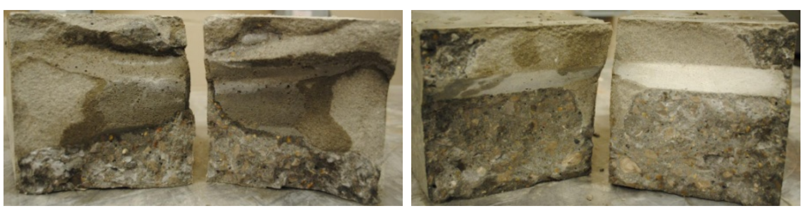
A.1 Normal Temperature(73°F) and Different Substrate Surface Moisture Conditions at 28 Days

(a) Dry (b) SSD (c) Wet

Figure A1 - Failure patterns of flexural bond test for BASF Master Flow 928 at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #1)

(a) Dry (b) SSD (c) Wet

Figure A2 - Failure patterns of flexural bond test for Sika Grout 328 at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #2)



(a) Dry (b) SSD

Figure A3 - Failure patterns of flexural bond test for Sika High Performance Grout 212 at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #3)

(a) Dry (b) SSD (c) Wet

Figure A4 - Failure patterns of flexural bond test for Dayton Superior 1107 at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #4)

(a) Dry (b) SSD (c) Wet

Figure A5 - Failure patterns of flexural bond test for Dayton Superior Sure Grip at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #5)

(a) Dry (b) SSD

Figure A6 - Failure patterns of flexural bond test for W.R Meadows 588-10K at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #6)

(a) Dry (b) SSD (c) Wet

Figure A7 - Failure patterns of flexural bond test for CTS CEMENT ALL at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #7)

(a) Dry (b) SSD (c) Wet

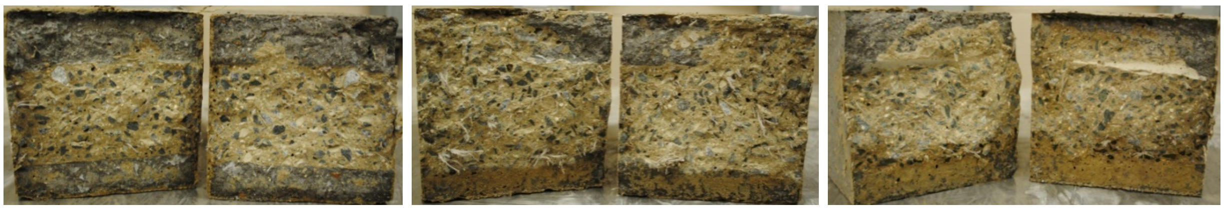
Figure A8 - Failure patterns of flexural bond test for Hilti Epoxy Grout CB-G EG at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #8)

(a) Dry (b) SSD (c) Wet

Figure A9 - Failure patterns of flexural bond test for SIMPSON Strong-Tie FX-228 at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #9)

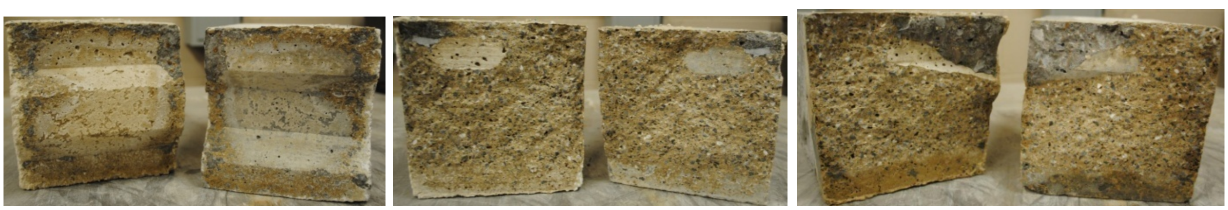
(a) Dry (b) SSD (c) Wet

Figure A10 - Failure patterns of flexural bond test for SIMPSON Strong-Tie FX-229 at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (#10)



(a) Dry (b) SSD (c) Wet

Figure A11 - Failure patterns of flexural bond test for Ceratech Pavemend DOTLine at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #11)

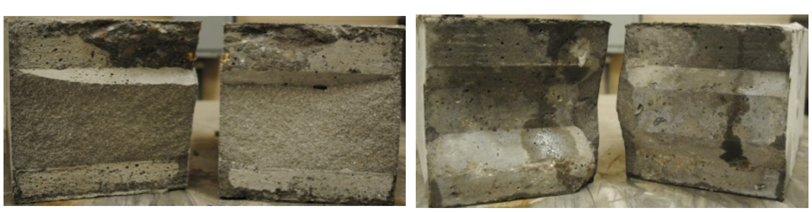


(a) Dry (b) SSD (c) Wet

Figure A12 - Failure patterns of flexural bond test for Ceratech Pavemend SL at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #12)

(a) Dry (b) SSD (c) Wet

Figure A13 - Failure patterns of flexural bond test for Vexcon Certi-Vex Grout #1000 at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #13)

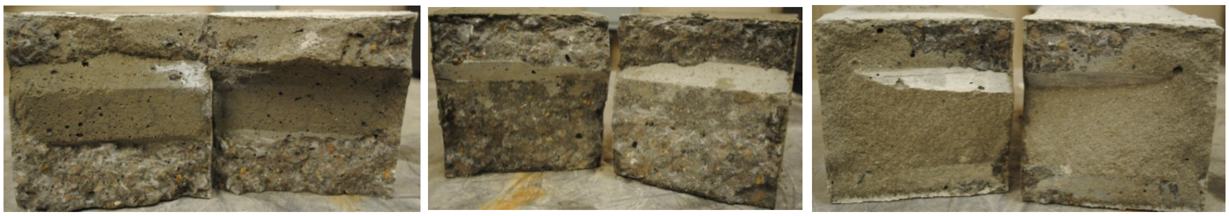


(a) Dry (b) SSD

Figure A14 - Failure patterns of flexural bond test for Quikrete Non-Shrink Precision Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #14)

(a) Dry (b) SSD (c) Wet

Figure A15 - Failure patterns of flexural bond test for ChemMasters Conset^{TM} Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #15)

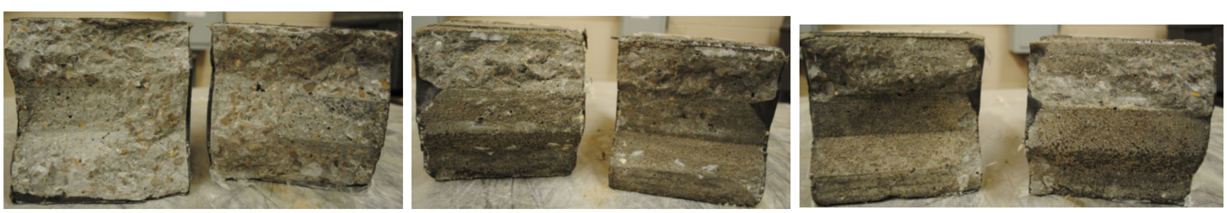


(a) Dry (b) SSD (c) Wet

Figure A16 - Failure patterns of flexural bond test for Ash Grove Non-shrink Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #16)

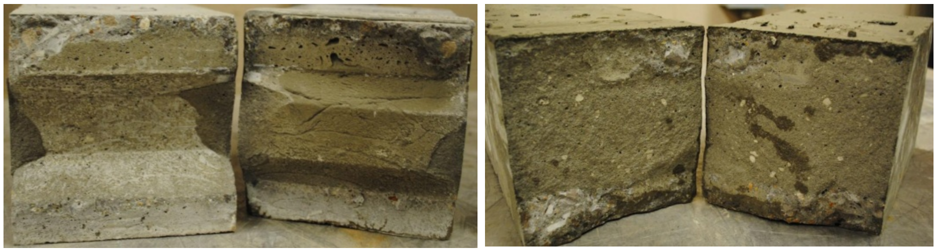
(a) Dry (b) SSD (c) Wet

Figure A17 - Failure patterns of flexural bond test for Kaufman Non-Shrinking Precision Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #17)



(a) Dry (b) SSD (c) Wet

Figure A18 - Failure patterns of flexural bond test for Euclid E3-DP at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #18)

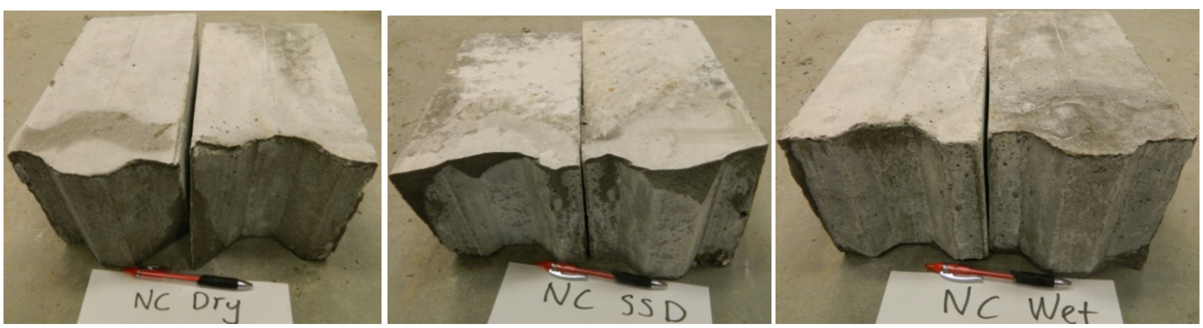


(a) Dry (b) SSD

Figure A19 - Failure patterns of flexural bond test for TAMMs Grout Supreme at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #19)

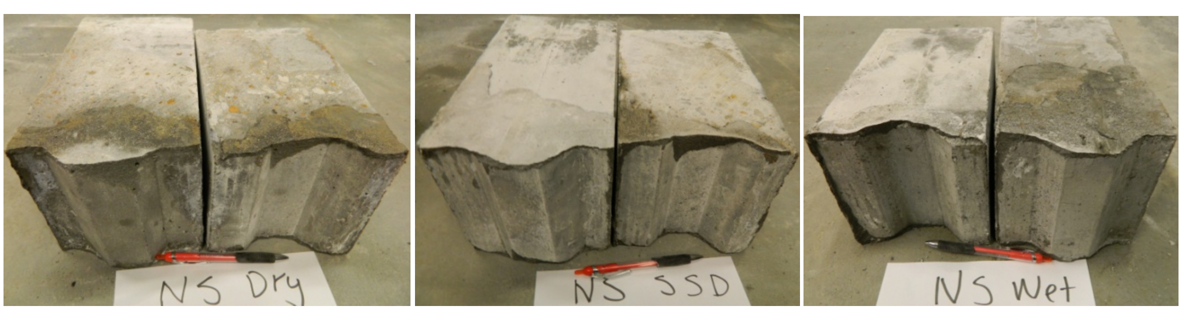
(b) SSD

Figure A20 - Failure patterns of flexural bond test for Euco Precast Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (note: dry and wet specimens were debonded during demolding and the failure mode was not recorded) (Mix #20)



(a) Dry (b) SSD (c) Wet

Figure A21 - Failure patterns of flexural bond test for Euclid NC Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #21)



(a) Dry (b) SSD (c) Wet

Figure A22 - Failure patterns of flexural bond test for Euclid NS Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #22)

(a) Dry (b) SSD (c) Wet

Figure A23 - Failure patterns of flexural bond test for Euclid Hi-flow Grout at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #23)

(a) Dry (b) SSD (c) Wet

Figure A24 - Failure patterns of flexural bond test for Phoscrete Four Seasons at different substrate surface moisture conditions at normal temperature (73°F) at 28 days (Mix #24)

Figure A25 – Specimen broke at demolding for Phoscrete VO-Plus for all substrate surface moisture conditions (Mix #25)

A2. Medium Temperature (85°F) and Different Ages

(a) 1 day (b) 7 days

Figure A26 - Failure patterns of flexural bond test for BASF 928 Grout at different ages at medium temperature (85°F) (Mix #1)

(a) 1 day (b) 7 days (c) 28 days

Figure A27 - Failure patterns of flexural bond test for Sika 328 Grout at different ages at medium temperature (85°F) (Mix #2)

(a) 1 day (b) 7 days (c) 28 days

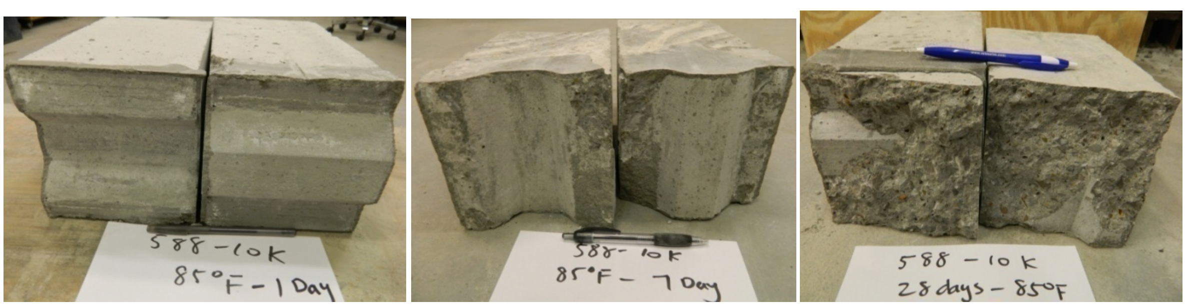
Figure A28 - Failure patterns of flexural bond test for Sika 212 Grout at different ages at medium temperature (85°F) (Mix #3)

(a) 1 day (b) 7 days (c) 28 days

Figure A29 - Failure patterns of flexural bond test for Dayton Superior 1107 Grout at different ages at medium temperature (85°F) (Mix #4)

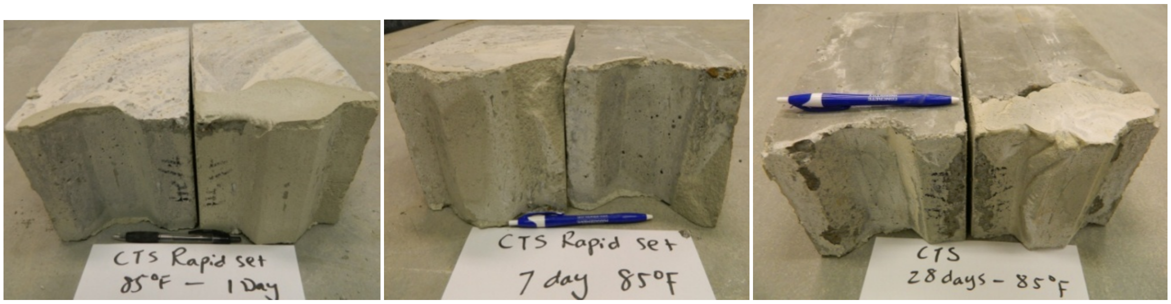
(a) 1 day (b) 7 days

Figure A30 - Failure patterns of flexural bond test for Dayton Superior Sure Grip at different ages at medium temperature (85°F) (Mix #5)



(a) 1 day (b) 7 days (c) 28 days

Figure A31 - Failure patterns of flexural bond test for W.R. Meadows 588-10K at different ages at medium temperature (85°F) (Mix #6)



(a) 1 day (b) 7 days (c) 28 days

Figure A32 - Failure patterns of flexural bond test for CTS CEMENT ALL at different ages at medium temperature (85°F) (Mix #7)

(a) 1 day (b) 7 days

Figure A33 - Failure patterns of flexural bond test for Simpson StrongTie FX-228 Grout at different ages at medium temperature (85°F) (Mix #9)

(a) 1 day (b) 7 days (c) 28 days

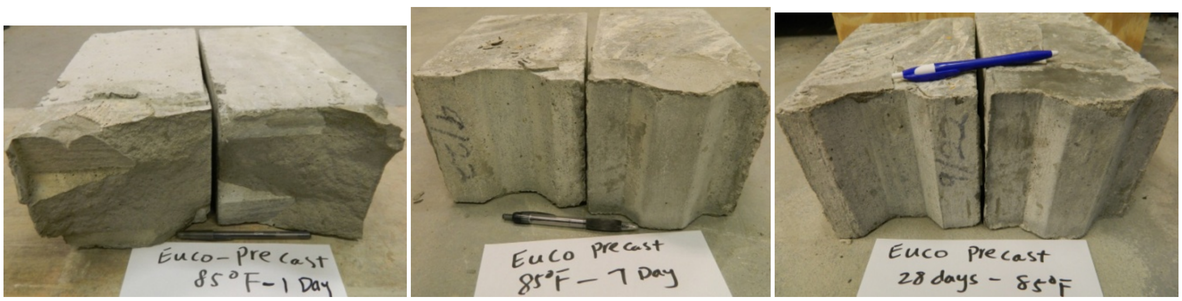
Figure A34 - Failure patterns of flexural bond test for Simpson StrongTie FX-229 Grout at different ages at medium temperature (85°F) (Mix #10)

(a) 1 day (b) 7 days (c) 28 days

Figure A35 - Failure patterns of flexural bond test for Quikrete Non-shrink Precision Grout at different ages at medium temperature (85°F) (Mix #14)

(a) 1 day (b) 7 days (c) 28 days

Figure A36 - Failure patterns of flexural bond test for TAMM's Grout Supreme at different ages at medium temperature (85°F) (Mix #19)



(a) 1 day (b) 7 days (c) 28 days

Figure A37 - Failure patterns of flexural bond test for Euclid Euco-Precast Grout at different ages at medium temperature (85°F) (Mix #20)

(a) 1 day (b) 7 days (c) 28 days

Figure A38 - Failure patterns of flexural bond test for Euclid NC Grout at different ages at medium temperature (85°F) (Mix #21)

(a) 1 day (b) 7 days (c) 28 days

Figure A39 - Failure patterns of flexural bond test for Euclid NS Grout at different ages at medium temperature (85°F) (Mix #22)

(a) 1 day (b) 7 days (c) 28 days

Figure A40 - Failure patterns of flexural bond test for Euclid Hi-Flow Grout at different ages at medium temperature (85°F) (Mix #23)

A3. High Temperature (95°F) and Different Ages

(a) 1 day (b) 7 days (c) 28 days

Figure A41 - Failure patterns of flexural bond test for BASF Masterflow 928 Grout at different ages at high temperature (95°F) (Mix #1)

(a) 1 day (b) 7 days (c) 28 days

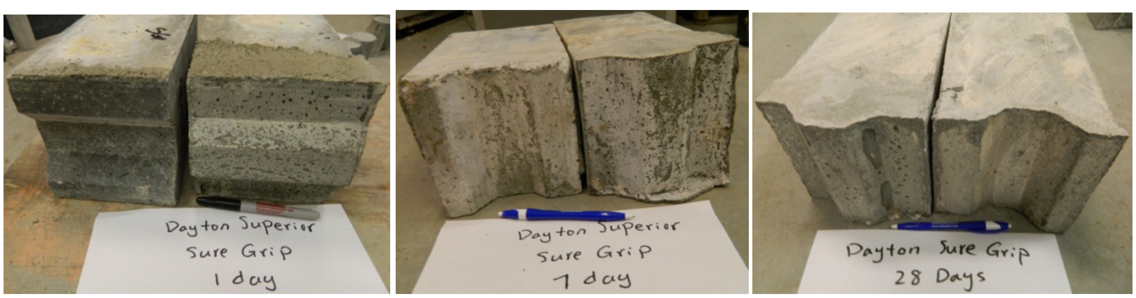
Figure A42 - Failure patterns of flexural bond test for Sika 328 Grout at different ages at high temperature (95°F) (Mix #2)

(a) 1 day (c) 28 days

Figure A43 - Failure patterns of flexural bond test for Sika 212 Grout at different ages at high temperature (95°F) (Mix #3)

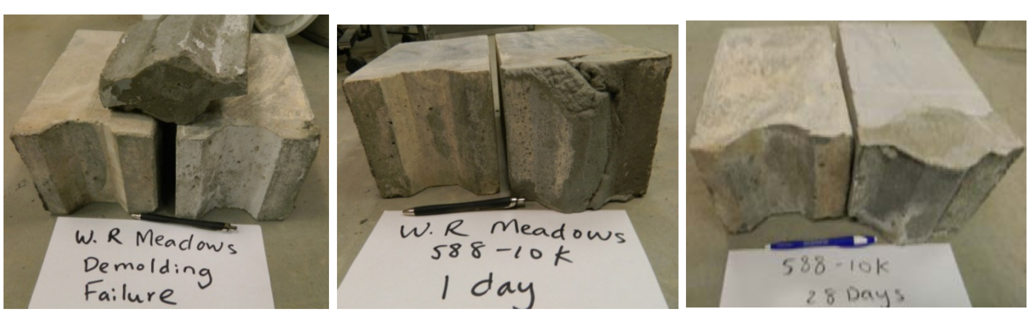
(a) 1 day (b) 7 days (c) 28 days

Figure A44 - Failure patterns of flexural bond test for Dayton Superior 1107 Grout at different ages at high temperature (95°F) (Mix #4)



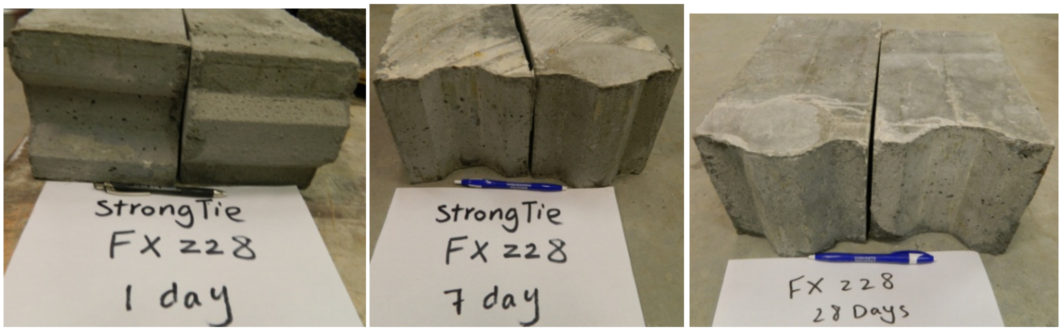
(a) 1 day (b) 7 days (c) 28 days

Figure A45 - Failure patterns of flexural bond test for Dayton Superior SureGrip Grout at different ages at high temperature (95°F) (Mix #5)



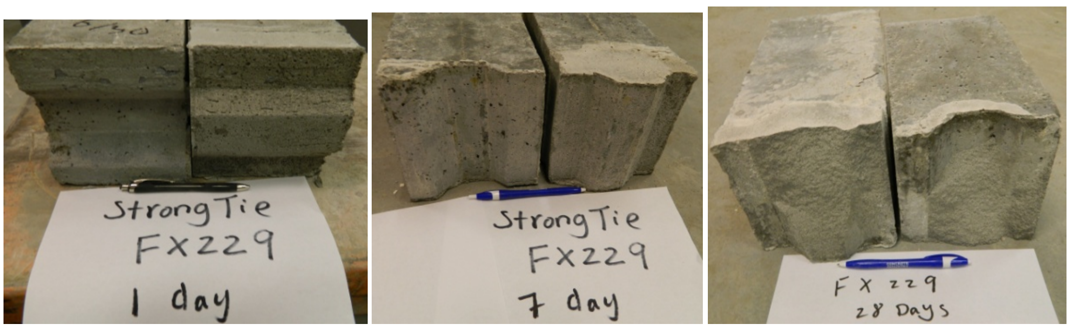
(a) 1 day (b) 7 days (c) 28 days

Figure A46 - Failure patterns of flexural bond test for W.R. Meadows 588-10KGrout at different ages at high temperature (95°F) (Mix #6)



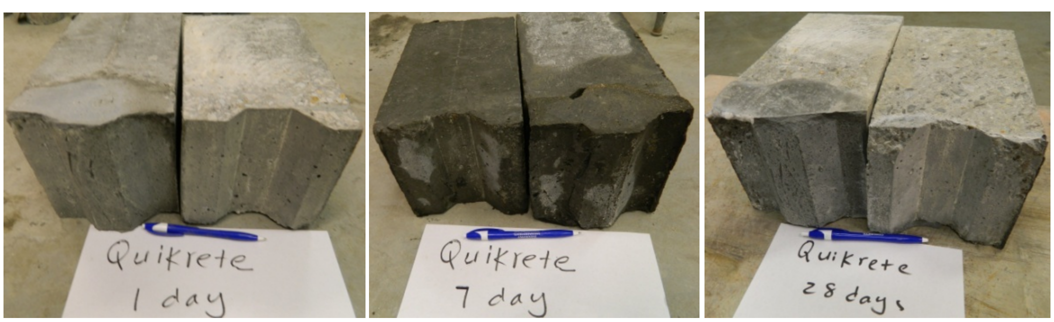
(a) 1 day (b) 7 days (c) 28 days

Figure A47 - Failure patterns of flexural bond test for Simpson StrongTie FX-228 Grout at different ages at high temperature (95°F) (Mix #9)



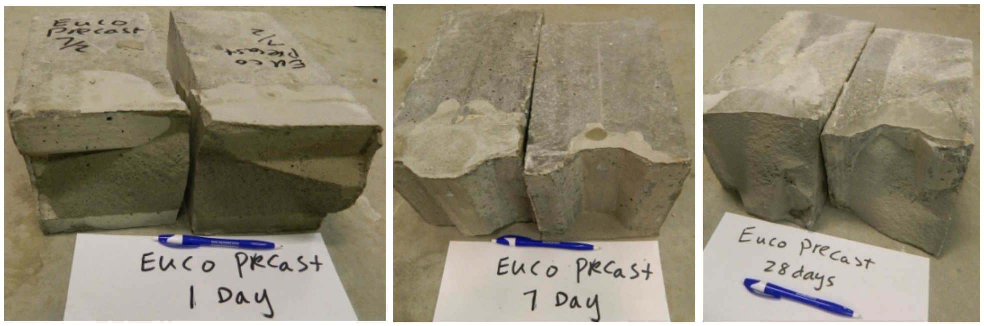
(a) 1 day (b) 7 days (c) 28 days

Figure A48 - Failure patterns of flexural bond test for Simpson StrongTie FX-229 Grout at different ages at high temperature (95°F) (Mix #10)



(a) 1 day (b) 7 days (c) 28 days

Figure A49 - Failure patterns of flexural bond test for Quikrete Non-Shrink Precision Grout at different ages at high temperature (95°F) (Mix #14)

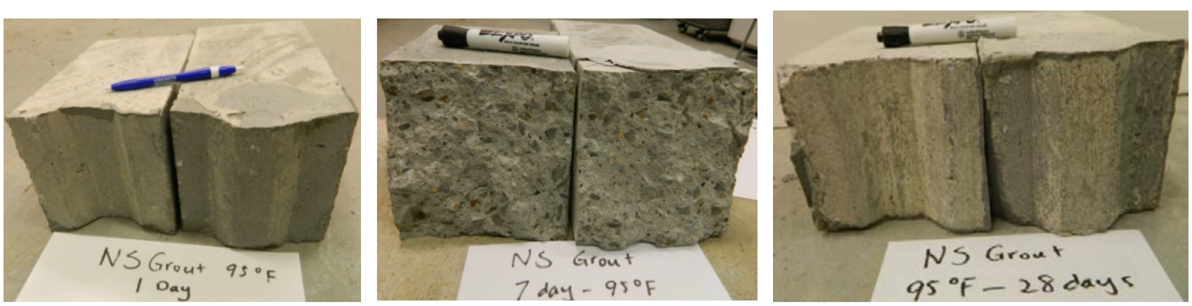


(a) 1 day (b) 7 days (c) 28 days

Figure A50 - Failure patterns of flexural bond test for Euclid Euco-Precast Grout at different ages at high temperature (95°F) (Mix #20)

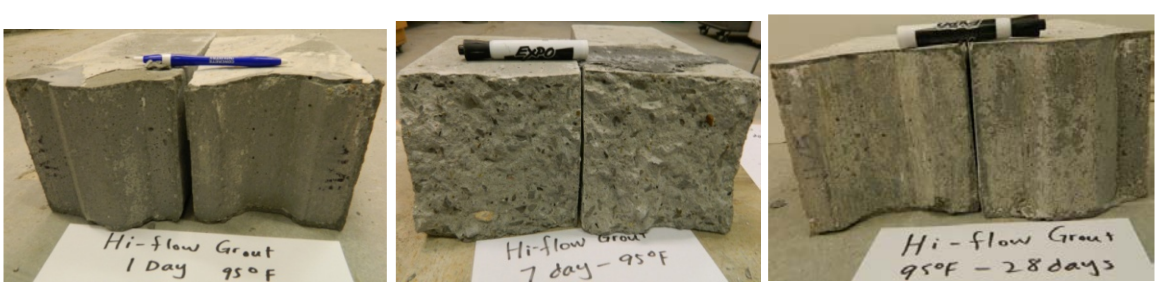
(a) 1 day (b) 7 days (c) 28 days

Figure A51 - Failure patterns of flexural bond test for Euclid NC Grout at different ages at high temperature (95°F) (Mix #21)



(a) 1 day (b) 7 days (c) 28 days

Figure A52 - Failure patterns of flexural bond test for Euclid NS Grout at different ages at high temperature (95°F) (Mix #22)



(a) 1 day (b) 7 days (c) 28 days

Figure A53 - Failure patterns of flexural bond test for Euclid Hi-Flow Grout at different ages at high temperature (95°F) (Mix #23)

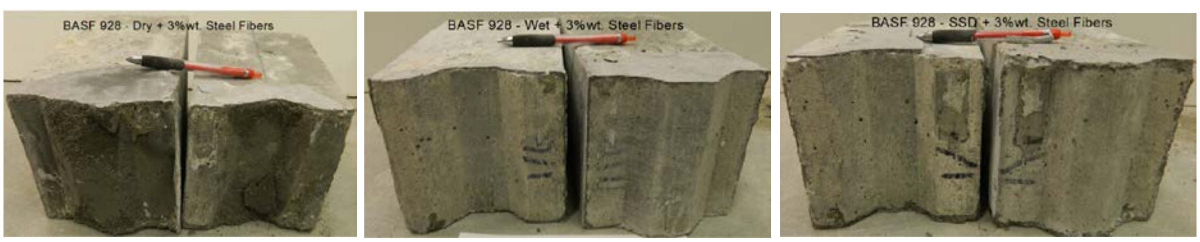
A4. Steel Fiber Addition at Normal Temperature (73°F) at 28 Days with Different Fiber Dosages or Substrate Surface Moisture Conditions

(a) 1% (b) 3% (c) 6%

Figure A54 - Failure patterns of flexural bond test for Dayton Superior SureGrip at different fiber dosages at normal temperature (73°F) (Mix #5)

(a) 1% (b) 3% (c) 6%

Figure A55 - Failure patterns of flexural bond test for Simpson StrongTie FX-229 at different fiber dosages at normal temperature (73°F) (Mix #10)

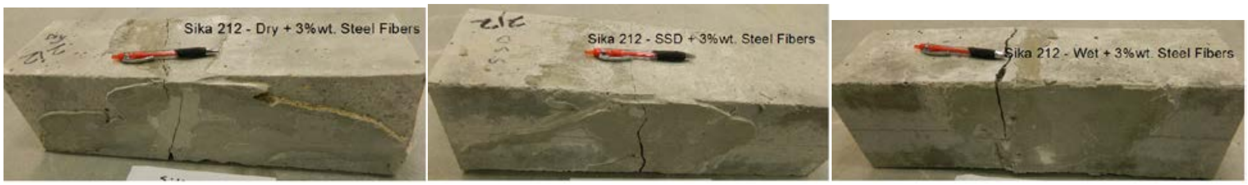


(a) Dry (b) SSD (c) Wet

Figure A56 - Failure patterns of flexural bond test for BASF Masterflow 928 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #1)

(a) Dry (b) SSD (c) Wet

Figure A57 - Failure patterns of flexural bond test for Sika 328 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #2)



(a) Dry (b) SSD (c) Wet

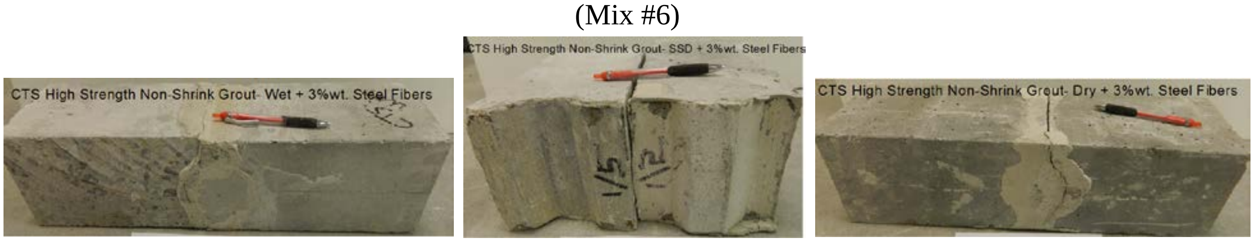
Figure A58 - Failure patterns of flexural bond test for Sika 212 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #3)

(a) Dry (b) SSD (c) Wet

Figure A59 - Failure patterns of flexural bond test for Dayton Superior 1107 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #4)

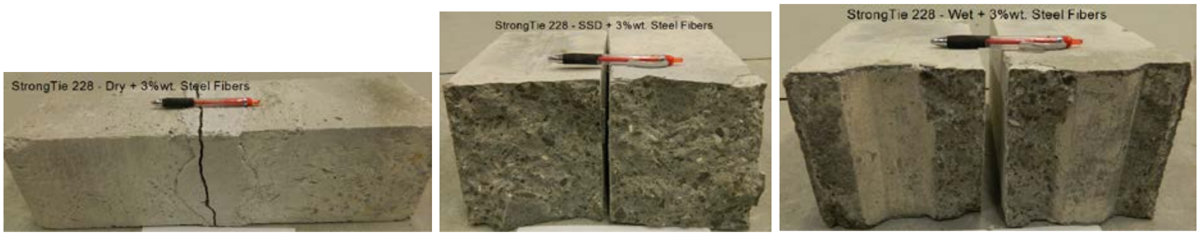
(a) Dry (b) SSD (c) Wet

Figure A60 - Failure patterns of flexural bond test for W.R. Meadows 588-10K with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #6)



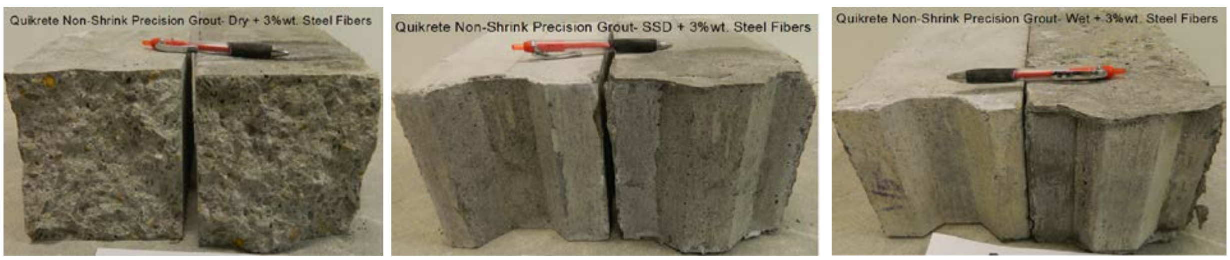
(a) Dry (b) SSD (c) Wet

Figure A61 - Failure patterns of flexural bond test for CTS CEMENT ALL grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #7)



(a) Dry (b) SSD (c) Wet

Figure A62 - Failure patterns of flexural bond test for Simpson StrongTie FX-228 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #9)

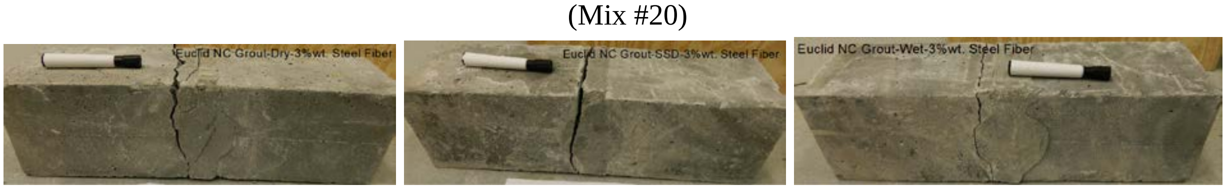


(a) Dry (b) SSD (c) Wet

Figure A63 - Failure patterns of flexural bond test for Quikrete Non-shrink Precision grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #14)

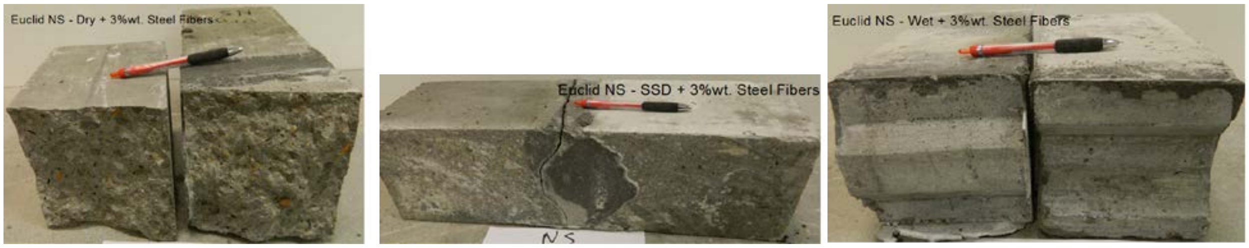
(a) Dry (b) SSD (c) Wet

Figure A64 - Failure patterns of flexural bond test for Euclid Euco Precast grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #20)



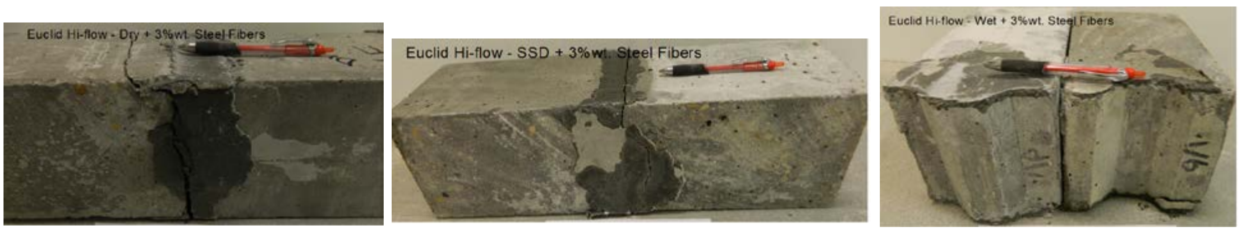
(a) Dry (b) SSD (c) Wet

Figure A65 - Failure patterns of flexural bond test for Euclid NC grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #21)



(a) Dry (b) SSD (c) Wet

Figure A66 - Failure patterns of flexural bond test for Euclid NS grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #22)



(a) Dry (b) SSD (c) Wet

Figure A67 - Failure patterns of flexural bond test for Euclid Hi-flow grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #23)

APPENDIX B – FAILURE MODE OF SLANT SHEAR BOND TEST FOR GROUT PRODUCTS

B1. Normal Temperature (73°F) and Different Substrate Surface Moisture Conditions at 28 Days

(a) Dry (b) SSD (c) Wet

Figure B1 - Failure patterns of slant shear bond test for BASF Master Flow 928 at different substrate surface moisture conditions at normal temperature (73°F) (Mix #1)

(a) Dry (b) SSD (c) Wet

Figure B2 - Failure patterns of slant shear bond test for Sika Grout 328 at different substrate surface moisture conditions at normal temperature (73°F) (Mix #2)

(a) Dry (b) SSD (c) Wet

Figure B3 - Failure patterns of slant shear bond test for Sika High Performance Grout 212 at different substrate surface moisture conditions at normal temperature (73°F) (Mix #3)

(a) Dry (b) SSD (c) Wet

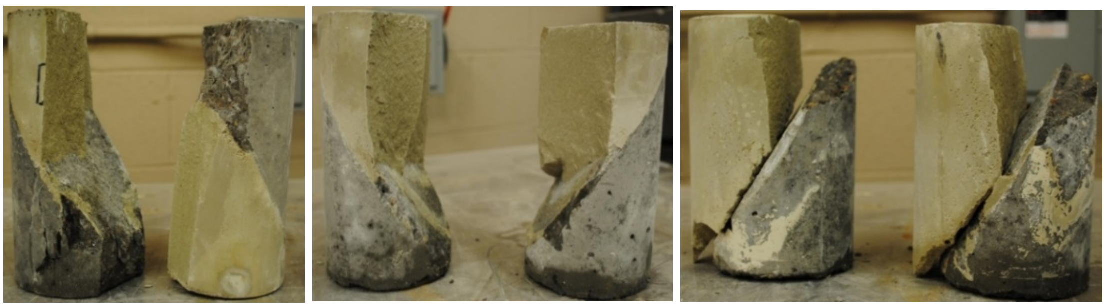
Figure B4 - Failure patterns of slant shear bond test for Dayton Superior 1107 at different substrate surface moisture conditions at normal temperature (73°F) (Mix #4)

(a) Dry (b) SSD (c) Wet

Figure B5 - Failure patterns of slant shear bond test for Dayton Superior Sure Grip at different substrate surface moisture conditions at normal temperature (73°F) (Mix #5)

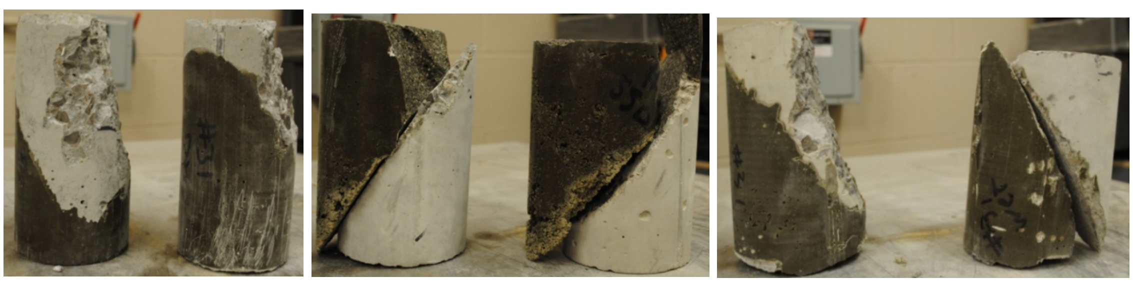
(a) Dry

Figure B6 - Failure patterns of slant shear bond test for W.R Meadows 588-10K at different substrate surface moisture conditions at normal temperature (73°F) (Mix #6)



(a) Dry (b) SSD (c) Wet

Figure B7 - Failure patterns of slant shear bond test for CTS CEMENT ALL at different substrate surface moisture conditions at normal temperature (73°F) (Mix #7)



(a) Dry (b) SSD (c) Wet

Figure B8 - Failure patterns of slant shear bond test for Hilti Epoxy Grout CB-G EG at different substrate surface moisture conditions at normal temperature (73°F) (Mix #8)

(a) Dry (b) SSD (c) Wet

Figure B9 - Failure patterns of slant shear bond test for SIMPSON Strong-Tie FX-228 at different substrate surface moisture conditions at normal temperature (73°F) (Mix #9)

(a) Dry (b) SSD (c) Wet

Figure B10 - Failure patterns of slant shear bond test for SIMPSON Strong-Tie FX-229 at different substrate surface moisture conditions at normal temperature (73°F) (Mix #10)

(a) Dry (b) SSD (c) Wet

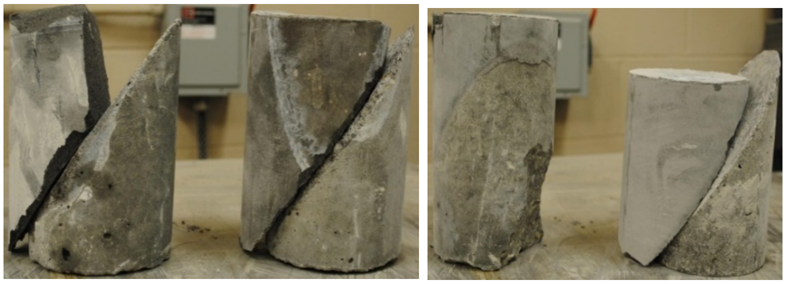
Figure B11 - Failure patterns of slant shear bond test for Ceratech Pavemend DOTLine at different substrate surface moisture conditions at normal temperature (73°F) (Mix #11)

(a) Dry (b) SSD (c) Wet

Figure B12 - Failure patterns of slant shear bond test for Ceratech Pavemend SL at different substrate surface moisture conditions at normal temperature (73°F) (Mix #12)

(a) Dry (b) SSD (c) Wet

Figure B13 - Failure patterns of slant shear bond test for Vexcon Certi-Vex Grout 1000 at different substrate surface moisture conditions at normal temperature (73°F) (Mix #13)



(a) Dry (b) SSD

Figure B14 - Failure patterns of slant shear bond test for Quikrete Non-Shrink Precision Grout at different substrate surface moisture conditions at normal temperature (73°F) (Mix #14)

(a) Dry (b) SSD (c) Wet

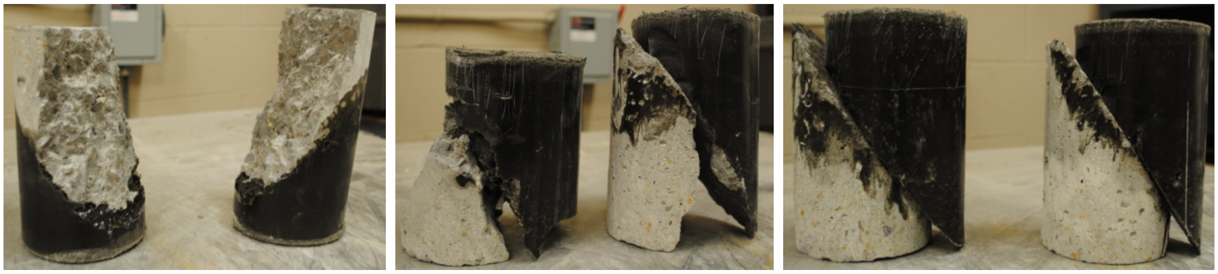
Figure B15 - Failure patterns of slant shear bond test for ChemMasters Conset Grout at different substrate surface moisture conditions at normal temperature (73°F) (Mix #15)

(a) Dry (b) SSD (c) Wet

Figure B16 - Failure patterns of slant shear bond test for Ash Grove Non-Shrink Grout at different substrate surface moisture conditions at normal temperature (73°F) (Mix #16)

(a) Dry (b) SSD (c) Wet

Figure B17 - Failure patterns of slant shear bond test for Kaufman Non-Shrinking Precision Grout at different substrate surface moisture conditions at normal temperature (73°F) (Mix #17)



(a) Dry (b) SSD (c) Wet

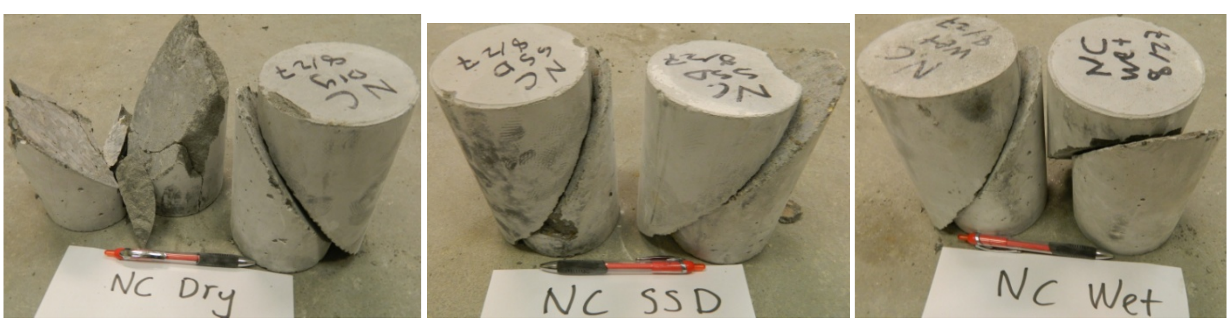
Figure B18 - Failure patterns of slant shear bond test for Euclid E3-DP at different substrate surface moisture conditions at normal temperature (73°F) (Mix #18)

(b) SSD (c) Wet

Figure B19 - Failure patterns of slant shear bond test for TAMMs Grout Supreme at different substrate surface moisture conditions at normal temperature (73°F) (Mix #19)

(b) SSD

Figure B20 - Failure patterns of slant shear bond test for Euco Precast Grout at different substrate surface moisture conditions at normal temperature (73°F) (Mix #20)

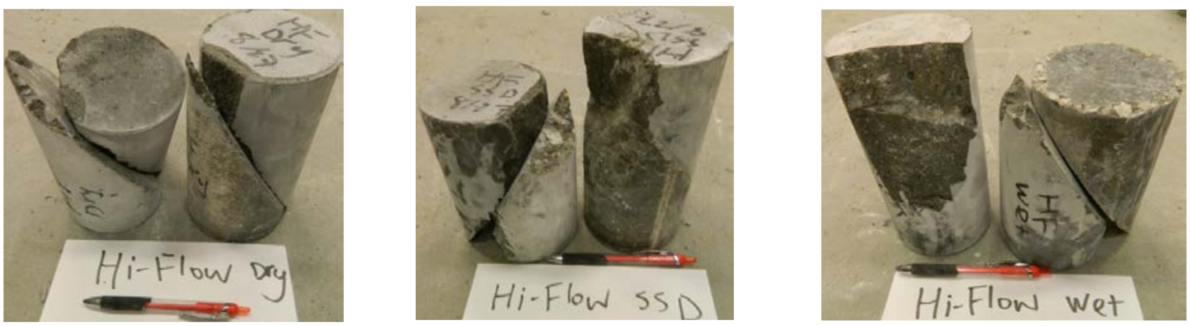


(a) Dry (b) SSD (c) Wet

Figure B21 - Failure patterns of slant shear bond test for Euclid NC grout at different substrate surface moisture conditions at normal temperature (73°F) (Mix #21)

(a) Dry (b) SSD (c) Wet

Figure B22 - Failure patterns of slant shear bond test for Euclid NS at different substrate surface moisture conditions at normal temperature (73°F) (Mix #22)



(a) Dry (b) SSD (c) Wet

Figure B23 - Failure patterns of slant shear bond test for Euclid Hi-flow grout at different substrate surface moisture conditions at normal temperature (73°F) (Mix #23)


(a) Dry (b) SSD (c) Wet

Figure B24 - Failure patterns of slant shear bond test for Phoscrete Four Seasons at different substrate surface moisture conditions at normal temperature (73°F) (Mix #24)


(a) Dry (b) SSD (c) Wet

Figure B25 - Failure patterns of slant shear bond test for Phoscrete VO-Plus at different substrate surface moisture conditions at normal temperature (73°F) (Mix #25)

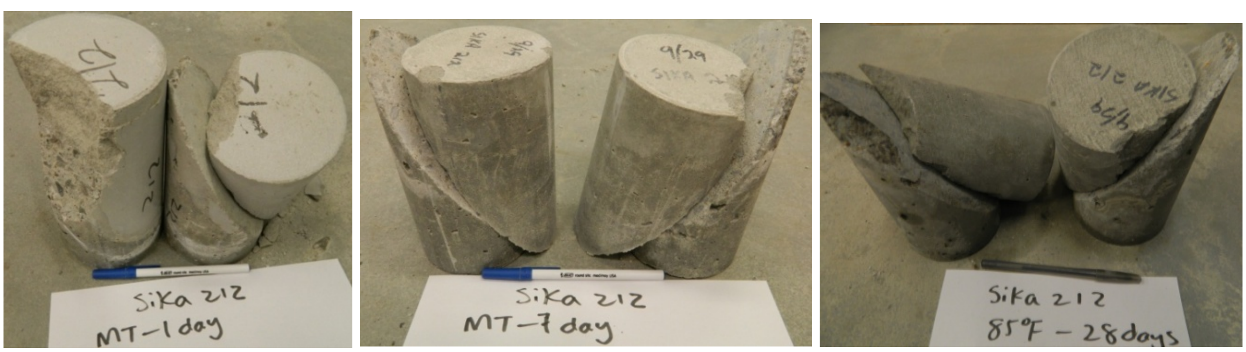
B2. Medium Temperature (85°F) and Different Ages

(a) 1 day (b) 7 days

Figure B26 - Failure patterns of slant shear bond test for BASF Masterflow 928 Grout at different ages at medium temperature (85°F) (Mix #1)

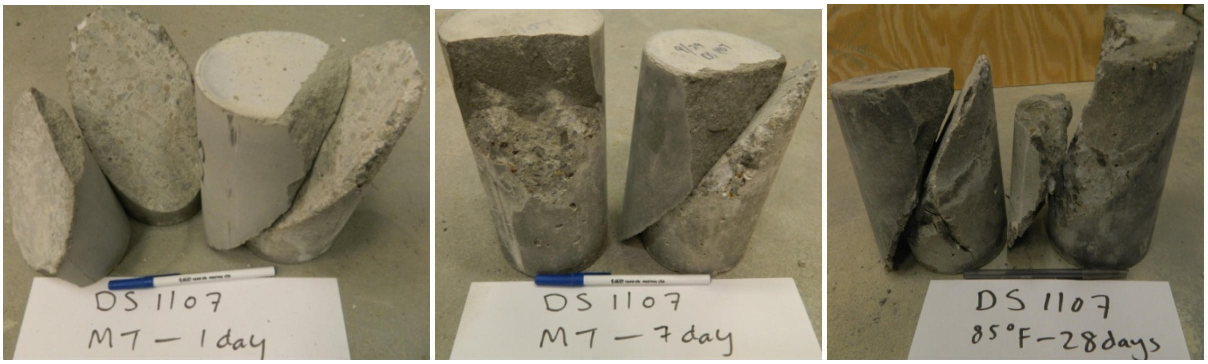
(a) 1 day (b) 7 days (c) 28 days

Figure B27 - Failure patterns of slant shear bond test for Sika 328 Grout at different ages at medium temperature (85°F) (Mix #2)



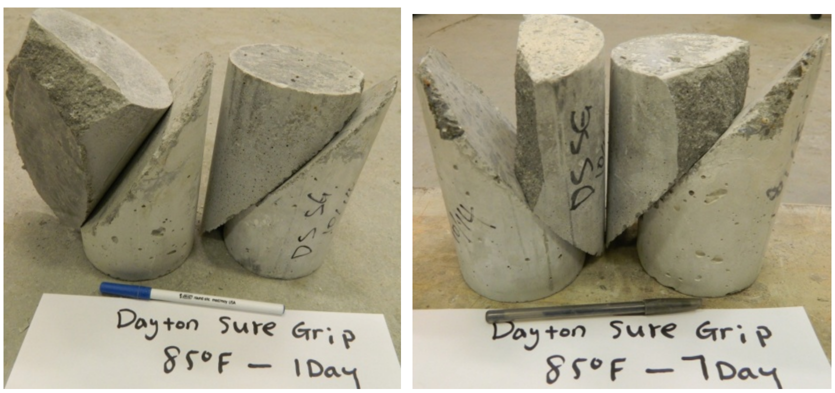
(a) 1 day (b) 7 days (c) 28 days

Figure B28 - Failure patterns of slant shear bond test for Sika 212 Grout at different ages at medium temperature (85°F) (Mix #3)



(a) 1 day (b) 7 days (c) 28 days

Figure B29 - Failure patterns of slant shear bond test for Dayton Superior 1107 Grout at different ages at medium temperature (85°F) (Mix #4)



(a) 1 day (b) 7 days

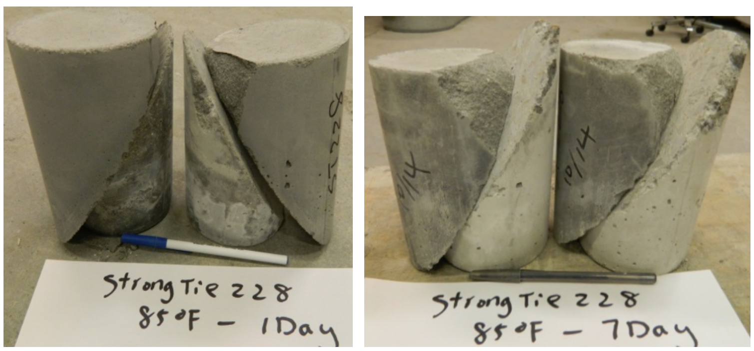
Figure B30 - Failure patterns of slant shear bond test for Dayton Superior SureGrip Grout at different ages at medium temperature (85°F) (Mix #5)

(a) 1 day (b) 7 days (c) 28 days

Figure B31 - Failure patterns of slant shear bond test for W.R Meadows 588-10K Grout at different ages at medium temperature (85°F) (Mix #6)

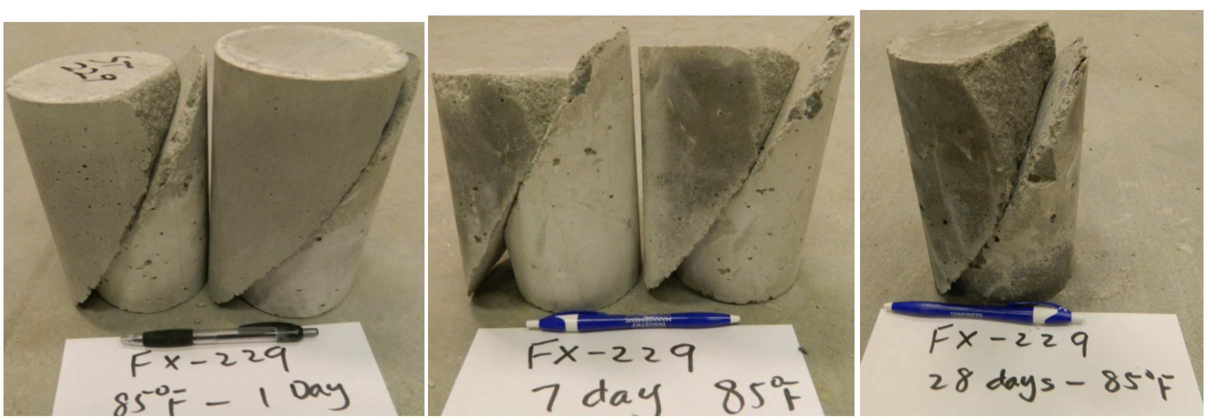
(a) 1 day (b) 7 days (c) 28 days

Figure B32 - Failure patterns of slant shear bond test for CTS CEMENT ALL at different ages at medium temperature (85°F) (Mix #7)



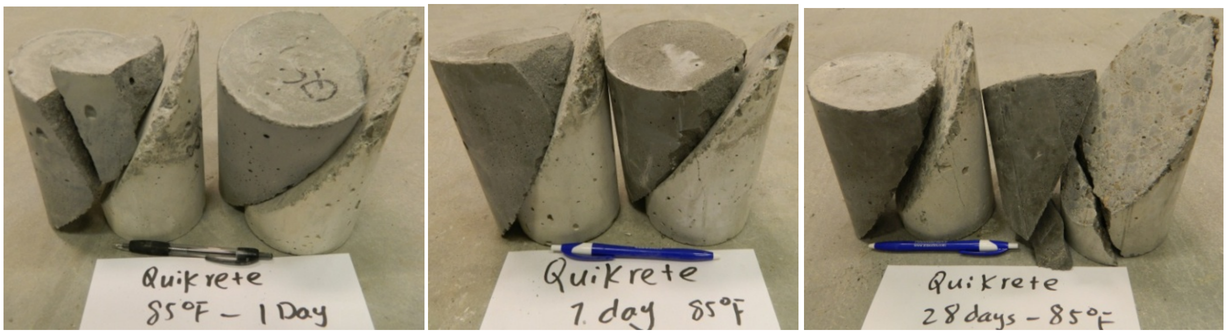
(a) 1 day (b) 7 days

Figure B33 - Failure patterns of slant shear bond test for Fox Industries StrongTie FX-228 Grout at different ages at medium temperature (85°F) (Mix #9)



(a) 1 day (b) 7 days (c) 28 days

Figure B34 - Failure patterns of slant shear bond test for Fox Industries StrongTie FX-229 Grout at different ages at medium temperature (85°F) (Mix #10)



(a) 1 day (b) 7 days (c) 28 days

Figure B35 - Failure patterns of slant shear bond test for Quikrete Non-Shrink Precision Grout at different ages at medium temperature (85°F) (Mix #14)

(a) 1 day (b) 7 days (c) 28 days

Figure B36 - Failure patterns of slant shear bond test for TAMM's Grout Supreme at different ages at medium temperature (85°F) (Mix #19)

(a) 1 day (b) 7 days (c) 28 days

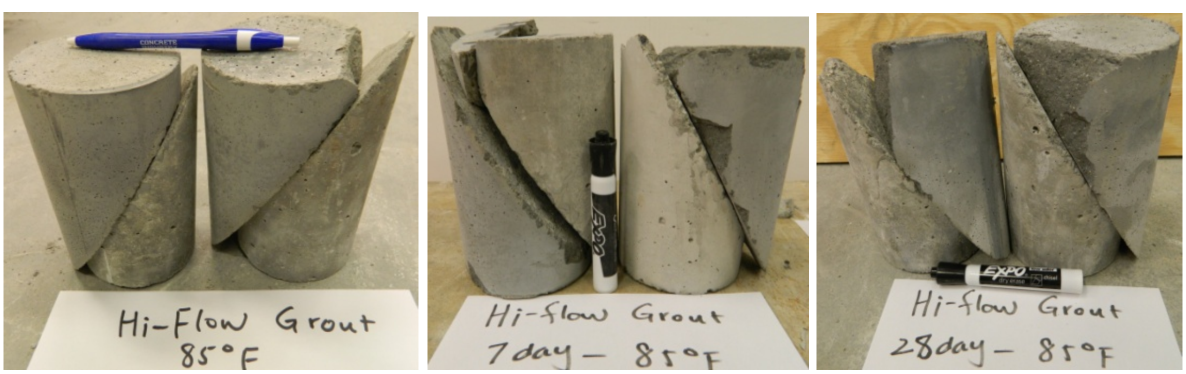
Figure B37 - Failure patterns of slant shear bond test for Euclid Euco Pre-cast Grout at different ages at medium temperature (85°F) (Mix #20)

(a) 1 day (b) 7 days (c) 28 days

Figure B38 - Failure patterns of slant shear bond test for Euclid Euco NC Grout at different ages at medium temperature (85°F) (Mix #21)

(a) 1 day (b) 7 days (c) 28 days

Figure B39 - Failure patterns of slant shear bond test for Euclid Euco NS Grout at different ages at medium temperature (85°F) (Mix #22)



(a) 1 day (b) 7 days (c) 28 days

Figure B40 - Failure patterns of slant shear bond test for Euclid Euco Hi-Flow Grout at different ages at medium temperature (85°F) (Mix #23)

B3. High Temperature (95°F) and Different Ages

(a) 1 day (b) 7 days (c) 28 days

Figure B41 - Failure patterns of slant shear bond test for BASF Master flow 928 Grout at different ages at high temperature (95°F) (Mix #1)

(a) 1 day (b) 7 days (c) 28 days

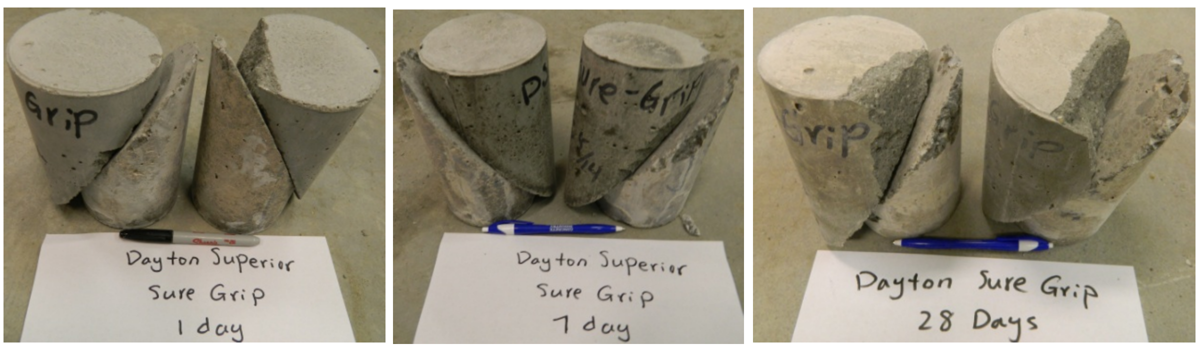
Figure B42 - Failure patterns of slant shear bond test for Sika 328 Grout at different ages at high temperature (95°F) (Mix #2)

(a) 1 day (b) 7 days (c) 28 days

Figure B43 - Failure patterns of slant shear bond test for Sika 212 Grout at different ages at high temperature (95°F) (Mix #3)

(a) 1 day (b) 7 days (c) 28 days

Figure B44 - Failure patterns of slant shear bond test for Dayton Superior 1107 Grout at different ages at high temperature (95°F) (Mix #4)

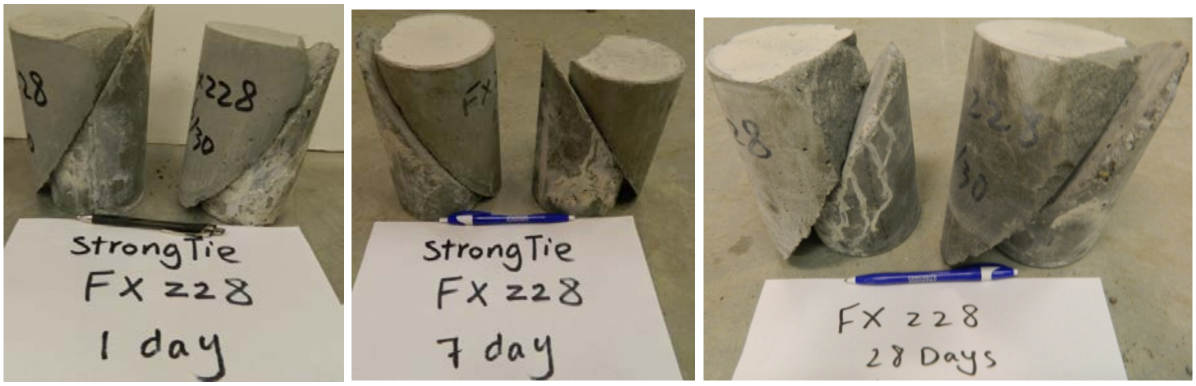


(a) 1 day (b) 7 days (c) 28 days

Figure B45 - Failure patterns of slant shear bond test for Dayton Superior SureGrip Grout at different ages at high temperature (95°F) (Mix #5)

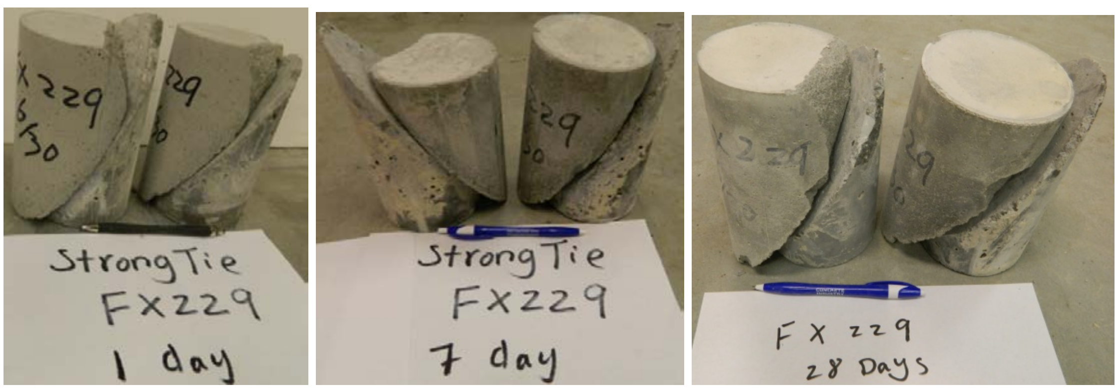
(a) 1 day (b) 7 days (c) 28 days

Figure B46 - Failure patterns of slant shear bond test for W.R. Meadows 588-10K Grout at different ages at high temperature (95°F) (Mix #6)



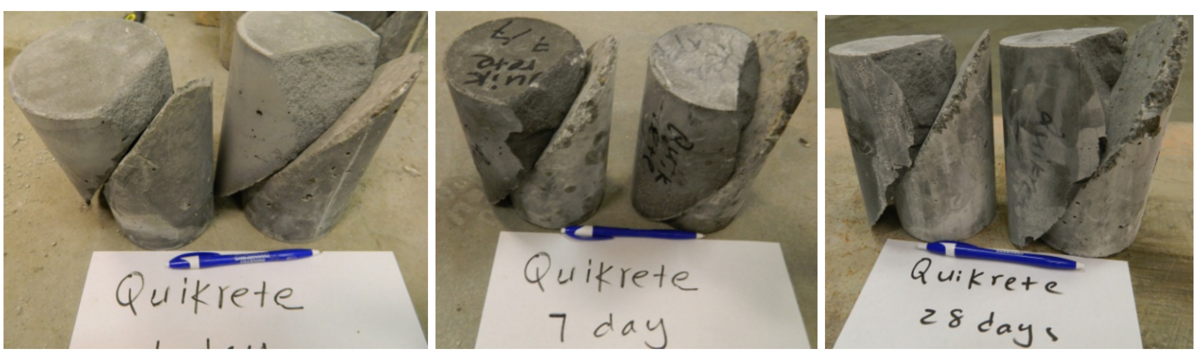
(a) 1 day (b) 7 days (c) 28 days

Figure B47 - Failure patterns of slant shear bond test for Fox Industries StrongTie FX-228 Grout at different ages at high temperature (95°F) (Mix #9)



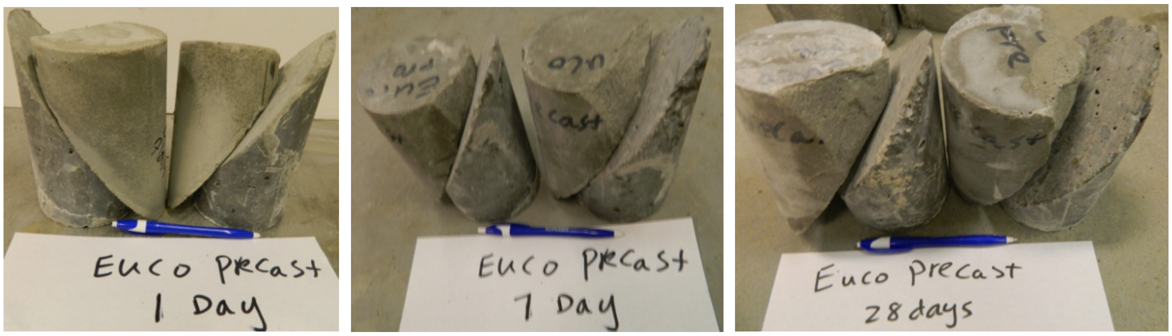
(a) 1 day (b) 7 days (c) 28 days

Figure B48 - Failure patterns of slant shear bond test for Fox Industries StrongTie FX-229 Grout at different ages at high temperature (95°F) (Mix #10)



(a) 1 day (b) 7 days (c) 28 days

Figure B49 - Failure patterns of slant shear bond test for Quikrete Non-Shrink Precision Grout at different ages at high temperature (95°F) (Mix #14)



(a) 1 day (b) 7 days (c) 28 days

Figure B50 - Failure patterns of slant shear bond test for Euclid Euco-Precast Grout at different ages at high temperature (95°F) (Mix #20)

(a) 1 day (b) 7 days (c) 28 days

Figure B51 - Failure patterns of slant shear bond test for Euclid Euco NC Grout at different ages at high temperature (95°F) (Mix #21)

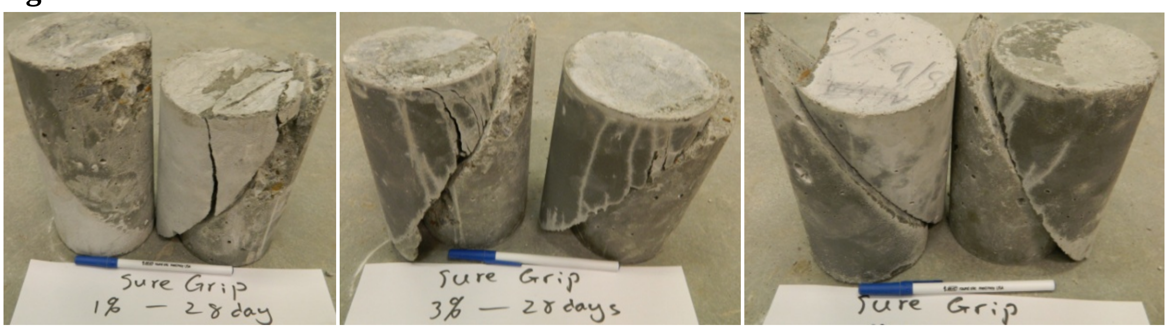
(a) 1 day (b) 7 days (c) 28 days

Figure B52 - Failure patterns of slant shear bond test for Euclid Euco NS Grout at different ages at high temperature (95°F) (Mix #22)

(a) 1 day (b) 7 days (c) 28 days

Figure B53 - Failure patterns of slant shear bond test for Euclid Euco Hi-Flow Grout at different ages at high temperature (95°F) (Mix #23)

B4. Steel Fiber Addition at Normal Temperature (73°F) at 28 days with Different Fiber Dosages or Substrate Surface Moisture Conditions

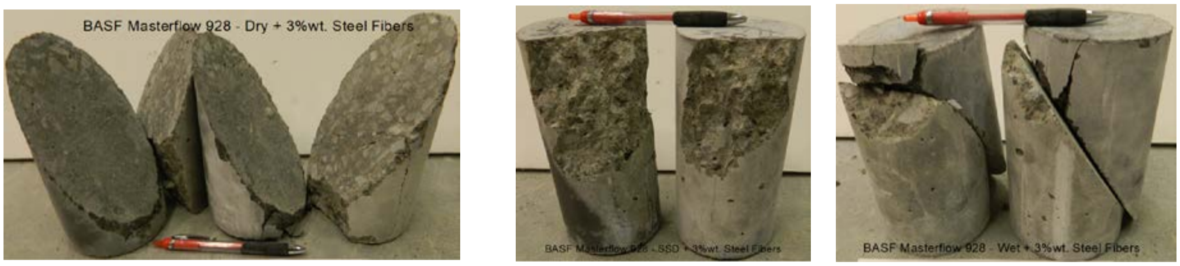


(a) 1% (b) 3% (c) 6%

Figure B54 - Failure patterns of slant shear bond test for Dayton Superior SureGrip Grout at different fiber dosages at normal temperature (73°F) and SSD moisture condition (Mix #5)

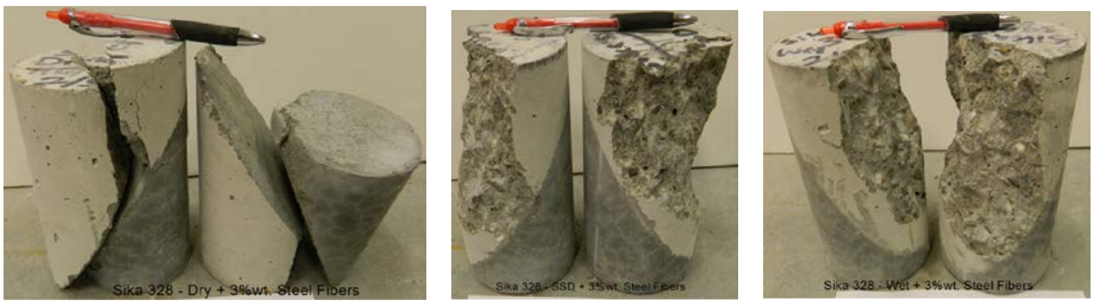
(a) 1% (b) 3% (c) 6%

Figure B55 - Failure patterns of slant shear bond test for Fox Industries StrongTie FX-229 Grout at different fiber dosages at normal temperature (73°F) and SSD moisture condition (Mix #10)



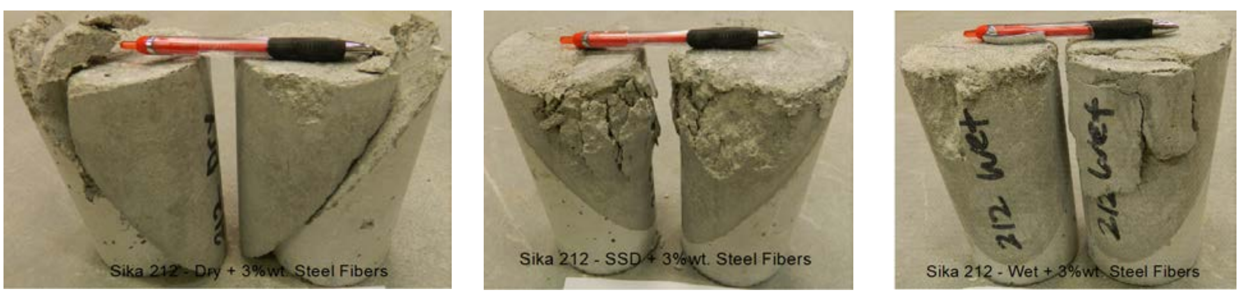
(a) Dry (b) SSD (c) Wet

Figure B56 - Failure patterns of slant shear bond test for BASF Masterflow 928 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #1)



(a) Dry (b) SSD (c) Wet

Figure B57 - Failure patterns of slant shear bond test for Sika 328 Grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #2)



(a) Dry (b) SSD (c) Wet

Figure B58 - Failure patterns of slant shear bond test for Sika 212 Grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #3)

(a) Dry (b) SSD (c) Wet

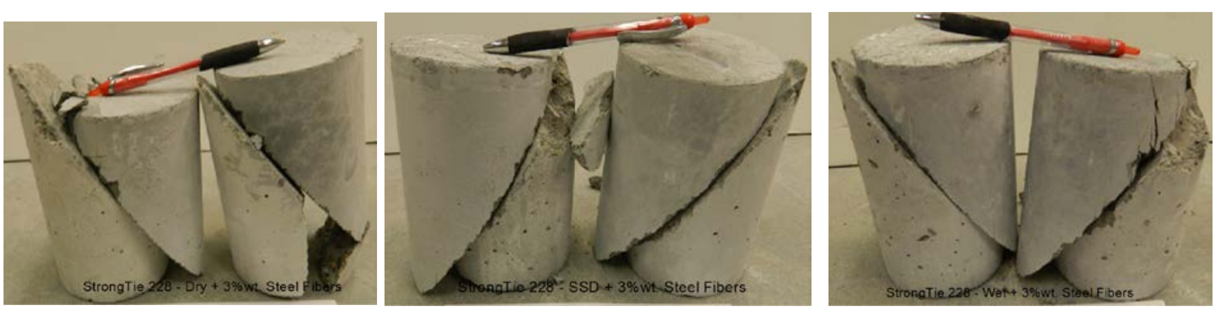
Figure B59 - Failure patterns of slant shear bond test for Dayton Superior 1107 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #4)

(a) Dry (b) SSD (c) Wet

Figure B60 - Failure patterns of slant shear bond test for W.R. Meadows 588-10K with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #6)

(a) Dry (b) SSD (c) Wet

Figure B61 - Failure patterns of slant shear bond test for CTS CEMENT ALL with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #7)



(a) Dry (b) SSD (c) Wet

Figure B62 - Failure patterns of slant shear bond test for Simpson StrongTie FX-228 with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #9)

(a) Dry (b) SSD (c) Wet

Figure B63 - Failure patterns of slant shear bond test for Quikrete non-shrink precision with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #14)

(a) Dry (b) SSD (c) Wet

Figure B64 - Failure patterns of slant shear bond test for Euco Precast grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #20)

(a) Dry (b) SSD (c) Wet

Figure B65 - Failure patterns of slant shear bond test for Euclid NC grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #21)

(a) Dry (b) SSD (c) Wet

Figure B66 - Failure patterns of slant shear bond test for Euclid NS grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #22)

(a) Dry (b) SSD (c) Wet

Figure B67 - Failure patterns of slant shear bond test for Euclid Hi-flow grout with 3% steel fiber addition at different substrate surface moisture conditions and normal temperature (73°F) (Mix #23)

APPENDIX C–MINI SLUMP TEST AT DIFFERENT TIME FOR GROUT PRODUCTS

C1. Normal Temperature (73°F) and Different Time

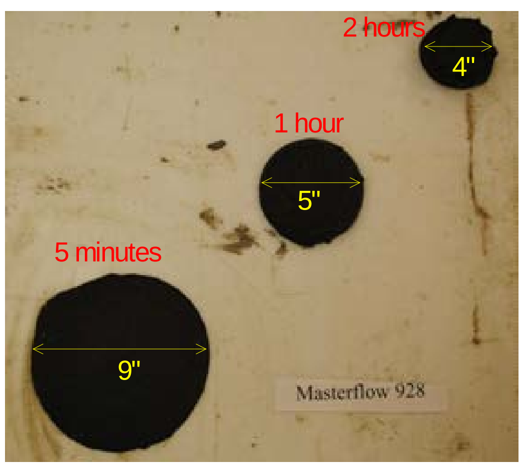


Figure C1 - Spread of mini slump test for BASF Master Flow 928 at different time at normal temperature (73°F) (Mix #1)

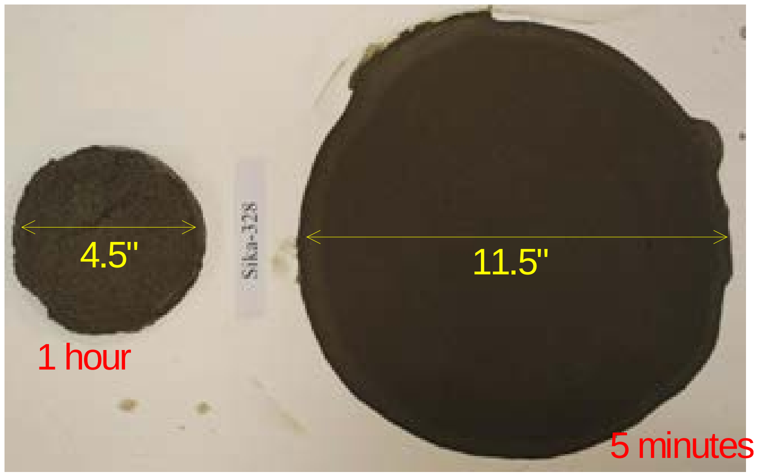


Figure C2 - Spread of mini slump test for Sika Grout 328 at different time at normal temperature (73°F) (Mix #2)

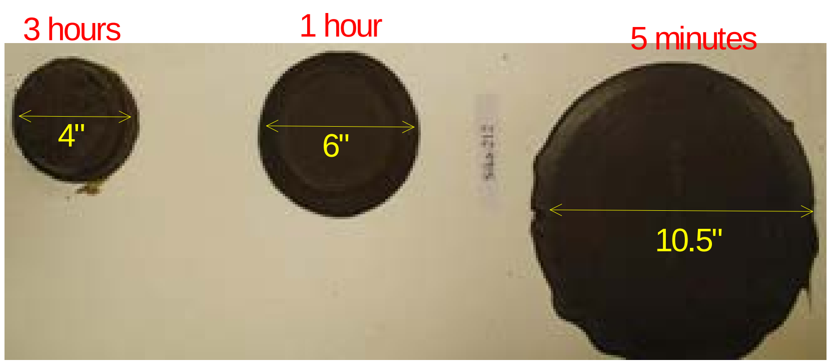


Figure C3 - Spread of mini slump test for Sika High Performance Grout 212 at different time at normal temperature (73°F) (Mix #3)

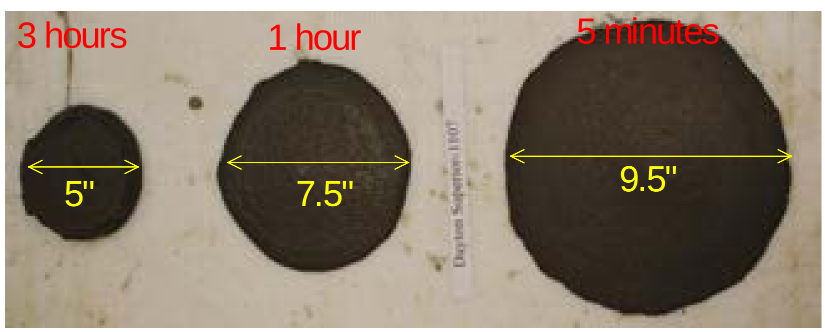


Figure C4 - Spread of mini slump test for Dayton Superior 1107 at different time at normal temperature (73°F) (Mix #4)

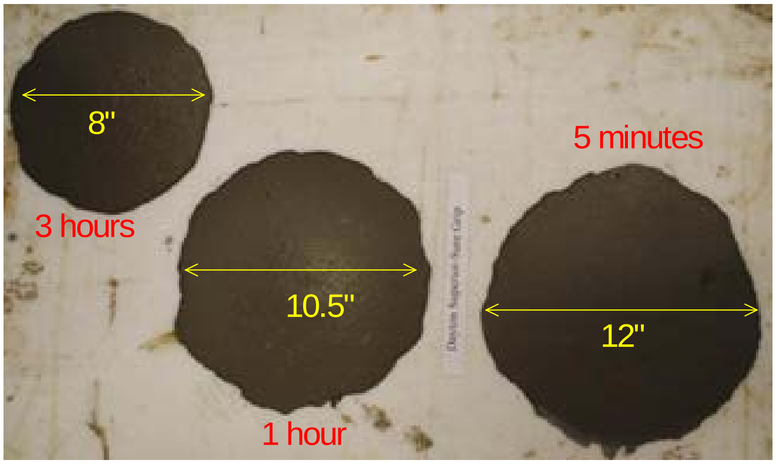


Figure C5 - Spread of mini slump test for Dayton Superior Sure Grip at different time at normal temperature (73°F) (Mix #5)

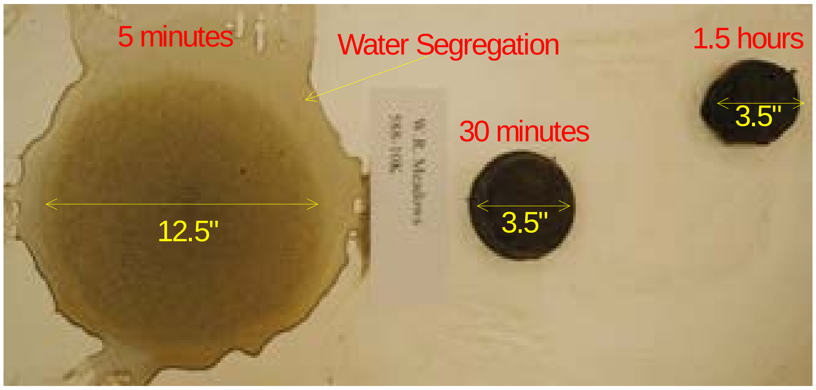


Figure C6 - Spread of mini slump test for W.R Meadows 588-10K at different time at normal temperature (73°F) (note: bleeding at the 5 minutes measurement) (Mix #6)

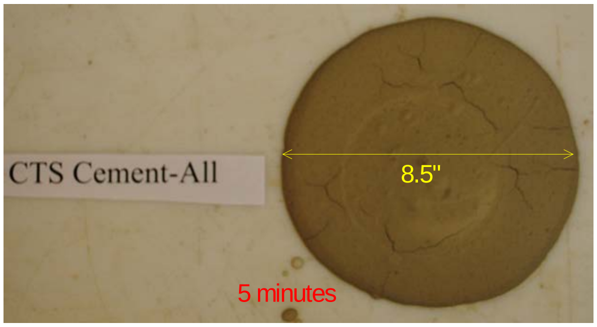


Figure C7 - Spread of mini slump test for CTS CEMENT ALL at 5 minutes at normal temperature (73°F) (Mix #7)

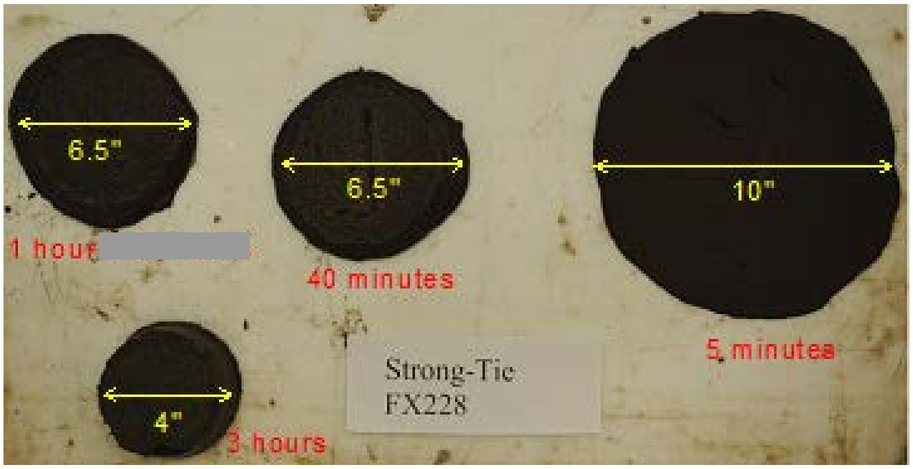


Figure C8 - Spread of mini slump test for SIMPSON Strong-Tie FX-228 at different time at normal temperature (73°F) (Mix #9)

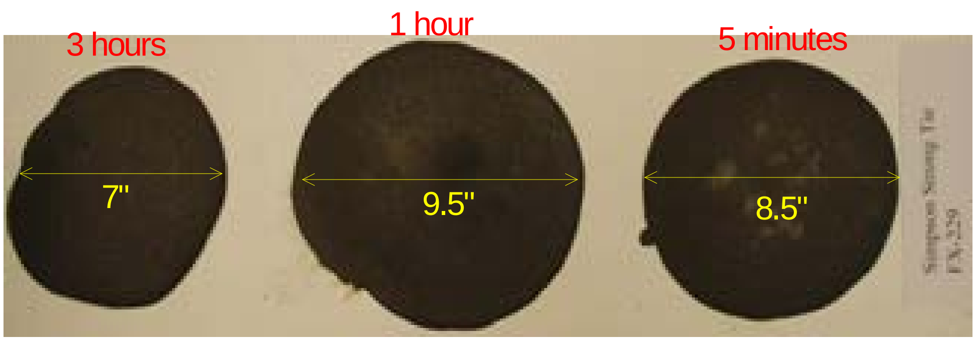


Figure C9 - Spread of mini slump test for SIMPSON Strong-Tie FX-229 at different time at normal temperature (73°F) (Mix #10)

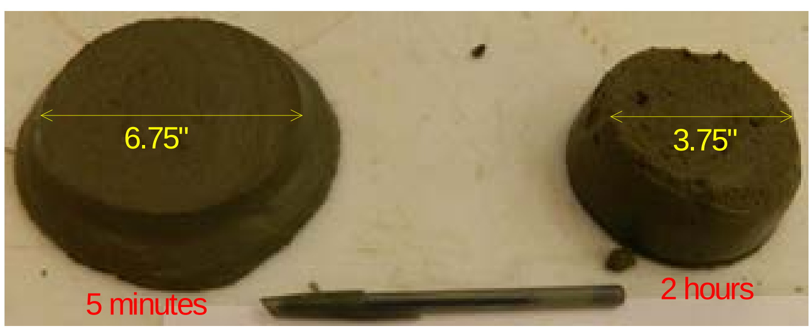


Figure C10 - Spread of mini slump test for VexconCerti-Vex Grout 1000 at different time at normal temperature (73°F) (Mix #13)

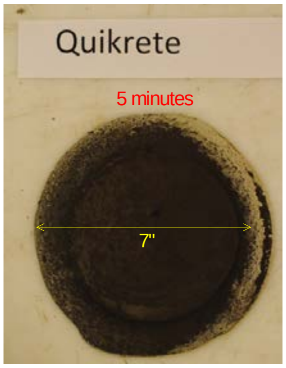


Figure C11 - Spread of mini slump test for Quikrete Non-Shrink Precision Grout at 5 minutes at normal temperature (73°F) (Mix #14)

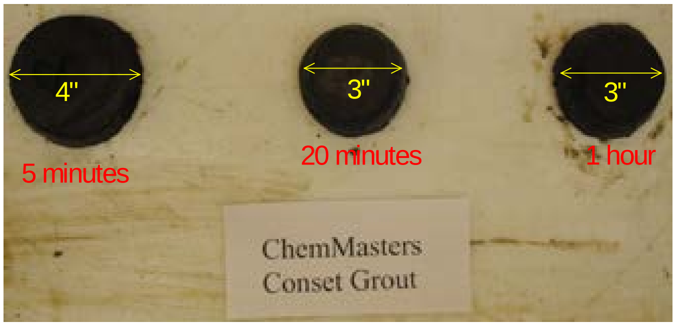


Figure C12 - Spread of mini slump test for ChemMaster Conset Grout at different time at normal temperature (73°F) (Mix #15)

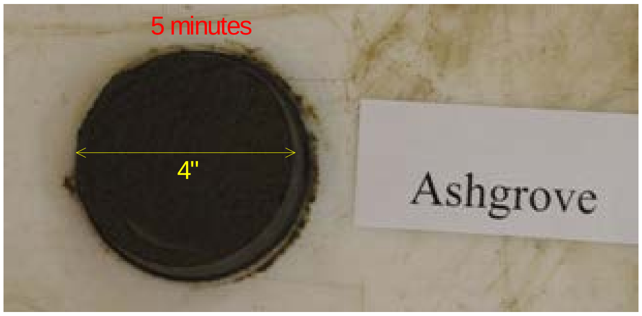


Figure C13 - Spread of mini slump test for Ash Grove Non-Shrink Grout at 5 minutes at normal temperature (73°F) (Mix #16)

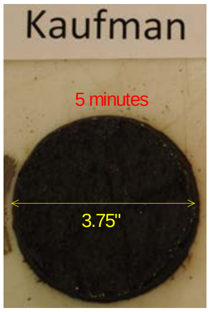


Figure C14 - Spread of mini slump test for Kaufman Non-Shrinking Precision Grout at 5 minutes at normal temperature (73°F) (Mix #17)

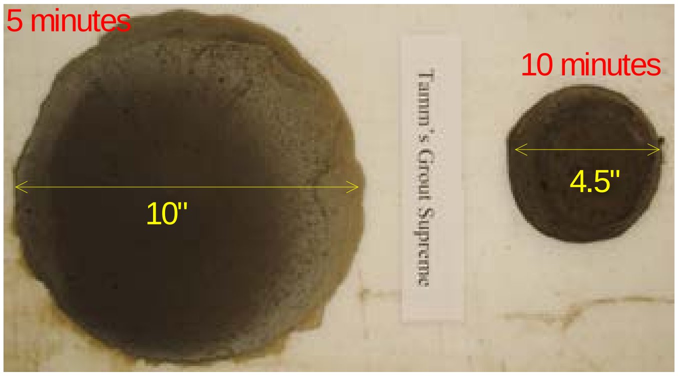


Figure C15- Spread of mini slump test for TAMMs Grout Supreme at different time at normal temperature (73°F) (Mix #19)

Figure C16 - Spread of mini slump test for Euco Precast Grout at different time at normal temperature (73°F) (note: bleeding occurred especially at the 5 minutes measurement) (Mix #20)

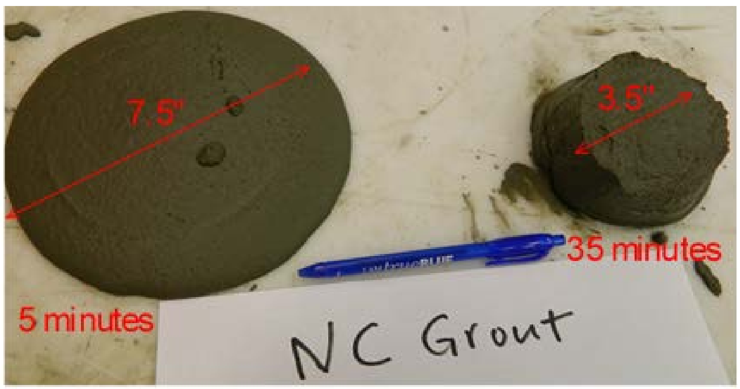


Figure C17 - Spread of mini slump test for Euclid NC Grout at different time at normal temperature (73°F) (Mix #21)

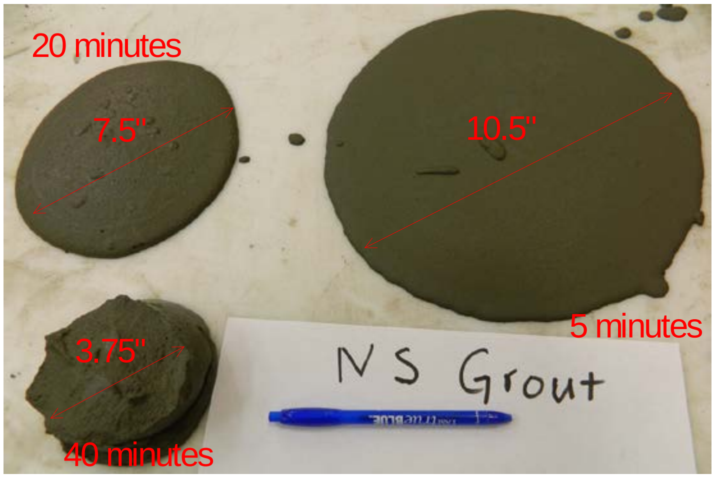


Figure C18 - Spread of mini slump test for Euclid NS Grout at different time at normal temperature (73°F) (Mix #22)

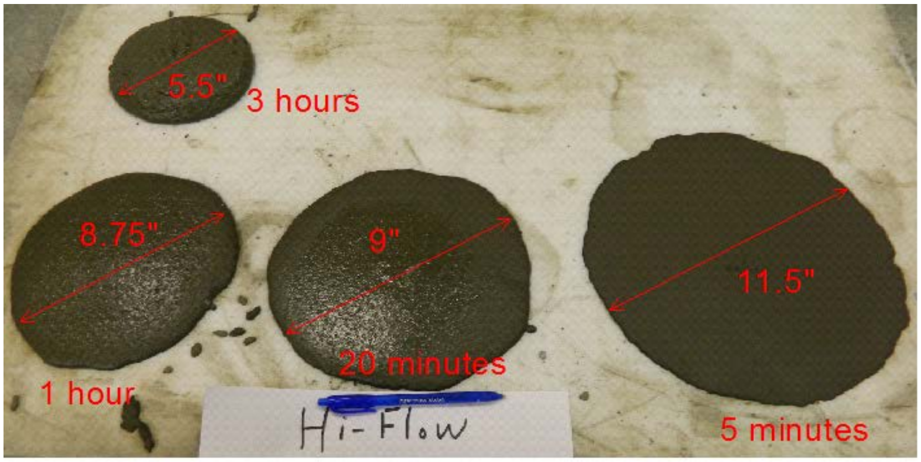


Figure C19 - Spread of mini slump test for Euclid Hi-Flow Grout at different time at normal temperature (73°F) (Mix #23)

C2. Medium Temperature (85°F) and Different Time

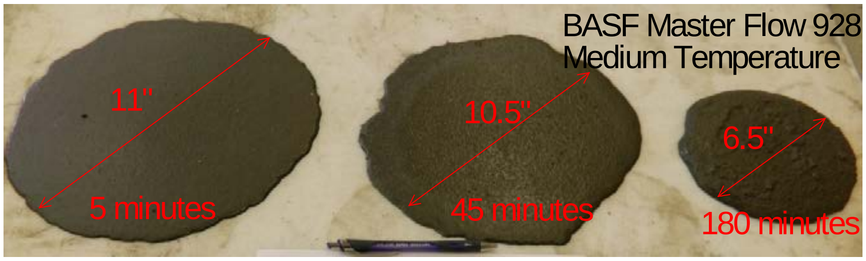


Figure C20 - Spread of mini slump test for BASF Masterflow 928 Grout at different time at medium temperature (85°F) (Mix #1)

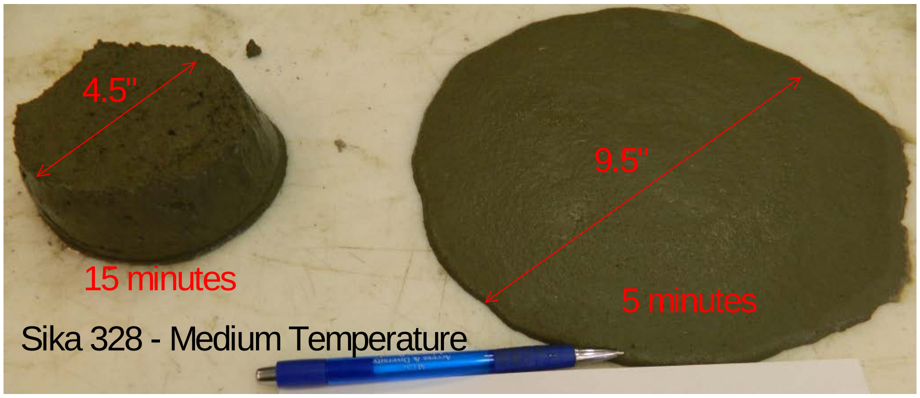


Figure C21 - Spread of mini slump test for Sika 328 Grout at different time at medium temperature (85°F) (Mix #2)

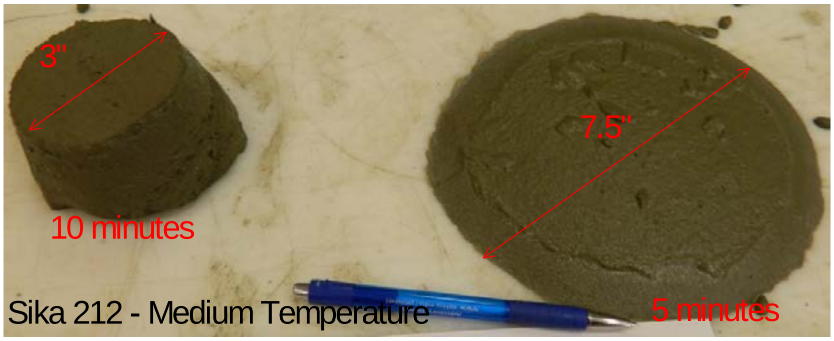


Figure C22 - Spread of mini slump test for Sika 212 Grout at different time after mixing at medium temperature (85°F) (Mix #3)

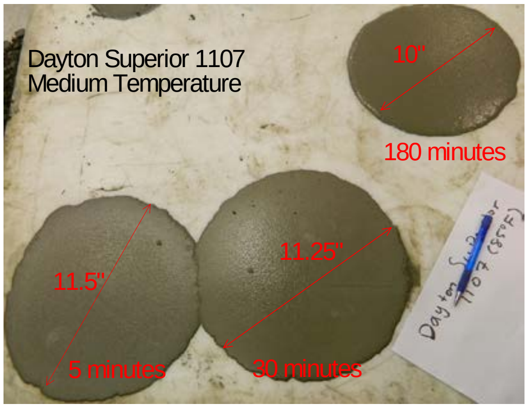


Figure C23 - Spread of mini slump test for Dayton Superior 1107 Grout at different time at medium temperature (85°F) (Mix #4)

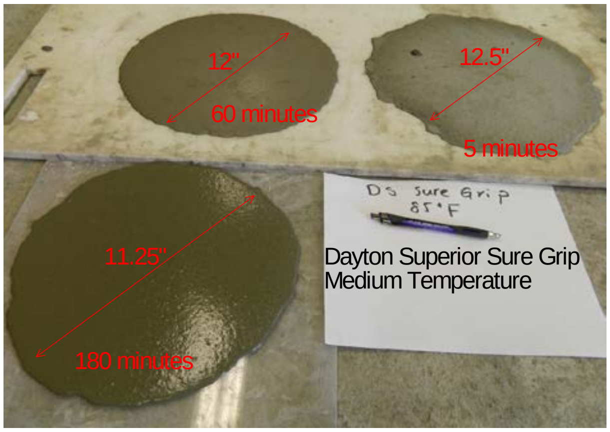


Figure C24 - Spread of mini slump test for Dayton Superior SureGrip Grout at different time at medium temperature (85°F) (Mix #5)

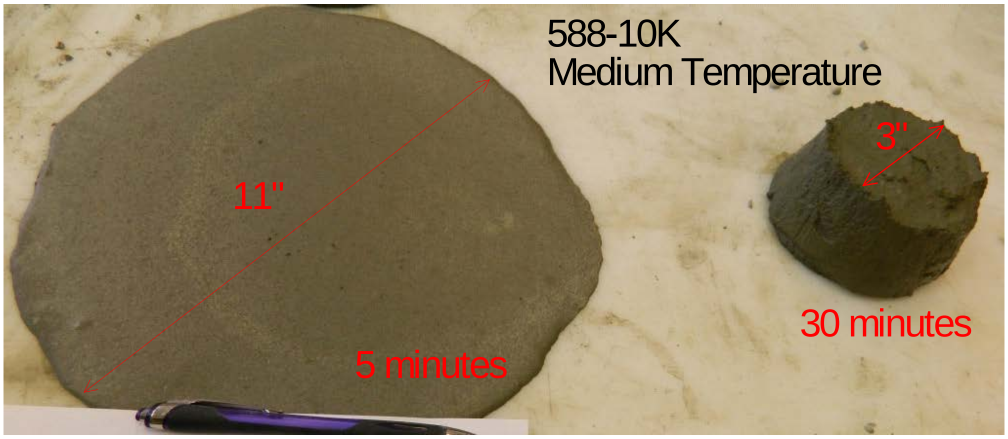


Figure C25 - Spread of mini slump test for W.R. Meadows 588-10K Grout at different time at medium temperature (85°F) (Mix #6)

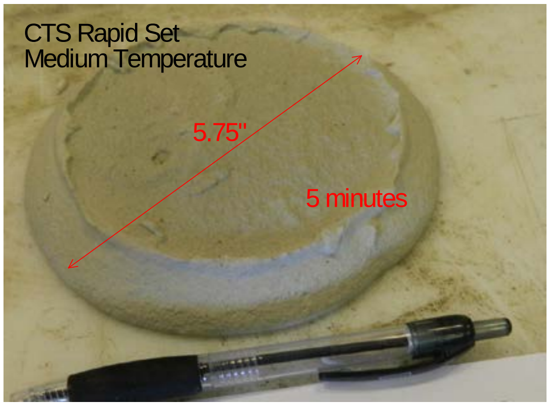


Figure C26 - Spread of mini slump test for CTS rapid set CEMENT ALL at 5 minutes at medium temperature (85°F) (Mix #7)

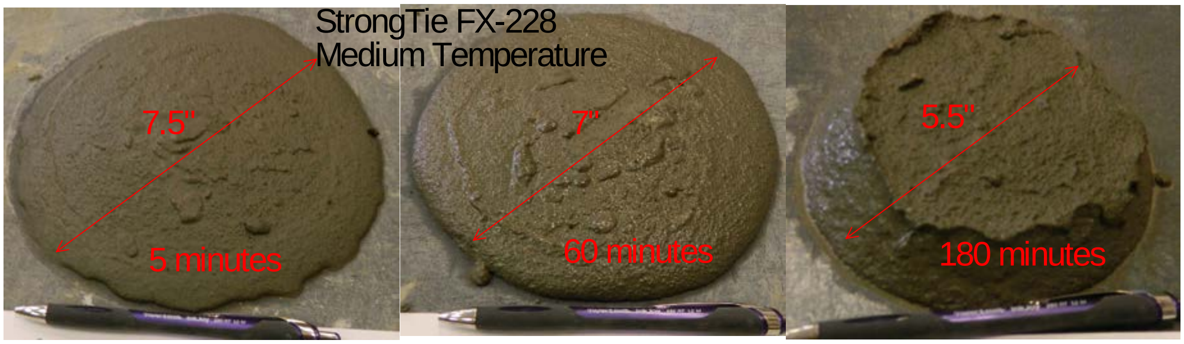


Figure C27 - Spread of mini slump test for Fox Industries StrongTie FX-228 Grout at different time at medium temperature (85°F) (Mix #9)

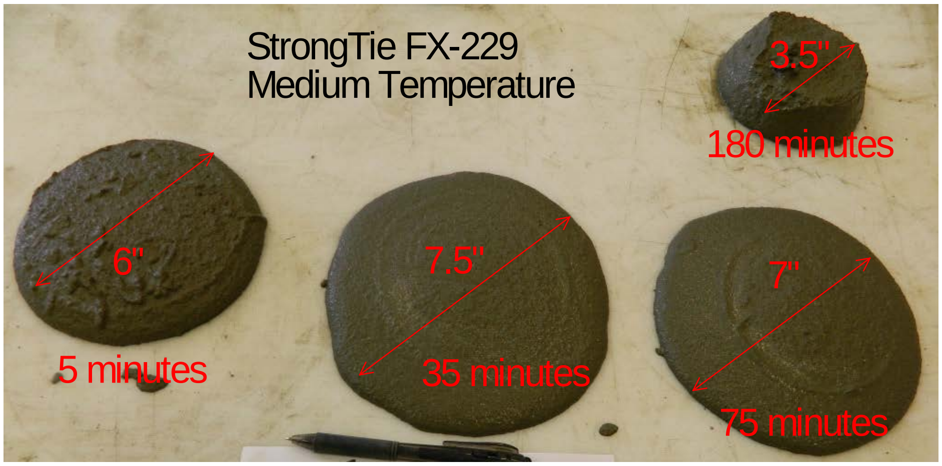


Figure C28 - Spread of mini slump test for Fox Industries StrongTie FX-229 Grout at different time at medium temperature (85°F) (Mix #10)

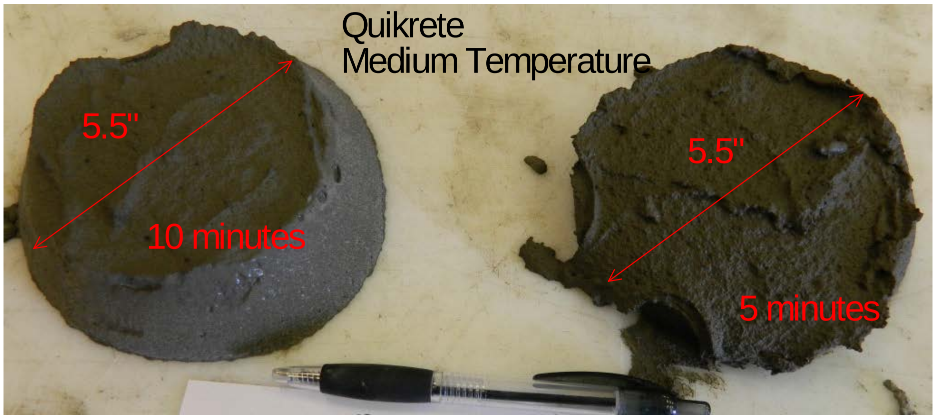


Figure C29 - Spread of mini slump test for Quikrete Non-Shrink Precision Grout at different time at medium temperature (85°F) (Mix #14)

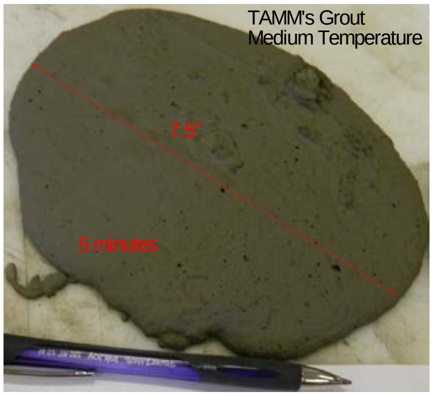


Figure C30 - Spread of mini slump test for TAMM's Grout Supreme at 5 minutes at medium temperature (85°F) (Mix #19)

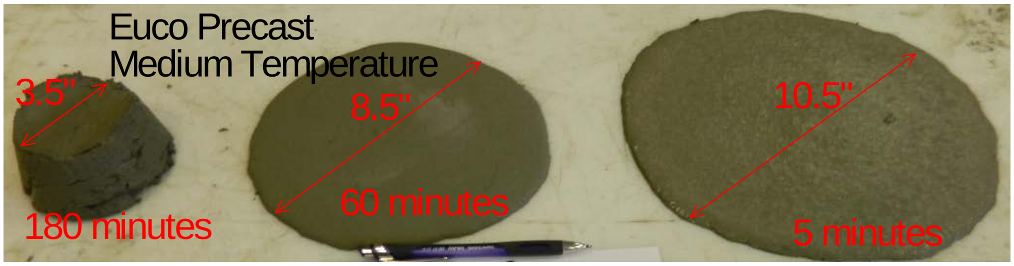


Figure C31 - Spread of mini slump test for Euclid Euco-Precast Grout at different time at medium temperature (85°F) (Mix #20)

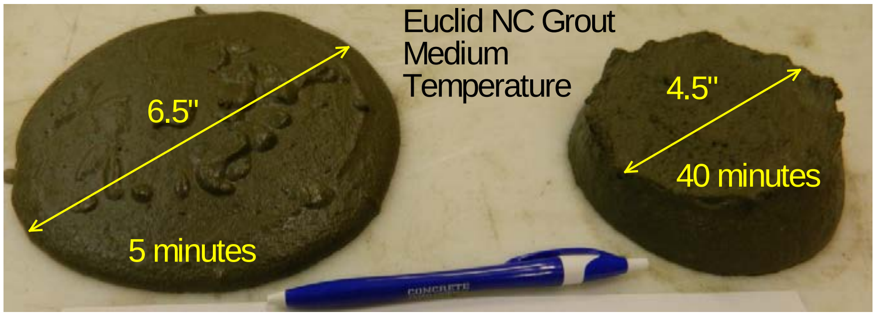


Figure C32 - Spread of mini slump test for Euclid NC Grout at different time at medium temperature (85°F) (Mix #21)

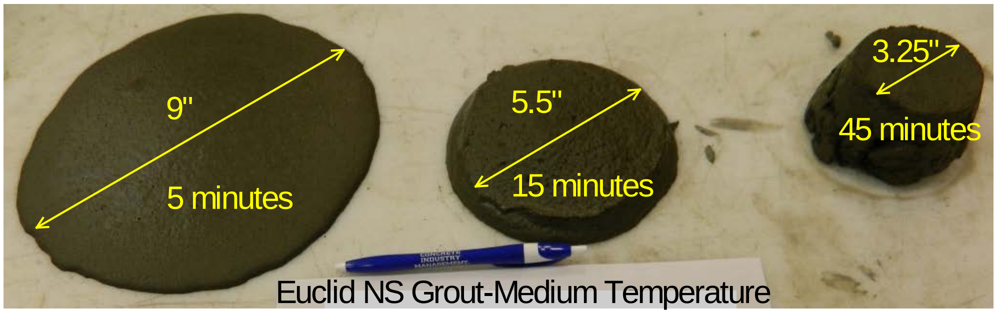


Figure C33 - Spread of mini slump test for Euclid NS Grout at different time at medium temperature (85°F) (Mix #22)

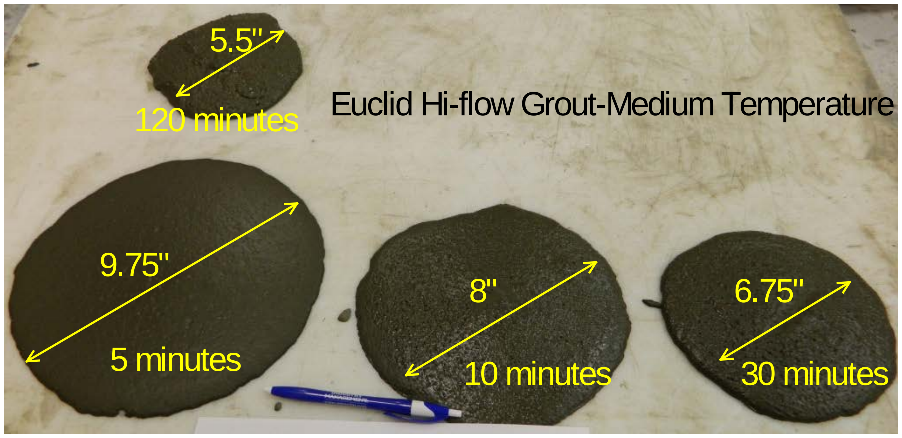


Figure C34 - Spread of mini slump test for Euclid Hi-flow Grout at different time at medium temperature (85°F) (Mix #23)

C3. High Temperature (95°F) and Different Time

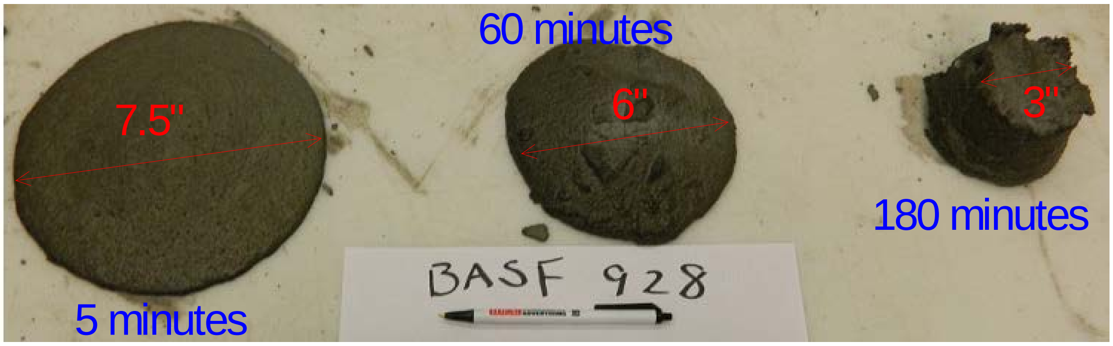


Figure C35 - Spread of mini slump test for BASF Masterflow 928 Grout at different time at high temperature (95°F) (Mix #1)

Figure C36 - Spread of mini slump test for Sika 328 Grout at different time at high temperature (95°F) (Mix #2)

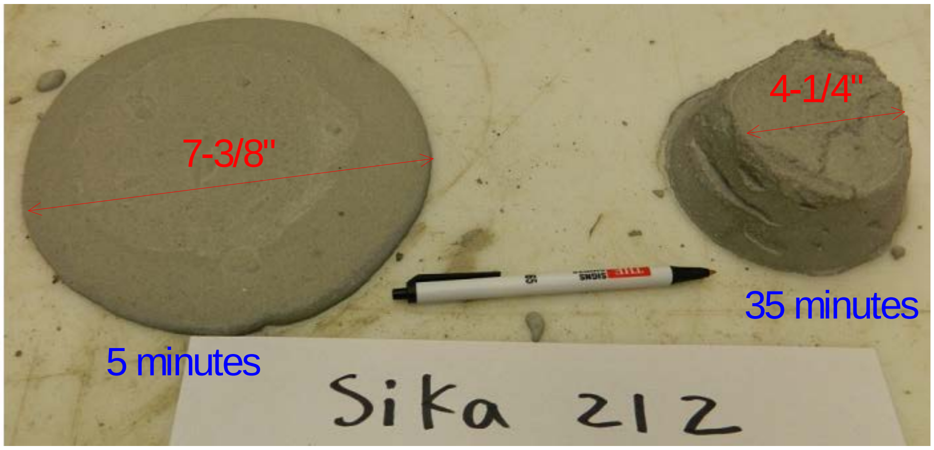


Figure C37 - Spread of mini slump test for Sika 212 Grout at different time at high temperature (95°F) (Mix #3)

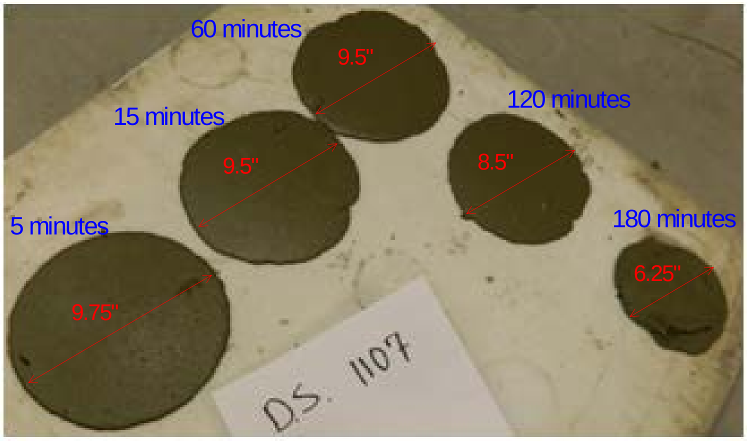


Figure C38 - Spread of mini slump test for Dayton Superior 1107 Grout at different time at high temperature (95°F) (Mix #4)

Figure C39 - Spread of mini slump test for Dayton Superior SureGrip Grout at different time at high temperature (95°F) (Mix #5)

Figure C40 - Spread of mini slump test for W.R Meadows 588-10K Grout at different time at high temperature (95°F) (Mix #6)

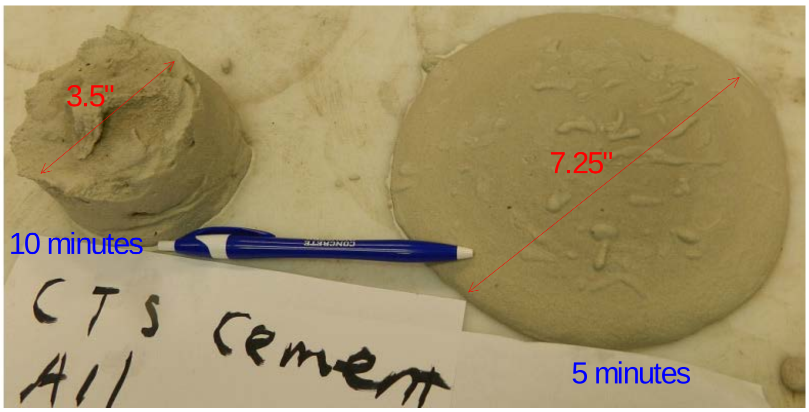


Figure C41 - Spread of mini slump test for CTS rapid-set CEMENT ALL at different time at high temperature (95°F) (Mix #7)

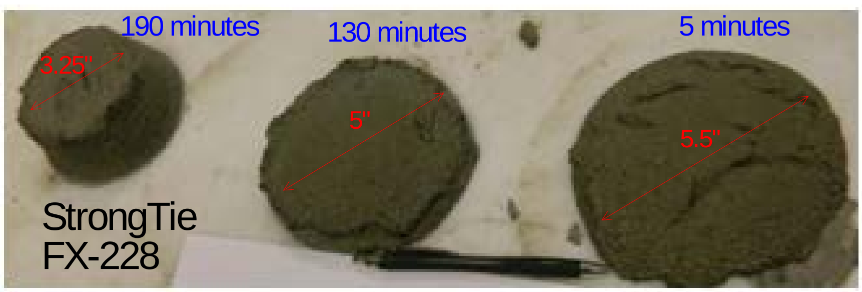


Figure C42 - Spread of mini slump test for Simpson StrongTie FX-228 Grout at different time at high temperature (95°F) (Mix #9)

Figure C43 - Spread of mini slump test for Simpson StrongTie FX-229 Grout at different time at high temperature (95°F) (Mix #10)

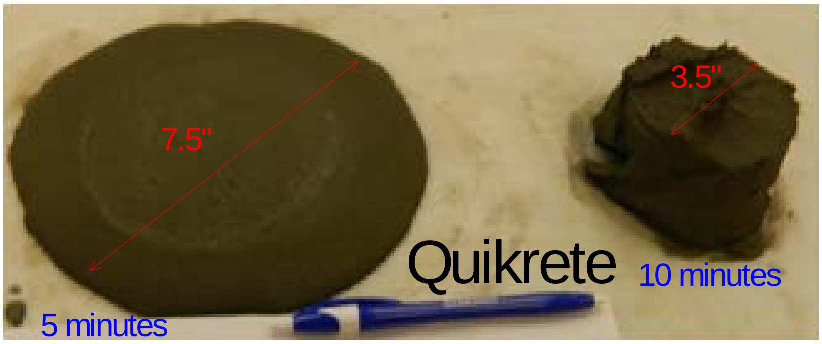


Figure C44 - Spread of mini slump test for Quikrete Non-Shrink Precision Grout at different time at high temperature (95°F) (Mix #14)

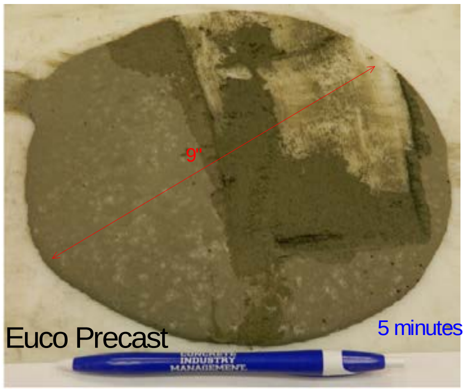


Figure C45 - Spread of mini slump test for Euclid Euco-Precast Grout at 5 minutes at high temperature (95°F) (Mix #20)

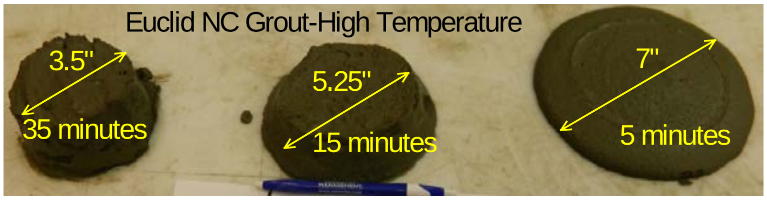


Figure C46 - Spread of mini slump test for Euclid NC Grout at different time at high temperature (95°F) (Mix #21)

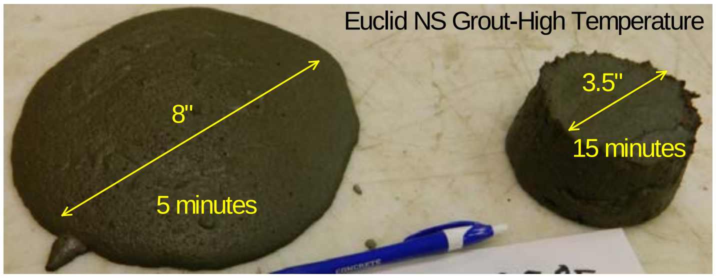


Figure C47 - Spread of mini slump test for Euclid NS Grout at different time at high temperature (95°F) (Mix #22)

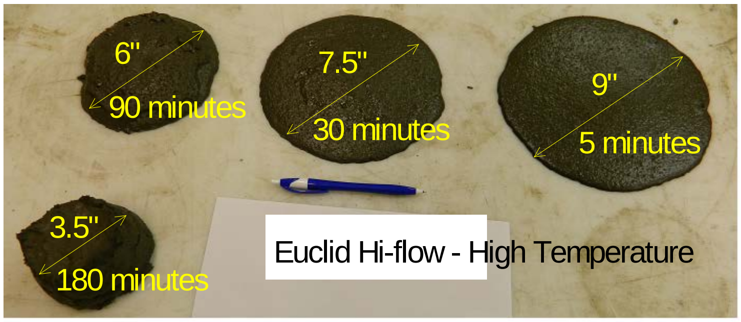


Figure C48 - Spread of mini slump test for Euclid Hi-flow Grout at different time at high temperature (95°F) (Mix #23)

C4. Steel Fiber Addition at Normal Temperature (73°F) with Different Fiber Dosages and Different Time

Figure C49 - Spread of mini slump test for Dayton Superior Sure Grip Grout at different time at normal temperature (73°F) with 1% steel fiber addition (note: bleeding occurred in 5 minutes measurement) (Mix #5)

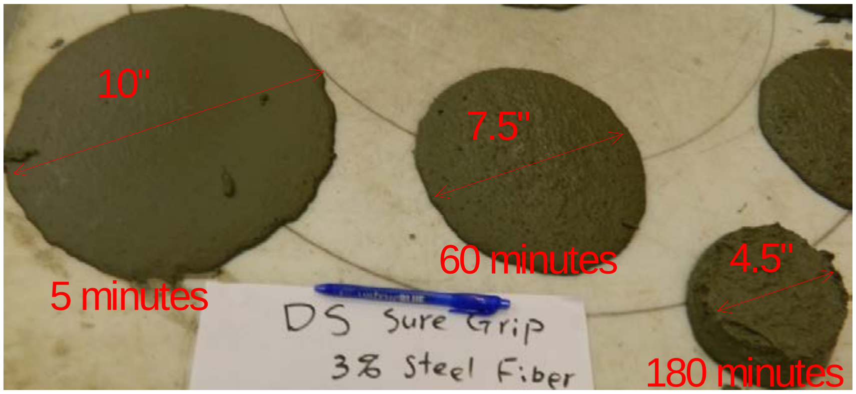


Figure C50 - Spread of mini slump test for Dayton Superior Sure Grip Grout at different time at normal temperature (73°F) with 3% steel fiber addition (Mix #5)

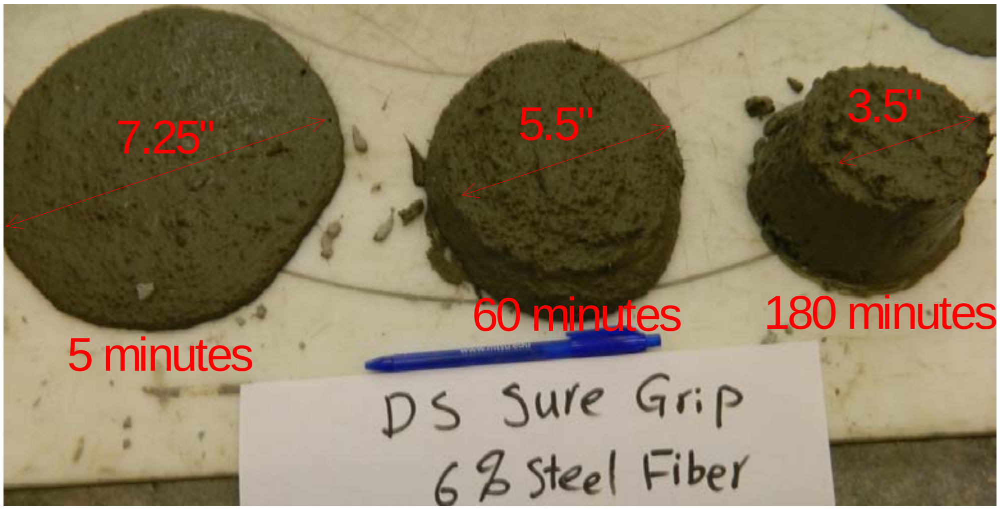


Figure C51 - Spread of mini slump test for Dayton Superior Sure Grip Grout at different time at normal temperature (73°F) with 6% steel fiber addition (Mix #5)

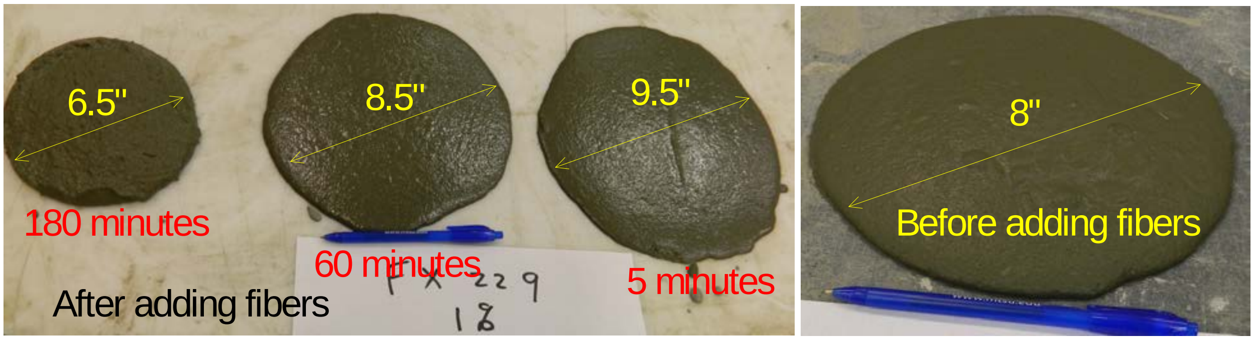


Figure C52 - Spread of mini slump test for Simpson StrongTie FX-229 Grout at different time at normal temperature (73°F) with 1% steel fiber addition (Mix #10)

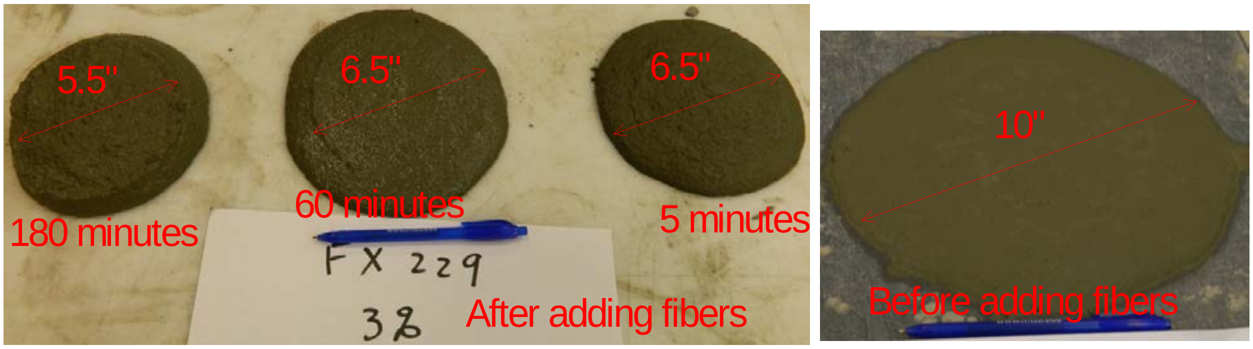


Figure C53 - Spread of mini slump test for Simpson StrongTie FX-229 Grout at different time at normal temperature (73°F) with 3% steel fiber addition (Mix #10)

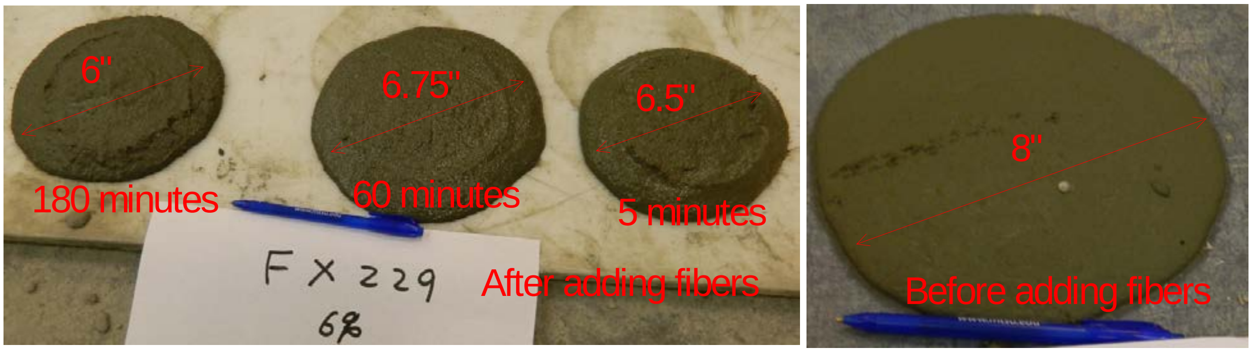


Figure C54 - Spread of mini slump test for Simpson StrongTie FX-229 Grout at different time at normal temperature (73°F) with 6% steel fiber addition (Mix #10)

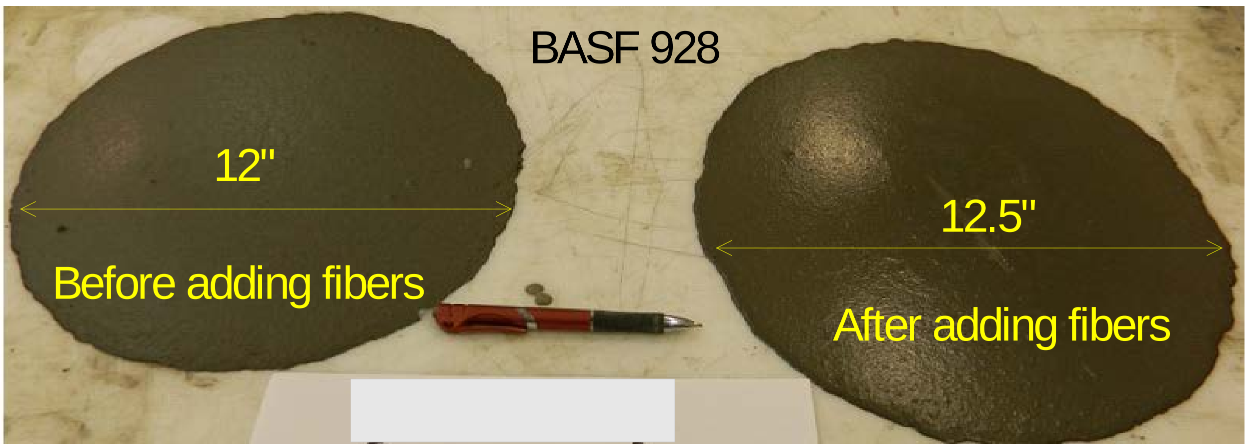


Figure C55 - Spread of mini slump test for BASF Masterflow 928 Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #1)

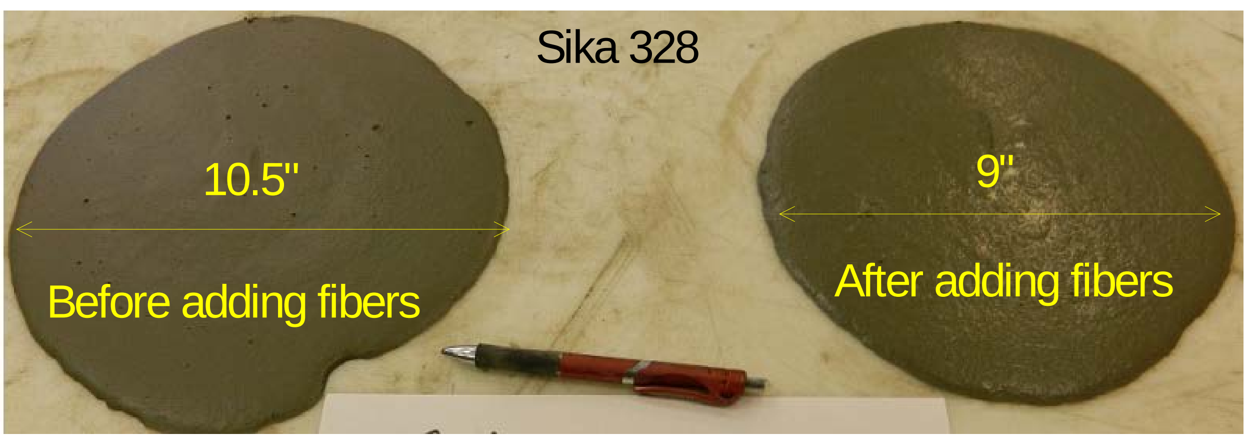


Figure C56 - Spread of mini slump test for Sika 328 Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #2)

Figure C57 - Spread of mini slump test for Sika 212 Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #3)

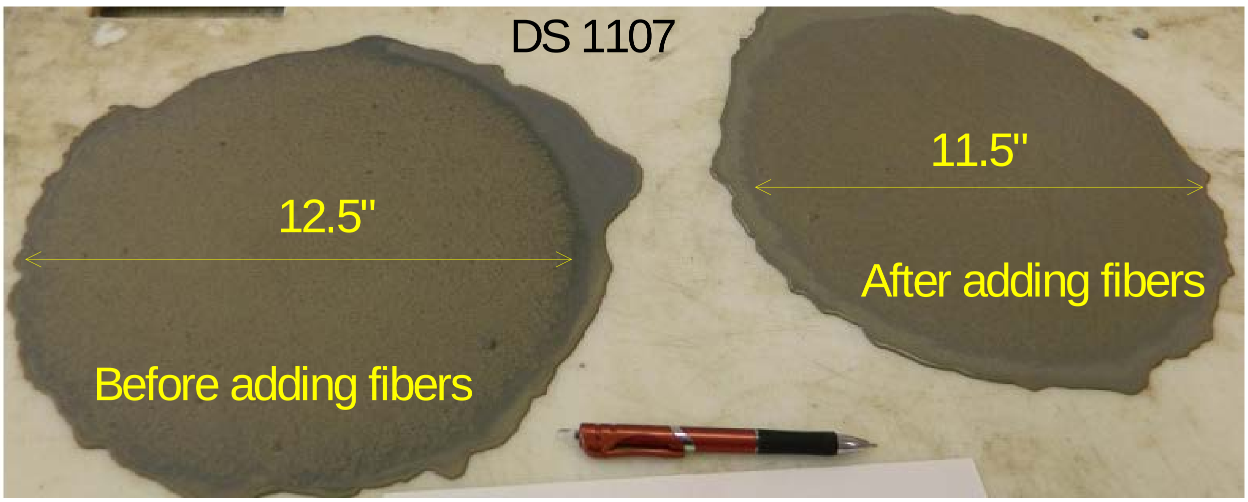


Figure C58 - Spread of mini slump test for Dayton Superior 1107 Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #4)

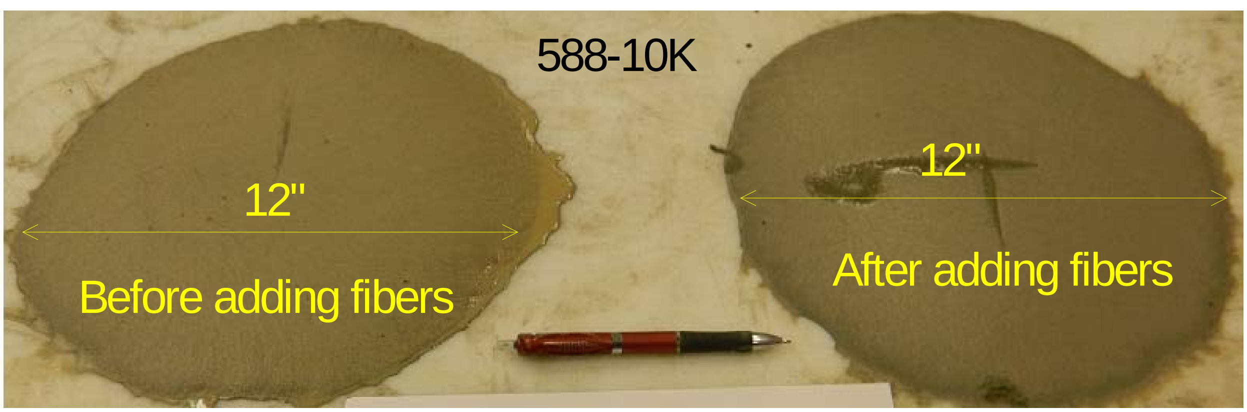


Figure C59 - Spread of mini slump test for W.R Meadows 588-10K Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #6)

Figure C60 - Spread of mini slump test for CTS Rapid Set CEMENT ALL Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #7)

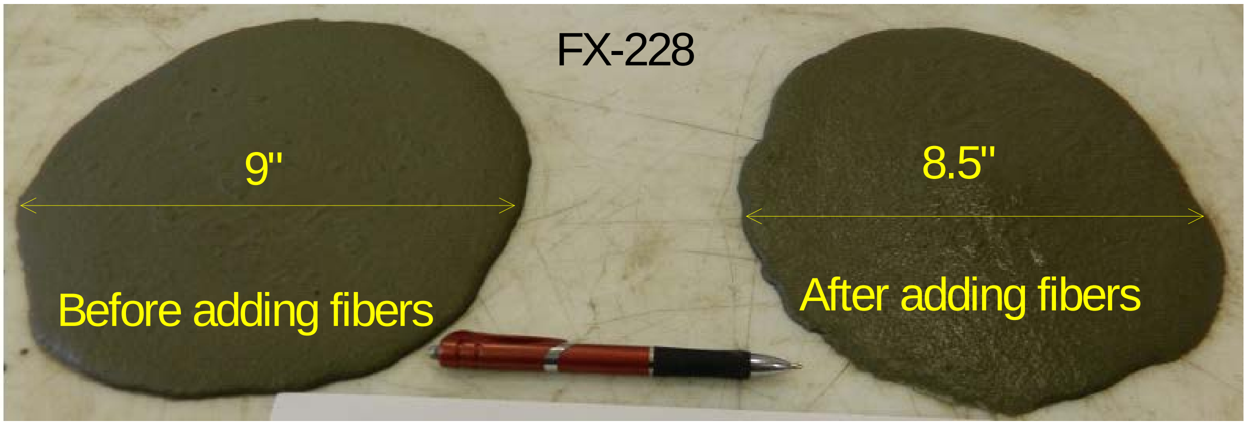


Figure C61 - Spread of mini slump test for Simpson StrongTie FX-228 Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #9)

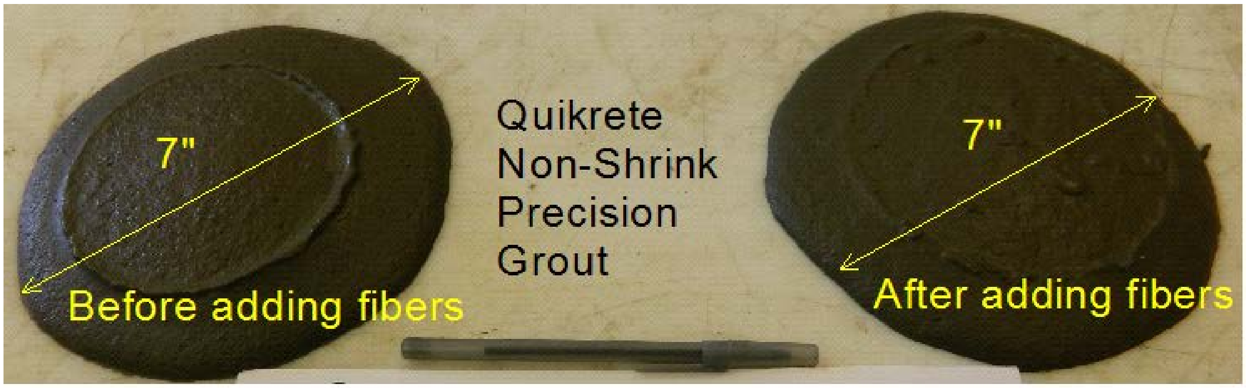


Figure C62 - Spread of mini slump test for Quikrete Non-Shrink Precision Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #14)

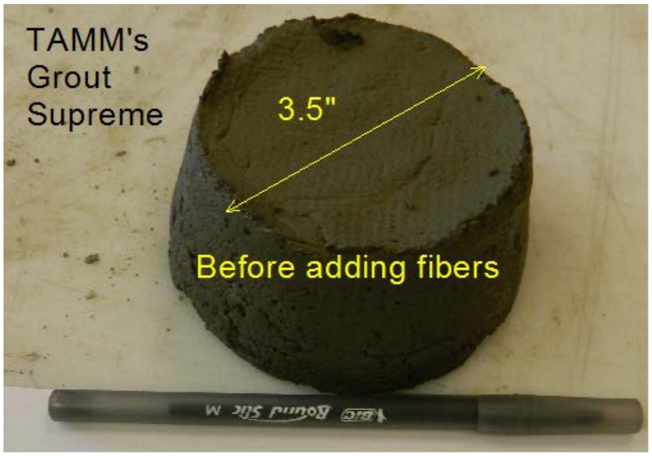


Figure C63 - Spread of mini slump test for TAMM's Grout Supreme at normal temperature (73°F) (Note: Steel fibers were not added because the mixture was very dry) (Mix #19)

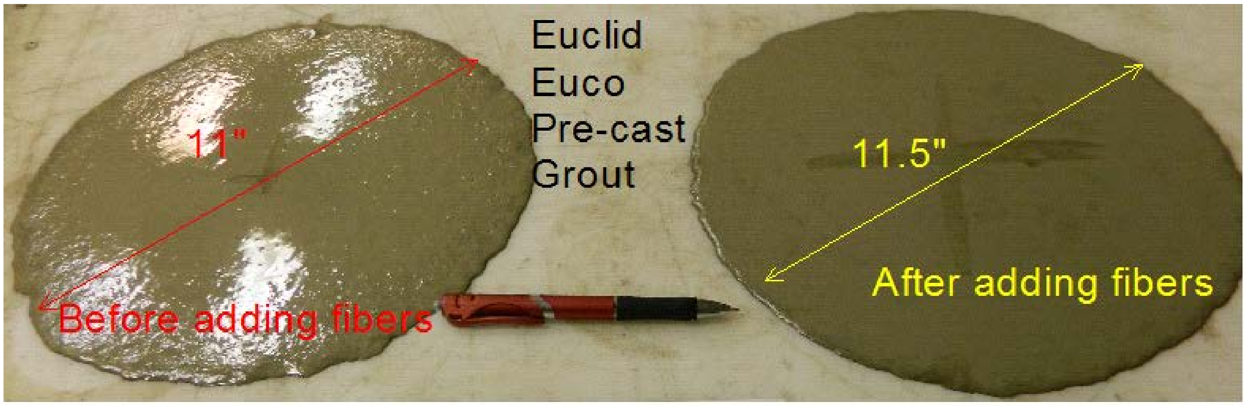


Figure C64 - Spread of mini slump test for Euclid Euco Precast Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #20)

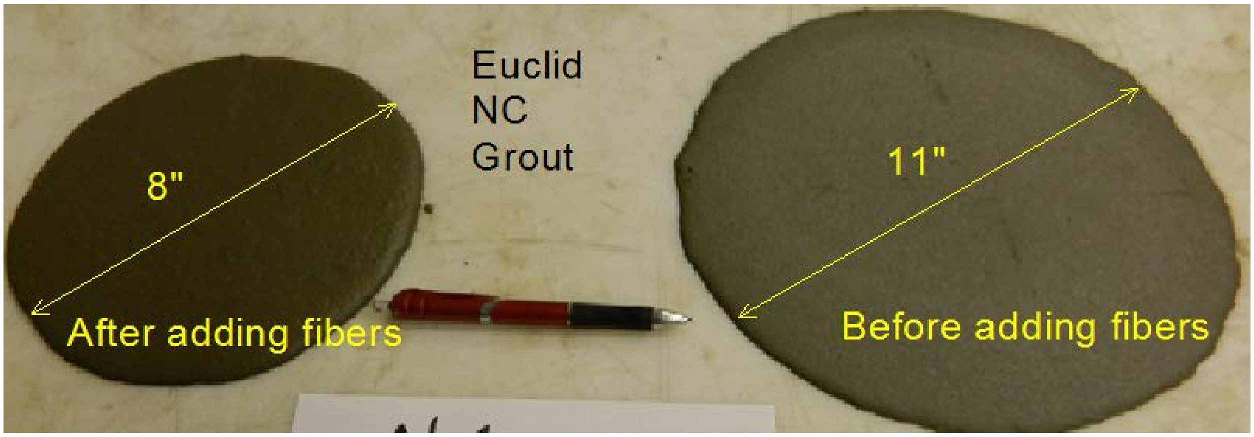


Figure C65 - Spread of mini slump test for Euclid NC Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #21)

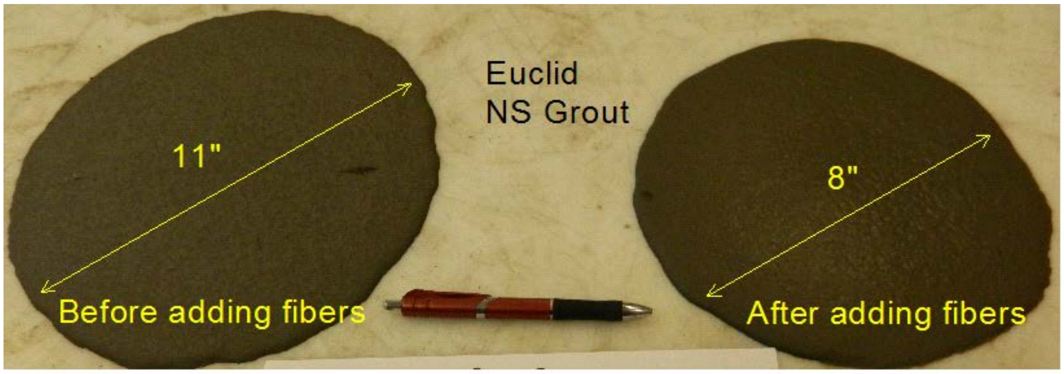


Figure C66 - Spread of mini slump test for Euclid NS Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #22)

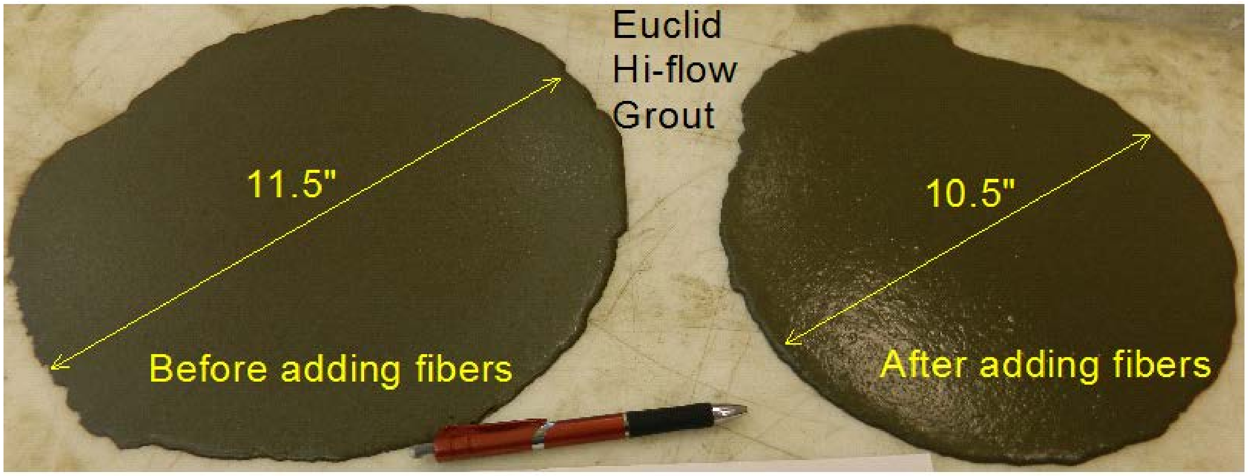


Figure C67 - Spread of mini slump test for Euclid Hi-flow Grout at normal temperature (73°F) with 3% steel fiber addition (Mix #23)

APPENDIX D – VISUAL APPEARANCE OF FREEZE AND THAW TEST SPECIMENS

Figure D1- Visual appearance of specimens before and after freeze and thaw test for BASF Masterflow 928 (Mix #1)

Figure D2- Visual appearance of specimens before and after freeze and thaw test for SikaGrout 328 (Mix #2)

Figure D3- Visual appearance of specimens before and after freeze and thaw test for SikaGrout 212 (Mix #3)

Figure D4- Visual appearance of specimens before and after freeze and thaw test for Dayton Superior 1107 Advantage Grout (Mix #4)

Figure D5 - Visual appearance of specimens before and after freeze and thaw test for Dayton Superior Sure-Grip High Performance Grout (Mix #5)

Figure D6- Visual appearance of specimens before and after freeze and thaw test for W.R Meadow SEALTIGHT 588-10K (Mix #6)

Figure D7- Visual appearance of specimens before and after freeze and thaw test for CTS Rapid Set CEMENT ALL Grout (Mix #7)

Figure D8- Visual appearance of specimens before and after freeze and thaw test for Simpson StrongTie FX-228 (Mix #9)

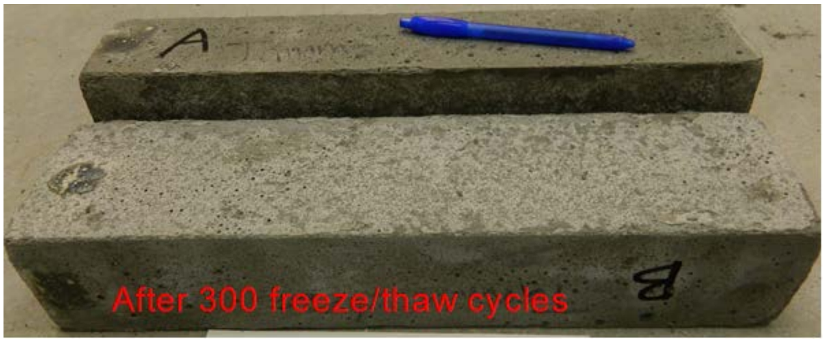


Figure D9- Visual appearance of specimens after freeze and thaw test for Euclid TAMMs GROUT SUPREME (Mix #19)

Figure D10- Visual appearance of specimens after freeze and thaw test for Euclid Euco Precast Grout (Mix #20)

Figure D11- Visual appearance of specimens after freeze and thaw test for Euclid NC Grout (Mix #21)

Figure D12- Visual appearance of specimens after freeze and thaw test for Euclid NS Grout (Mix #22)

Figure D13- Visual appearance of specimens after freeze and thaw test for Euclid Hi-flow Grout (Mix #23)

Appendix E – Mini Slump Test for Cementitious Grout Materials Developed in This Study

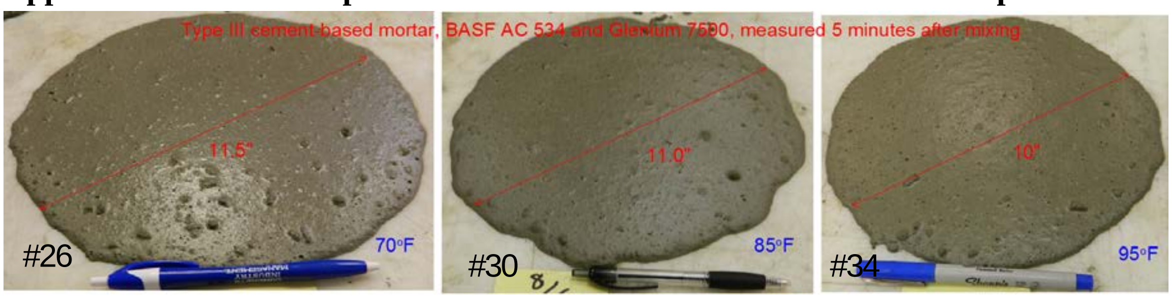


Figure E1-Spread of mini slump test for type III cement-based mortars (#26, #30, and #34) using BASF AC534 (accelerator) and Glenium 7500 (superplsticizer) at different temperatures

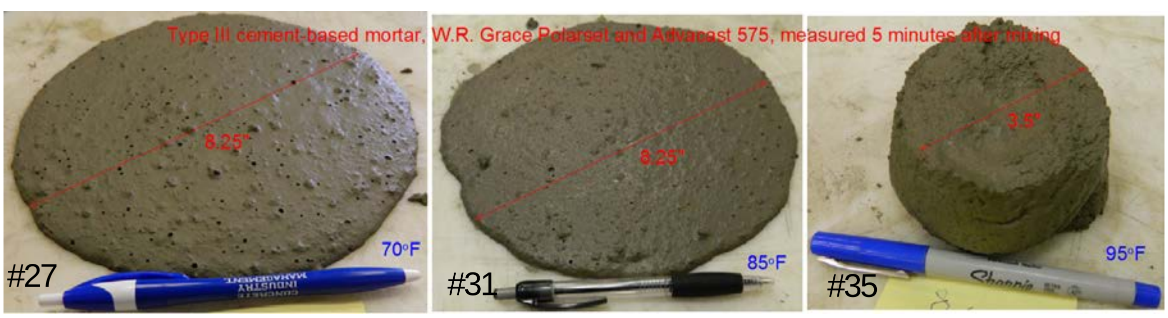


Figure E2-Spread of mini slump test for type III cement-based mortars (#27, #31, and #35) using W.R. Grace Polarset (accelerator) and Adva-Cast 575 (superplsticizer) at different temperatures

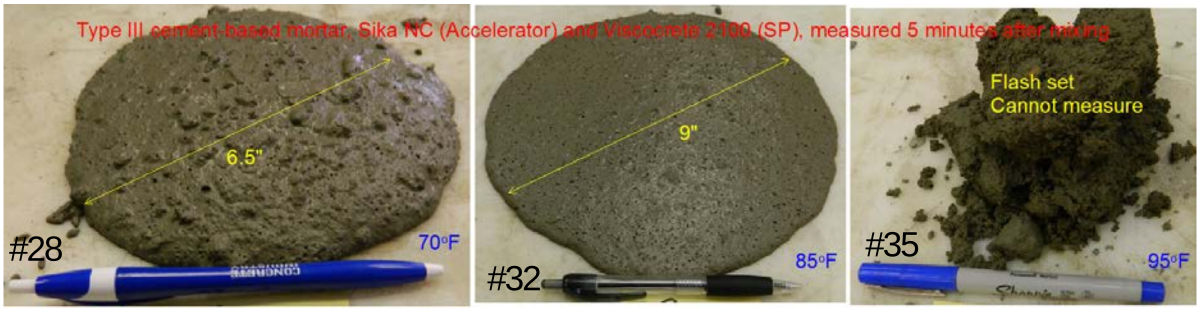


Figure E3-Spread of mini slump test for type III cement-based mortars (#28, #32, and #36) using Sika NC (accelerator) and Viscocrete 2100 (superplsticizer) at different temperatures

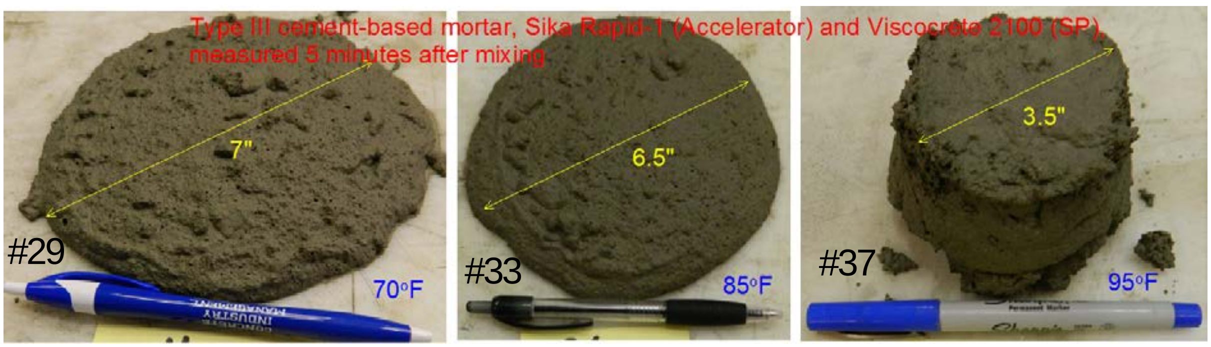


Figure E4-Spread of mini slump test for type III cement-based mortars (#29, #33, and #37) using Sika Rapid-1 (accelerator) and Viscocrete 2100 (superplsticizer) at different temperatures

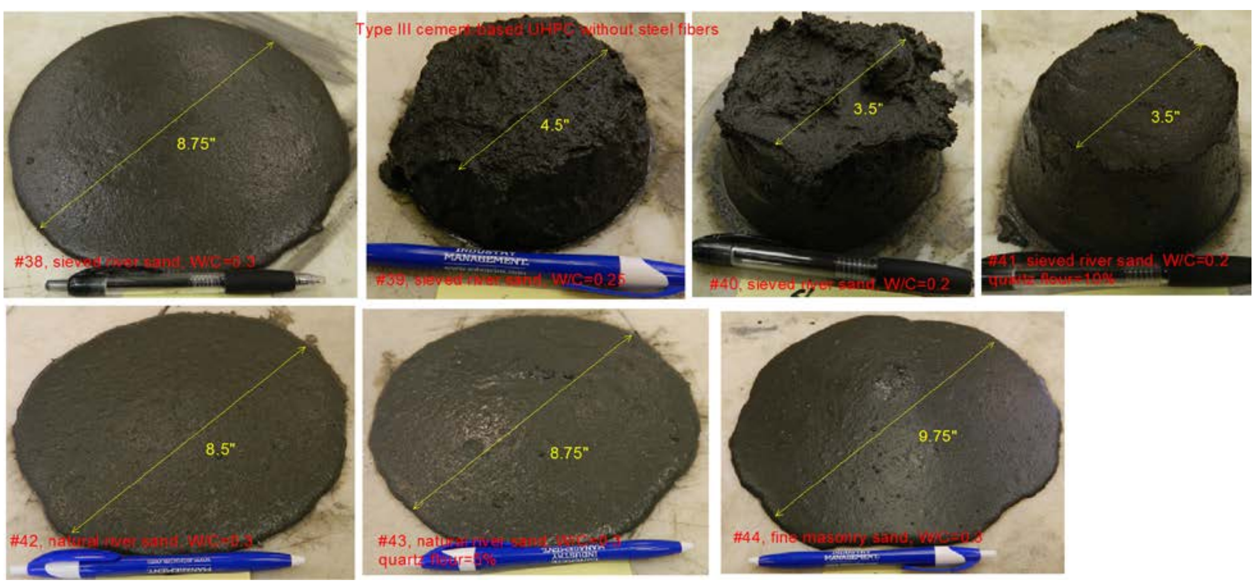


Figure E5-Spread of mini slump test for type III cement-based ultra-high performance concrete without steel fibers (#38 - #44)

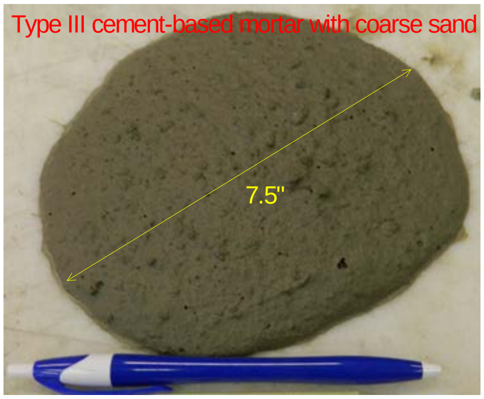


Figure E6-Spread of mini slump test for type III cement-based normal mortar with natural river sand (#45)

Figure E7-Spread of mini slump test for type III cement-based mortar with sieved river sand (#46) (note: water separation possibly due to insufficient paste)

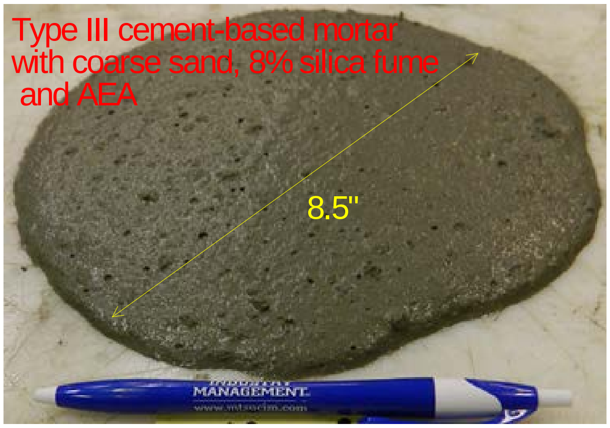


Figure E8-Spread of mini slump test for type III cement-based normal mortar with natural river sand, silica fume, and AEA (#47)

Figure E9-Spread of mini slump test for type III cement-based high performance mortar with natural river sand (#48)

Figure E10 -Spread of mini slump test for type III cement-based high performance mortar with natural river sand, AEA, and SRA (#49)

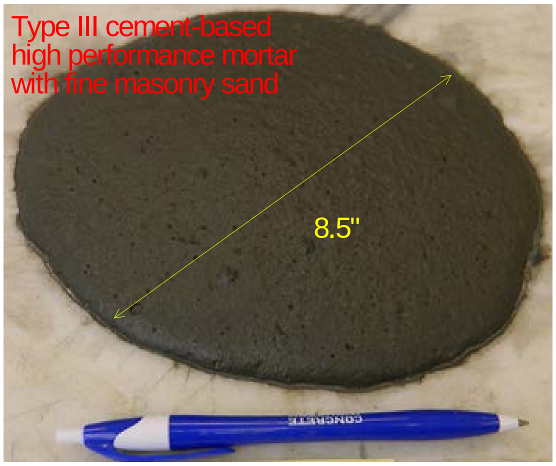


Figure E11-Spread of mini slump test for type III cement-based high performance mortar with fine masonry sand (#50)

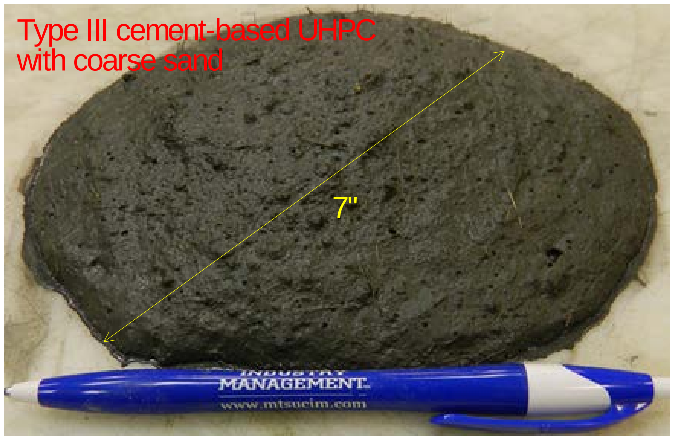


Figure E12-Spread of mini slump test for type III cement-based UHPC (#51)

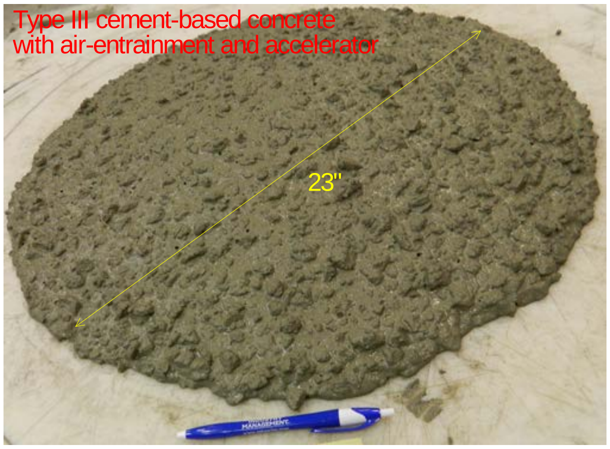


Figure E13-Spread of slump test for type III cement-based concrete with accelerator (#52)

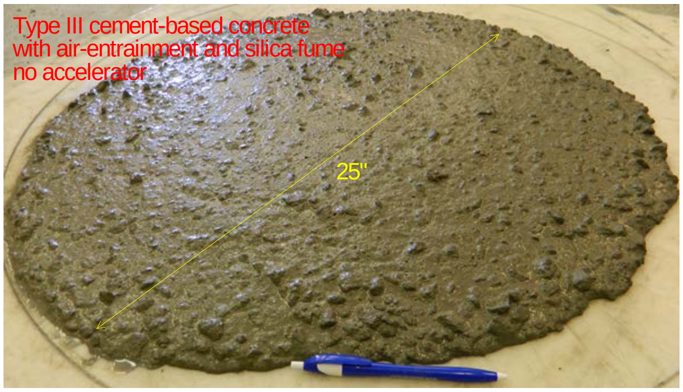


Figure E14-Spread of slump test for type III cement-based concrete without accelerator (#53)

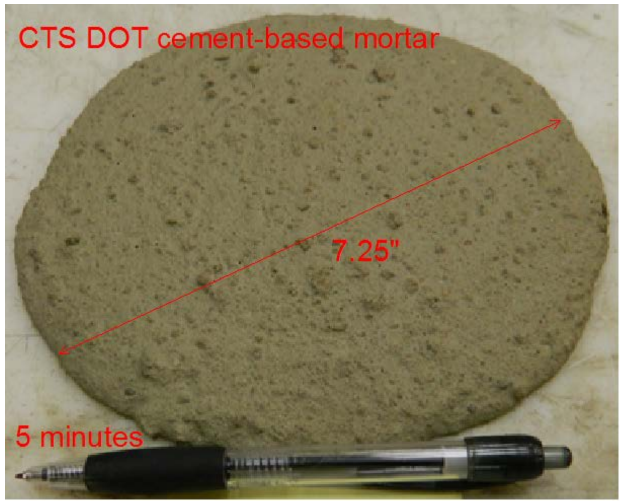


Figure E15-Spread of mini slump test for CTS rapid set cement-based mortar (#54)

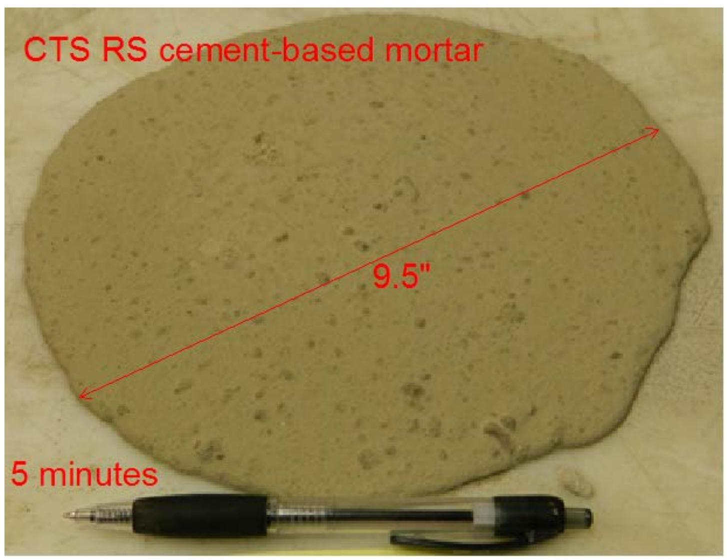


Figure E16-Spread of mini slump test for CTS DOT cement-based mortar (#55)

Appendix F –Failure Mode of Slant Shear Bond Test for Cementitious Grout Materials Developed in This Study

Figure F1-Failure mode of flexural bond test at 28 days for type III cement-based mortar using natural river sand and different substrate surface moisture conditions (#45)

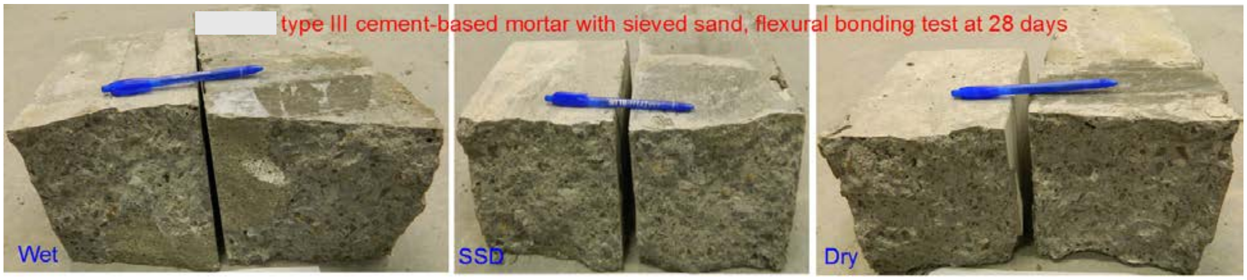


Figure F2-Failure mode of flexural bond test at 28 days for type III cement-based mortar using sieved river sand and different substrate surface moisture conditions (#46)

Figure F3-Failure mode of flexural bond test at 28 days for type III cement-based mortar using natural river sand, AEA, and different substrate surface moisture conditions (#47)

Figure F4-Failure mode of flexural bond test at 28 days for type III cement-based high performance mortar using natural river sand and different substrate surface moisture conditions (#48)

Figure F5-Failure mode of flexural bond test at 28 days for type III cement-based high performance mortar using natural river sand, AEA, and different substrate surface moisture conditions (#49)

Figure F6-Failure mode of flexural bond test at 28 days for type III cement-based high performance mortar using fine masonry sand and different substrate surface moisture conditions (#50)

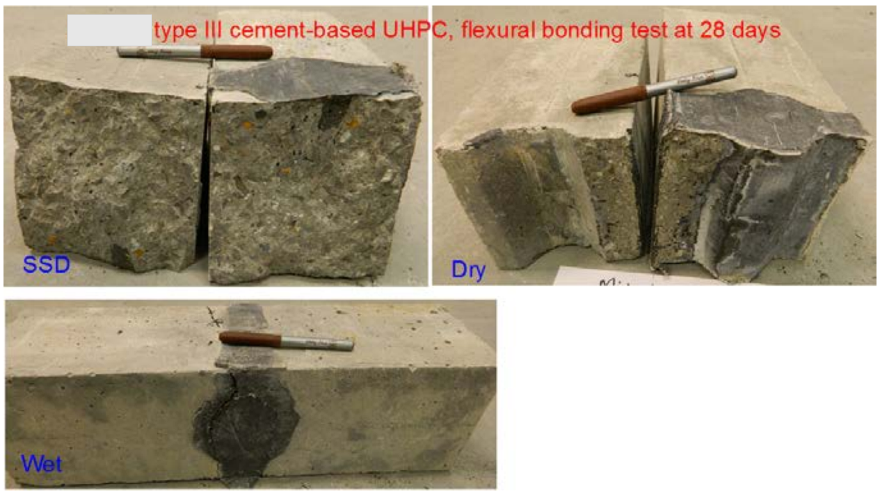


Figure F7-Failure mode of flexural bond test at 28 days for type III cement-based UHPC with different substrate surface moisture conditions (#51)

Figure F8-Failure mode of flexural bond test at 28 days for type III cement-based concrete with different substrate surface moisture conditions (#52)

Figure F9-Failure mode of flexural bond test at 28 days for CTS rapid set cement-based mortar with different substrate surface moisture conditions (#54)

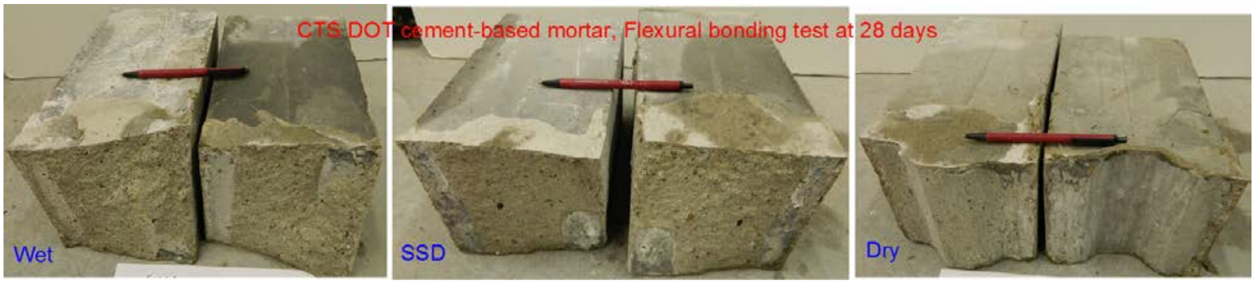


Figure F10-Failure mode of flexural bond test at 28 days for CTS DOT cement-based mortar with different substrate surface moisture conditions (#55)

Appendix G –Failure Mode of Slant Shear Bond Test for Cementitious Grout Materials Developed in This Study

Figure G1-Failure mode of slant shear bond test at 28 days for type III cement-based mortar using natural river sand and different substrate surface moisture conditions (#45)

Figure G2-Failure mode of slant shear bond test at 28 days for type III cement-based mortar using sieved river sand and different substrate surface moisture conditions (#46)

Figure G3-Failure mode of slant shear bond test at 28 days for type III cement-based mortar using coarse sand, AEA, and different substrate surface moisture conditions (#47)

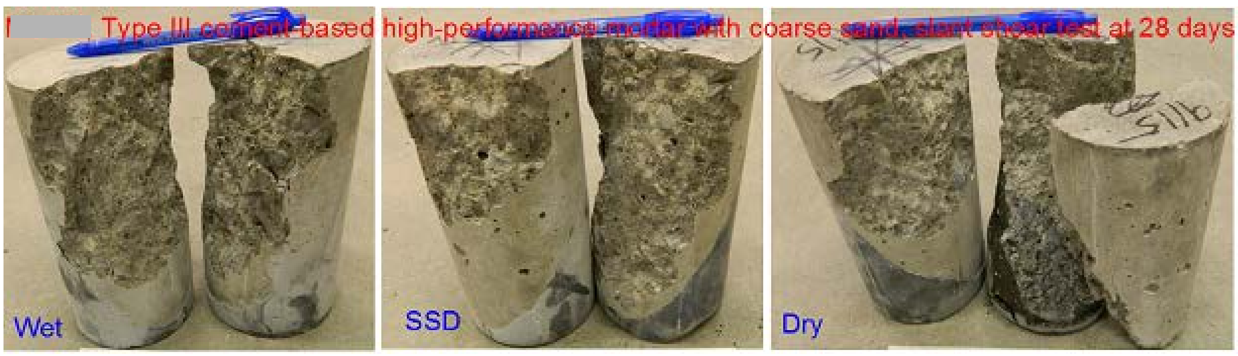


Figure G4-Failure mode of slant shear bond test at 28 days for type III cement-based high performance mortar using natural river sand and different substrate surface moisture conditions (#48)

Figure G5-Failure mode of slant shear bond test at 28 days for type III cement-based high performance mortar using natural river sand, AEA, and different substrate surface moisture conditions (#49)

Figure G6-Failure mode of slant shear bond test at 28 days for type III cement-based high performance mortar using fine masonry sand and different substrate surface moisture conditions (#50)

Figure G7-Failure mode of slant shear bond test at 28 days for type III cement-based UHPC with different substrate surface moisture conditions (#51)

Figure G8-Failure mode of slant shear bond test at 28 days for type III cement-based concrete with different substrate surface moisture conditions (#52)

Figure G9-Failure mode of slant shear bond test at 28 days for CTS rapid-set cement-based mortar with different substrate surface moisture conditions (#54)

Figure G10-Failure mode of slant shear bond test at 28 days for CTS DOT cement-based mortar with different substrate surface moisture conditions (#55)

Appendix H – Visual Appearance of Freeze and Thaw Test Specimens for Cementitious Grout Materials Developed in this study

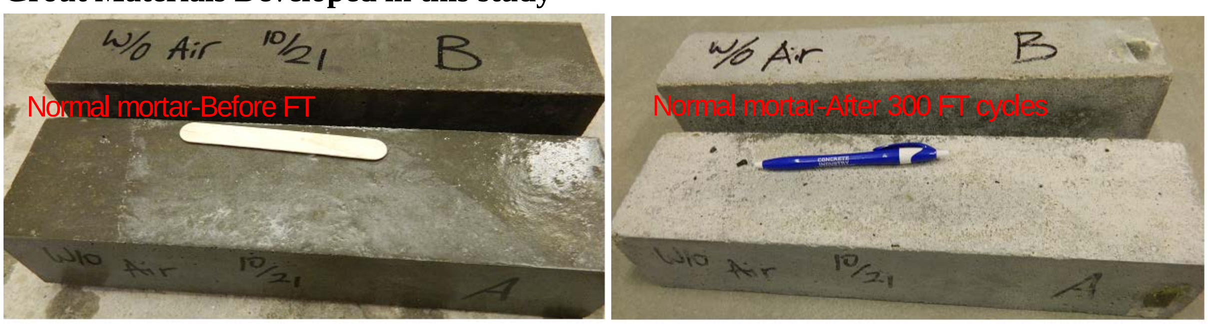


Figure H1-Visual appearance of freeze and thaw test specimens for type III cement-based mortar using natural river sand (#45)

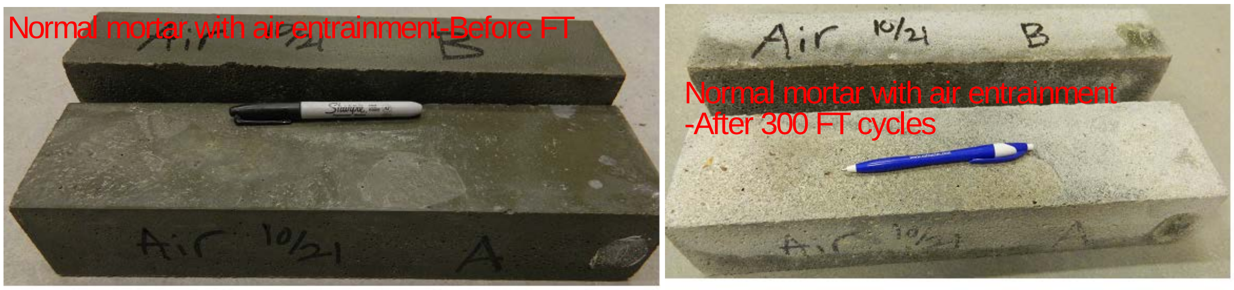


Figure H2-Visual appearance of freeze and thaw test specimens for type III cement-based mortar using natural river sand and AEA (#47)

Figure H3-Visual appearance of freeze and thaw test specimens for type III cement-based high performance mortar (#48)

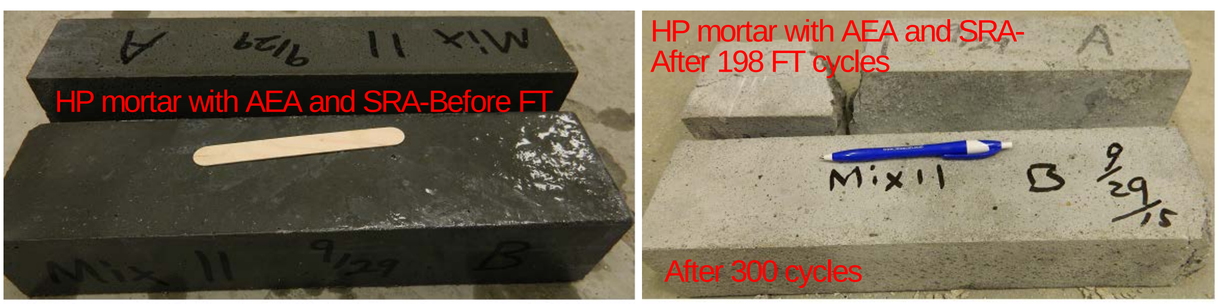


Figure H4-Visual appearance of freeze and thaw test specimens for type III cement-based mortar with AEA (#49)

Figure H5-Visual appearance of freeze and thaw test specimens for type III cement-based UHPC (#51)

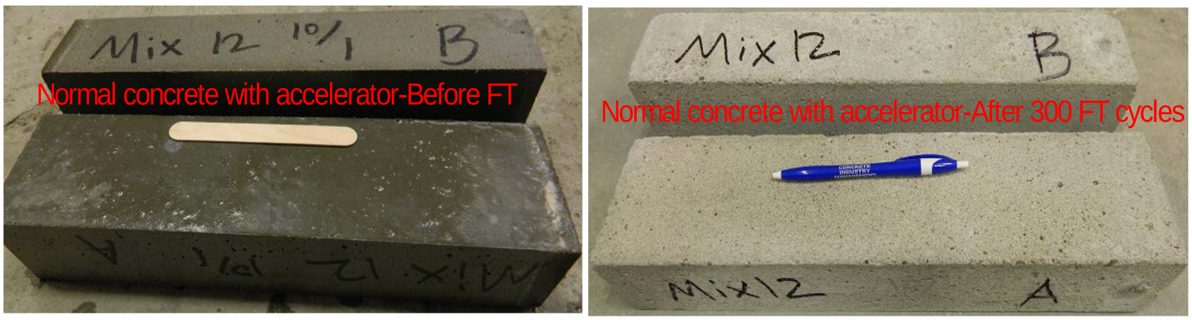


Figure H6-Visual appearance of freeze and thaw test specimens for type III cement-based concrete with accelerator (#52)

Figure H7-Visual appearance of freeze and thaw test specimens for type III cement-based concrete without accelerator (#53)

Figure H8-Visual appearance of freeze and thaw test specimens for CTS rapid-set cement-based mortar (#54)

Figure H9-Visual appearance of freeze and thaw test specimens for CTS DOT cement-based mortar (#55)