FINAL PROJECT REPORT #00042134-03

GRANT: DTRT13-G-UTC45
Project Period: 6/1/2016 – 12/31/19

Volume I:
Application of VFC Mixtures in Rapid Pavement Construction

Participating Consortium Member:
Southern University and A&M College

Author:
Alex Hak-Chul Shin
Southern University and A&M College

RE-CAST:
REsearch on Concrete Applications for Sustainable Transportation
Tier 1 University Transportation Center

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. RECAST UTC # 00042134	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Application of VFC Mixtures in Rapid Pavement Construction	**5. Report Date** January 2020
	6. Performing Organization Code:
7. Author(s) Alex Hak-Chul Shin	**8. Performing Organization Report No.** Project #00042134
9. Performing Organization Name and Address Department of Civil and Environmental Engineering Southern University and A&M College Baton Rouge, LA 70810	**10. Work Unit No.**
	11. Contract or Grant No. USDOT: DTRT13-G-UTC45
12. Sponsoring Agency Name and Address Office of the Assistant Secretary for Research and Technology U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered:** Final Report Period: 5/01/16 – 7/31/19
	14. Sponsoring Agency Code:

15. Supplementary Notes

The investigation was conducted in cooperation with the U. S. Department of Transportation.

16. Abstract

The experimental work attesting the validity of the proposed mix design procedure was performed in both fresh and hardened states via a series of VFC (Vibration Free Concrete) mixes provided by other researcher in separate project. The test mixes were found to meet the necessary self-compacting and the compressive strength criteria, thus fully validating the proposed mix proportioning method. Therefore, this method reduces considerably the extent of laboratory work, the testing time and the materials used.

Experimental study showed that the VFC has a lower viscosity comparing with conventional concrete due to the mix design criteria for the VFC which have smaller volume of coarse aggregates. The required force for VFC to flow is shown to be inversely proportional to its slump, and also the fines materials (slag) has significant effects on flow ability and shape-holding ability of VFC as shown clearly in results of the mixing design of SL-B-AC and AC, the results of SL-B-AC shows high compressive strength and slump comparing with AC mix design due to the slag material. “Increasing the filing material (slag) content of a cement-based material considerably increases its yield stress and viscosity”.

The SL-B-1 mix design need to be redesign because of its result of the slump tests. Two different samples were made for this mix and in both cases the slump tests were 0 and 0.5 in. From this it was found the clay is has significant effects on flow ability. The compressive strength and rate of the strength development of VFC tend to be higher than those of conventional concrete due to the lower water-to-binder ratio. The elastic modulus of VFC is lower due to its low coarse aggregate content. The porosity and rapid chloride ion permeability of VFC are noticeably higher than those of conventional pavement concrete at 28 days, but they become comparable at the later ages, probably due to the extensive use of supplementary materials. The heat of cementations material hydration of VFC is comparable to or lowers than that of conventional pavement concrete. The freeze-thaw durability of VFC is also comparable to that of conventional concrete, which is primarily dependent upon durability of the aggregates used. Scaling resistance to deicing chemicals varies with VFC mixes, and addition of filling material generally provides VFC with a better scaling resistance to deicing chemicals.

The AC mix was further modified to achieve high early strength by adding accelerator in the mixture and having different curing conditions. The optimum content of the accelerator to develop high early strength was to be 36 oz. Among the four different curing conditions with the AC mixtures having 36oz accelerator, oven dry condition is the best to achieve high early strength.

A comparison analysis shows that the material cost of VFC is equal to or greater than that of conventional pavement concrete. The main contributors to the higher cost in VFC are the use of more cementations materials and admixtures/additives. The total costs, the sum of material and construction costs, of VFC mixes are comparable to those of conventional concrete.

17. Key Words Vibration-free Concrete, early age strength, pavement repair and construction, life-cycle cost, pavement performance.	**18. Distribution Statement** No restrictions. This document is available to the public.

19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No of Pages** 00

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Research on Concrete Applications for Sustainable Transportation
RE-CAST

Application of VFC Mixtures in Rapid Pavement Construction

Alex Shin, Ph.D., P.E.
Professor and Interim Chair

January 17, 2020

Southern University and A&M College

Baton Rouge, Louisiana

ABSTRACT

Pavement repair and construction represents a significant percentage of federal and state funding, and new materials are being investigated to reduce material and construction cost, expedite construction time, and generate a more resilient material. The goal of the project is to develop cost-effective materials for rapid pavement construction.

The experimental work attesting the validity of the proposed mix design procedure was performed in both fresh and hardened states via a series of VFC (Vibration Free Concrete) mixes provided by other researcher in separate project. The test mixes were found to meet the necessary self-compacting and the compressive strength criteria, thus fully validating the proposed mix proportioning method. Therefore, this method reduces considerably the extent of laboratory work, the testing time and the materials used.

Experimental study showed that the VFC has a lower viscosity comparing with conventional concrete due to the mix design criteria for the VFC which have smaller volume of coarse aggregates. The required force for VFC to flow is shown to be inversely proportional to its slump, and also the fines materials (slag) has significant effects on flow ability and shape-holding ability of VFC as shown clearly in results of the mixing design of SL-B-AC and AC, the results of SL-B-AC shows high compressive strength and slump comparing with AC mix design due to the slag material. “Increasing the filing material (slag) content of a cement-based material considerably increases its yield stress and viscosity”.

The SL-B-1 mix design need to be redesign because of its result of the slump tests. Two different samples were made for this mix and in both cases the slump tests were 0 and 0.5 in. From this it was found the clay is has significant effects on flow ability.

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ACKNOWLEDGEMENTS

The U.S Department of Transportation, Federal Highway Administration (FHWA), Southern University and A&M College, and Missouri University S&T financially support this research project.

The author would like to thank to Dr. Ron Lee, Mr. Mustafa Najeeb, and Miss Tiffany for their participation in this project and made a hard works to get mix concrete, perform compression tests, and cleaning the laboratory for each mixes.

Dr. Dimitri Feys at the Missouri University of Science and Technology worked separated in the funded research to develop VFC concrete mixtures, and the author conveys sincere appreciation for his effort to provide the mixture designs.

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1. INTRODUCTION

With over 4 million miles of roadways in the U.S., pavement maintenance and construction represents a significant portion of federal and state funding for infrastructure. Compounding these financial burdens are the significant indirect costs to users during construction. The present study aims at applying cost-effective concrete materials for rapid pavement construction. The main idea is to utilize high performance concrete that is being developed in another project of RE-CAST Center in accelerated pavement construction. To decrease the level of the effort for placing concrete pavements and reduce the cost, and to produce durable pavements are the areas of focus in this project.

The approach to develop cost-effective concrete mixtures to be used in accelerated pavement construction is to develop flowable concrete with adaptive rheological properties to be used in slip form paving. Slip form paving is a process including the placement, casting, consolidating and finishing the surface of the concrete. Concrete is usually dumped in front of the paving machine and after the machine has moved over the concrete, concrete is spread out on the base while holding its slab shape. The typical concrete used for slip form paving is a mixture with less than 2.0 in. slump value. In order to consolidate the fresh concrete, extensive vibration energy is introduced to the concrete through equally spaced internal vibrators. However, if the vibration frequency is not set correctly or the paver moves slower than it should, the mixture will be over-vibrated. 12 This may lead to a decrease in the entrained air content, as well as increasing the bleeding and segregation potential which may result in cracking along the path of vibrators if such pavement is subjected to heavy traffic load. [2] Furthermore, a decrease in the entrained air content of the fresh concrete makes the hardened concrete susceptible to damage due to freeze and thaw cycles and scaling. To solve such problems, it would be desirable to eliminate the vibration required for consolidating the concrete. This means that the concrete should be modified to reach higher workability while avoiding the shape stability to be in danger. The goal is to design a concrete mixture that reaches maximum consolidation with minimum compaction energy while maintaining the desired slab shape. This requires improving the flowability of the mixture while maintaining the green strength. Green strength is defined as the strength of the freshly cast concrete determined by the weight of sand that a cylindrical fresh concrete sample can resist until collapse happens. A typical green strength of 0.15 up to 0.6 psi (10-40 kPa) is suggested. [3]

Self-consolidating concrete (SCC) mixtures suitable for use in slip form pavement applications are not as flowable as the typical SCC used for structural applications. A slump value about 8 in. (200 mm) and spread of 13-15 in. (350±25 mm) are obtained with the regular short cone shape after the slump cone was removed. [3] and [4] Feasibility of producing SCC for pavement applications has been demonstrated in earlier studies. [5] SCC was also reported to be applicable in slip form pavement constructions by Voigt et al. (2010). Increasing the fine content in the concrete mixture, as well as increasing the total cementitious materials was used as a method of producing the desired concrete. Class “F” fly ash, magnesium oxide, and three types of clay were also used as replacements for Portland cement for enhancing both the engineering properties and the environmental aspects. [6] To avoid further confusion, the “SCC” for slipforming is named “vibration-free concrete” (VFC) in the remainder of this proposal.

Due to the increasing amount of paste and the cementitious materials content in SCC/VFC mixtures, shrinkage and cracking potential will be an issue compared to the conventional concrete mixtures. [7] It is required to focus on optimizing the mix design in terms of the paste content, Portland cement content, w/cm, and incorporation of proper types and amounts of shrinkage reducing admixtures (SRAs) to decrease the shrinkage and control cracking potential in hardened concrete.

The project performed at Iowa State University [4] has revealed the economical and ecological feasibility of slip-form VFC mixtures (Figure 1). Although the material cost of VFC is higher, the total pavement construction cost can be made comparable to standard slipforming. In the top of Figure 1, the reference conventional concrete mixture is C3 (slip f). All other mixtures to the left of the QMC (which is an economical and ecological conventional pavement concrete) are VFC mixtures. The bottom graph shows the ecological aspect in terms of CO_2 emissions for materials, production and placement. The VFC mixtures show generally better performance than the conventional C3 (slip f) mixture. With the further advances in selection of aggregates and binders proposed in this project, the research team is convinced that the material and placement costs and CO_2 emission can be further reduced.

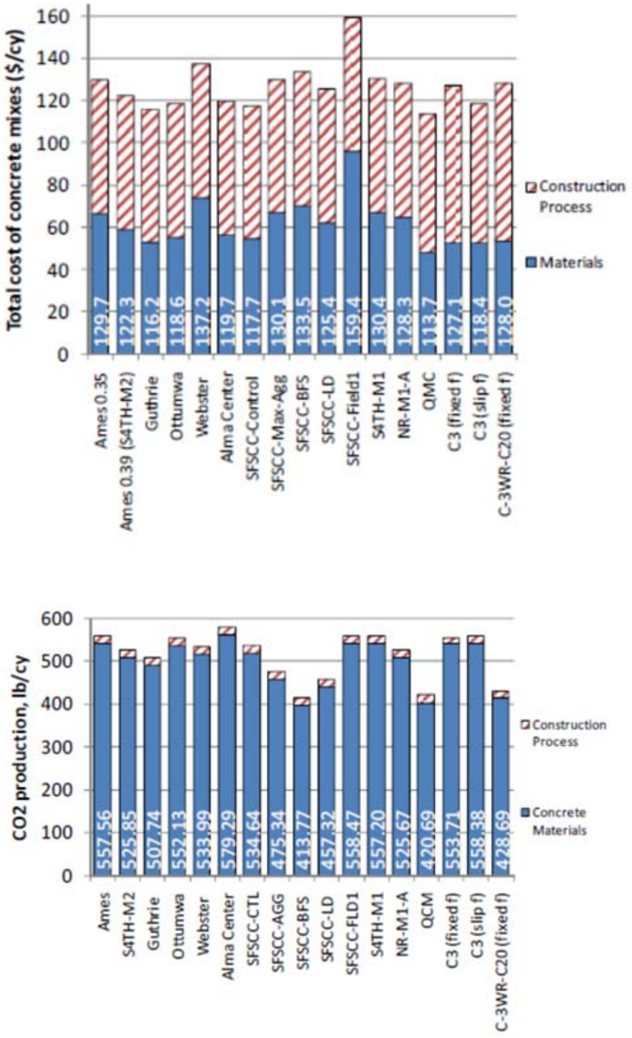


Figure 1. Cost (top) and CO_2 emission (bottom) of constituent materials, mixing and placement of slip-form SCC mixtures (all left from QMC), compared to conventional slipform mixtures (C3) indicate the economical and ecological performance of SCC mixtures for pavements. Figure from Wang et al. [4]

2. RESEARCH OBJECTIVES

The main ***objective*** of the proposed research is to determine the feasibility of using cost effective materials for rapid pavement construction. Vibration-free concrete mixture for slip form paving will be applied in this project. The study will focus on the application of the VFC mixtures developed in previous researches and other projects of RE-CAST Center in rapid pavement construction through laboratory tests and field implementation. Field implementation will be carried out to investigate in-situ performance of the proposed concrete in Louisiana. The final scope of the project and selection of field demonstration sites will be evaluated with other investigators as well as government and private partners interested in this project.

3. SIGNIFICANCE OF RESEARCH

To maximize the speed of pavement construction while taking into account the cost is the main benefit of this research. The optimized mix designs can decrease the cost of concrete materials used in the United States transportation infrastructures. The outcomes of the present research will provide guidelines for the selection of proper ingredients and mixture optimization methodology to make cost effective concrete pavement materials used in rapid pavement construction.

4 RESEARCH APPROACH AND METHODS

The work plan includes a description of the following tasks necessary to reach the defined goals of the project. The research tasks are elaborated below:

Task 1. Literature review

The purpose of this task is to conduct a comprehensive and critical literature review of past experiences and previous research on rapid construction of concrete pavements, made with VFC mixtures. Specifically, the literature review will focus on studies that investigated the behavior of concrete mixtures made with high-volume of SCMs. This includes binary and ternary cements, limestone fillers, etc. Published information on fresh concrete properties will be reviewed, including workability retention, admixture demand, rheology, thixotropy, air volume stability, ease of mixing, consolidation, and finishing. Hardened properties will include compressive strength, flexural strength, elastic modulus, Poisson's ratio, fracture energy, drying shrinkage and thermal properties. The porosity, impermeability, and durability of such concrete mixtures will be reviewed. This includes durability to freezing and thawing, de-icing salt scaling, and abrasion damage. A comprehensive literature review report will be submitted at the end of this task.

Figure 2. Concrete slab produced by the mini paver test set up (left) and the cross section of the sab (right) [3]

Task 2. Development of VFC Slipform mixtures: Fresh properties (Missouri)

Based on the literature review, previous experimental work, and the determination of main mix design factors affecting thixotropy and the strength of thixotropic bonds through project "RE-CAST: Research on thixotropy and workability loss of vibration-free concrete in view accelerating pavement construction by slipforming.", two baseline mix designs will be selected. In this latter project, the influence of different mix design parameters on thixotropic development and breakdown was investigated. These mixtures will be evaluated for fluidity, self-consolidation, meaning how much air is removed autonomously due to the concrete fluidity, thixotropic strength development, and shape stability. Fluidity will be evaluated using the slump flow test, while the static yield stress measurement on the ICAR rheometer and the portable vane measurement will be used to evaluate thixotropic strength development. The self-consolidation will be evaluated by comparing the mass of an unconsolidated and consolidated 4" by 8" cylinder, as a difference in mass indicates a change in air volume. The shape stability is determined by demoulding a 4" by 8" cylinder, using steel molds with screws, and measuring the decrease in cylinder height.

For each mixture, the fluidity, thixotropic strength development, and shape stability will be evaluated in 15 minute intervals until the shape is stable. The shape stability will be determined twice at each interval, once for a sample at rest since 15 min after cement-water contact (undisturbed), and once for a sample at rest for only 10 min (remixed). The undisturbed samples indicate how long the concrete needs to rest to achieve shape stability, while the remixed samples indicate at which age the concrete can achieve sufficient shape stability in a 10 minute period. Fluidity will be determined on remixed samples, to simulate transportation on-site. The thixotropic build-up will be measured on undisturbed samples.

Once the variation of fluidity, thixotropic strength development and shape stability with time is characterized, the mixture will be reproduced and re-tested to validate the time needed for shape stability, imitating transport to the site by agitation of the mixture and remixing prior to placement. Fluidity and self-consolidation are measured at the anticipated time of placement, while the shape stability is verified after an additional 10 minute rest period.

Modifications in mix design will be evaluated to accelerate or slow down the thixotropic strength development, and the impact of adding small amounts of thixotropy-enhancing materials just prior to final mixing (corresponding with the arrival of the mixture on-site) will be evaluated. In this way, guidelines for adoptions in mix design can be created as a function of the expected time needed for transport and delivery. The modifications in the mix design can be the amount and type of thixotropy-modifying agents, binder composition, aggregate amount and gradation, or chemical admixtures.

In summary, the following subtasks need to be performed:

- Task 2a: Fine tune two economic baseline mixtures to obtain acceptable self-consolidation and shape stability
- Task 2b: Six modifications in each baseline mix design which accelerate or slow down thixotropic strength development. Modifications consist of changes in thixotropy-enhancing materials, binder combination, admixture types and dosages and aggregate content and gradation
- Task 2c: From the 14 tested mixtures, the four most appropriate mixtures (in terms of fluidity retention and stiffening) will be retained and investigated to see how variations in transportation time (short = 15 min, medium = 45 min and long = 75 min) can be handled without negatively impacting fluidity and hardening. At this stage, the on-site addition of thixotropy-enhancing materials will be investigated

Eight optimized mix designs will be communicated to the Southern University of Baton Rouge to continue the research work on the performance of the concrete. If the concrete mixtures do not show adequate performance in the hardened state, the mixtures will be re-evaluated for fresh properties if large modifications in the mix design are needed.

Prior to starting the research, the characteristics of the materials available at SUBR and Missouri S&T will be compared to avoid large variations in the response of concrete to the induced modifications. Grain size distributions can be matched, cement types and SCM properties can be kept as close as possible to minimize the variations. Thixotropy-enhancing materials and chemical admixtures, which are expected to induce the largest variations in fresh concrete properties, will be ordered from the same producers. The first item in Task 3 will be to verify the fresh properties of the concrete by means of the flow retention and shape stability tests, and if necessary adjust the contents of the admixtures to ensure appropriate fresh properties in the fresh state. Once these are achieved, the investigation on the hardened scale can be performed.

Task 3. Validation of Hardened Concrete Quality of VFC Mixtures (Southern)

Eight concrete mixtures identified in Task 2 will be used for preparing concrete mixtures. Samples will be taken for investigating the development of setting time, compressive strength, splitting tensile strength, and drying shrinkage. The benefits of incorporating superplasticizer to reduce cement content and shrinkage reducing admixture to decrease shrinkage and cracking in concrete pavement will also be investigated.

The test results of the mixtures will be used to select adequate and economic mixtures for slipforming, with the best mechanical properties, and lowest shrinkage that are cost-effective. For selected mixtures, further testing will be conducted to evaluated modulus of elasticity, as well as sorptivity, as shown in Table 1.

Table 1. Proposed Concrete Test Methods and Protocols

PROPERTY	TEST METHOD	TEST TITLE/DESCRIPTION
HARDENED MECHANICAL PROPERTY TESTS		
Compressive Strength (1 to 56 d)	ASTM C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
Splitting Tensile Strength (7 to 56 d)	ASTM C 496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
Modulus of Elasticity and Poisson's ratio (28, 56 d)	ASTM C 469	Standard Test Method for Static Modulus of Elasticity
Drying shrinkage (after 7 d of moist curing)	ASTM C 157	Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
Autogeneous shrinkage	ASTM C1698	Standard Test Method for Autogenous Strain of Cement Paste and Mortar
DURABILITY TESTS		
Permeable void ratio (56 d)	ASTM C 642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
Sorptivity (56 d)	ASTM C 1585	Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes

Task 4. Pre-field construction of VFC slab (Southern and Missouri)

Utilizing the finalized VFC mixtures (two - four mixtures) in Task 2, pre-field construction of small-scale slipform pavements is planned to investigate the potential for field implementation. The construction will be in rectangular slabs (2m x 1m) and placed by a miniature slipformer outside the laboratory. The concrete properties will be monitored in terms of flowability and key mechanical properties. The testing slabs will be instrumented to monitor shrinkage and responses to thermal variations. Non-destructive tests, using the impact-echo testing equipment, will be performed to examine voids and homogeneity of concrete sections. The cross section of the slabs will be cut to observe air void and aggregate distribution through the depth. Cores will be taken at different places in the slabs to compare the in-situ mechanical properties of the slab to the intrinsic properties of the concrete.

Feedback of the pre-field implementation will be provided to adjust mixtures or placement strategy of VFC.

The research team will actively pursue the contribution of partners to perform a field validation in Louisiana, Missouri or another state. At the writing of this proposal, DOTs or other partners have not yet committed to provide a test site.

5. LITERATURE REVIEW

Vibration –free concrete (VFC) is the concrete that does not require vibration for casting and placing in the place. This type of concrete flow by own weight and fill the formwork required to by cast, there are many ways to achieve the stability of the concrete by adding a binder material which is classified as a powder and by adding chemical additives.

The use of the VFC starts increasing due to the cost effect, environmental effect and quality. The first consideration was in Japan in 1983 and on 1986 Prof. Okamura from Ouchi university-Japan put the first concept of the self-compacting concrete to improve the durability of concrete structures which was a major topic on interest in Japan at that time. [8]

The previous studies giving an idea about the differences between the properties of the self-compacting concrete and the normally vibrated concrete, some of these studies state that when the VFC and the conventional concrete have the same strength, then the creep, shrinkage and the elastic modulus will be the same also for example the studies which made by Bertil Persson [9], Philippe et. al. [10], while Kim et. al. [11] and Roziere et. al [12] found that the shrinkage and creep for the VFC larger than in conventional concrete for the same strength, the most property requirement for the VFC need to be checked are the flowing ability, passing ability, static segregation (coarse aggregate separation from mortar after casting the concrete in place) and the dynamic segregation (coarse aggregate separation from mortar during the process of placement).

The VFC can be used in the precast and pre-stress in addition to the normal structure, limited research are available for the precast and pre-stress industry due to the higher quality of control and high early strength required comparing with the conventional concrete.

VFC widely used all over the world spicily after the benefit of using the VFC can be list below:

- Good concrete finishing.
- Making less noise.
- Reduce the required time to place the concrete.
- Reduce labor demands and equipment costs.

The aim of using the mechanical vibration during concrete casting is to be sure the concrete compacted properly in another words to minimums the air voids to maximums the strength and durability of the concrete. Even with using the mechanical the full compaction will not occur, to maintain the compaction of the concrete some research held to find the ideal ways to use the concrete spicily area where the concrete with inaccessible location like deep piles and underwater concrete, one of the these ways is reducing the amount of water in the mixing design and adding the super plasticizers allowed for workability.

At the eighties of last century, the problem of the concrete durability became the biggest concern in the concrete work in Japan, to solve the problem of the durability of concrete due to the an adequate compaction because of the reduction of the skilled labors led to start searching for a method to achieve the construction durability requirement and one of these methods is self-compacting concrete or vibration free concrete which is proposed by Okamura-university of Tokyo in 1986. Before the 1990, the concept of the VFC already developed and ready for the tests. On 1989 the first paper on the VFC was presented at the second East-Asia and Pacific Conference on Structural Engineering and Construction, after that many studies presented during the American Concrete Institute (ACI) and Energy Diversification Research Laboratories (CANMET) meetings. Table 1 presents the history of VFC development.

Table 2. VFC development history

1983	First consideration in Japan
1986	First suggested solution by Okamura-university of Tokyo
1988	First practical concept in Japan
1989	First publication at EASEC-2
1992	Publication CANMET and ACI- international conference -Istanbul
1994	ACI workshop-Bangkok /start of worldwide research and development
1995	Beginning of intensive research in United State of America
1997	RILEM committee for VFC
1998	Start of intensive activities introduction of technology to US
2002	First north American conference on VFC
2005	Second north American conference on VFC
2008	Third north American conference on VFC

a. Advantages of VFC

VFC has many advantages over conventional concrete. These advantages are as follows: [8], [17], and [18]

1. Eliminating the need for vibration as it flows through and around obstacles (e.g. reinforcing steel) under self-weight.
2. Allowing for the placement of a large amount of reinforcement in small sections, especially in high-rise buildings.
3. Improving work environment and safety as it requires fewer workers for transport and placement of concrete.
4. Reducing the noise pollution and improving the construction environment in the absence of concrete vibrating equipment.
5. Decreasing the construction time and labor cost.
6. Ensuring a uniform architectural surface finish (appearance of concrete) with little to no remedial surface work.
7. Decreasing the permeability and thus, improving strength and durability of concrete.

b. Application of VFC

In past years the using of the VFC became commonly used in place of the conventional concrete due to the cost effect , time wise, as per Dr. Okamura [8] researches he discovered that “Whatever conventional concrete can do, VFC can do better, faster, and cheaper, especially for concrete elements with special textures, complex shapes, and congested reinforcements”. VFC project could be precast and cast in situ and throughout the structural and architectural concrete where we have in accessible elements and the smooth surface are required, in north America, the applications of the VFC transportation agencies have included bridges and buildings in different places, and below Table 3showing some of these projects:

Table 3. Existing projects used VFC

Project Name	Year built	VFC volume	Location	Project highlight
McDougal St. Bridge	2000	130 Cu.yd	Toronto	-Tight reinforcement - Continuous pour -Zero patching
Toronto Int. Airport	1999-2009	2750 Cu.yd	Toronto	-4.4$B, 500,000 Cu.yd -81 columns, 100 ft. tall pumped from bottom up
Habitat for Humanity	2001	200 Cu.yd	Houston, TX	-Sandwich wall system -Safe, simple construction by volunteers -Cast and strip in same day

Rosenthal Contemporary Art Center	2002	500 Cu.yd	Cincinnati, OH	-5 stories, small footprint -Curved Panels, Diamond columns -Dead areas within formwork
The citadel	2002-2003	10000 Cu.yd	Charleston, SC	-Continuous pour with numerous blackouts, 6" wall with 2 layers of seismic reinforcement
High-Five	2002-2006	25000 Cu.yd	Dallas, TX	-Precast 20000 Cu.yd, cast in situ 5000 Cu.yd -3000 psi/8h, 6500 psi/28d -30% fly ash, 7.5 sk total
American-Indian Museum	2003	30000 Cu.yd	Washington, DC	-Poured in single lift (30ft) -no right angles -75% reduction in column pour time
National Aquarium	2003	25000 Cu.yd	Baltimore, MD	-PainTable surface, zero patching -80 ft columns in single lift -VFC initially in columns, until labor reduction realized, then slabs and walls.
Tub girders for T-Rex	2003-2008	10000 Cu.yd	Denver, CO	-Poured from one side -$1.67B project -7000 psi in 10h, 11500psi, 28 d
Trump Int. tower	2006-2009	5000 Cu.yd	Chicago, IL	-5000 Cu.yd continuous mat pour -largest VFC pour to date

c. Materials and Mix Proportioning

It is important to limit the percentage of the course aggregate in VFC mix design to prevent the segregation and pass through the reinforcement and a rounding without any blockage [13], when coarse aggregate content increased in the VFC mixed design, the relative distance between the particles will decreased and it will cause a concrete honeycomb specially in the narrow area. As per Dr. Okamra studies [8], the coarse aggregate limitation range from 36% to 60%.

To achieve high flow ability for the concrete we need to increase the water/cement ratio (w/c)in the same time of increasing the w/c ratio the concrete viscosity will decreased and the increasing the chance of segregation and getting low concrete properties (low compression strength, low durability).

In case of using high range water reducers (HRWR) in normal concrete which are chemical admixtures or super plasticizers, we achieve the required flow ability [8]. For VFC, the optimization of the HRWR and w/c ratio is required to achieve the flow ability and to prevent the segregation. There is another method to prevent the segregation in the VFC likes using the viscosity-modifying admixture (VMA), in this method we can keep the bleeding and segregation under control. Another method to increase the viscosity is using the incorporate continuously graded pozzolanic additives or fillers in the mix design like fly ash, slag and silica which can increase the concrete strength, workability, durability and the flow ability by reducing the friction between the particles.

d. VFC Mix Design Concept

The mix design of the fresh VFC should provide sufficient flow ability, adequate viscosity and a proper green stress for the VFC to hold the shape of the concrete after being casted; these three items should be considered occurring in the concrete mixing design and in the time frame of the slip form concrete construction.

The general properties for the VFC are low yield stress which providing high flow ability and adequate viscosity which preventing aggregate segregation.

6. DEVELOPMENT OF VFC SLIPFORM MIXTURES (MISSOURI UNIV. S&T)

This task is developing VFC mixtures by modifying the acceptable self-consolidating concrete mixtures found in the literature review. Two base economic mixtures was used to make six modification mixtures by adding thixotropy-enhancing materials. Dr. Feys provided an interim report of this task in June 2017 (Appendix), however it was still not feasible to use the results in this study since the interim report is only providing cement paste properties.

On December 21, 2017, Dr. Feys updated the progress of the Task 2 as following:

On paste scale, everything went well, but on concrete scale, we have had some issues, changing the way we need to look at things.

In short, we cannot create a concrete with a 20" slump flow and being able to support 8" of height shortly after casting. The problem sits in the admixture, as more HRWRA (High Range Water Reducing Agent) reduces substantially the thixotropic development. Reducing HRWRA is not an option either, as it causes the concrete to lose its self-consolidation. Now we know why they didn't push it this far in Iowa.

Increasing paste volume actually helps us to get the thixotropic properties (which was completely against my intuition), any addition of fancy fine particles causes the HRWRA to go up, annihilating the beneficial effect of those substances. Basically, we have a standard mixture with a 40 µm excess paste layer, 25% replacement of cement by slag (by preference one which doesn't need a lot of HRWRA), nothing else which is fancy on top of that. We have thought about adding fibers, but logical thinking also says that the HRWRA will go up.

We're going to get some nice publications out of this, but I'm worried how we are going to complete your task.

I know you were supposed to evaluate strength, durability and shrinkage, right? But we were supposed to have a slipformed slab. I cannot guarantee you a stable slab, especially at 8" thickness. Maybe at 4" we could try something. Unless we find another application for this?

In response to the e-mail, Southern University asked Dr. Feys to provide the mixtures that had been developed so far in Missouri University of Science and Technology. Using the mixtures provided by Dr. Feys, we will work on the measurements of hardened properties of the mixtures and continue to see how we can modify and improve the properties of the mixtures, and find out the application of the mixtures in the construction industry. The following is the response of Dr. Feys:

Here are the mix designs of 3 flowable thixotropic concretes which could be used for (very slow) slip forming or for patching.(Table 4)

The paste volume has been determined by means of the excess paste layer concept. Table 5 is provided for our grain size distributions, leading to these numbers (try to match it as close as possible). The attapulgite clay is actigel (amount mentioned is the amount of solids). The plasticizer used is Glenium 7500. We have tried different slags. The chemical composition of the slags is also included (Table 6). We noticed that the one with the highest Ca-content showed the best fresh properties.

The SP content is adjusted to have a 500 mm slump flow after mixing, so no consolidation is required. The mixture without slag (mix AC) is more recommended if you have extended transportation time. The mixture without actigel (SL-B-1) has a relatively low workability retention. The ternary mix (SL-B-AC) is an intermediate solution. ***Note, for a given mix design, the higher the SP dosage, the lower the thixotropy development.***

Table 4. Mixture design of Flowable Thixotropic Concrete

Material (kg/m3)	SL-B-1	AC	SL-B-AC
Cement	355.6	478.3	352.2
Slag	118.6	-	118.2
Attapul-gite clay		2.4	2.4
19 mm agg.	517.5	517.5	517.1
9.5 mm agg	369.1	369.1	369.2
Sand	890.7	890.7	898.1
Water	159.7	159.8	150.4
SP	1	2.7	3
w/b	0.35	0.35	0.35

Table 5. Size Distribution of Coarse and Fine Aggregates

Sieve size	CA		Sand
	19 mm	9.5 mm	
1	100	100	100
3/4	79.76	100	100
1/2	33.53	100	100
3/8	18.07	75.6	100
No. 4	3.27	3.61	98.76
No. 8	0.81	0.29	91.76
No.16			78.14
No.30	0.49	0.22	46.03
No.50			10.17
No. 100	0.29	0.19	0.32
No. 200	0.12	0.15	0.21
<no. 200	0.01	0.04	0.21

Table 6. Chemical Composition of Slag-B

Basic compounds (%)	Slag - B
MgO	4.77
Al_2O_3	10.90
SiO_2	29.58
SO_3	3.10
K_2O	0.32
CaO	49.41
TiO_2	0.64
Mn_2O_3	0.28
Fe_2O_3	0.25
Specific gravity	2.73
Mean particle size (µm)	13.6

Three mixes which were designed by Missouri University of S&T was evaluated for fluidity, self-consolidation and shape stability by slump flow test, J ring test and L Box test. Figure 3, Figure 4, and Figure 5 shows the proportion of the mixture design for 1 ft^3 in lb unit.

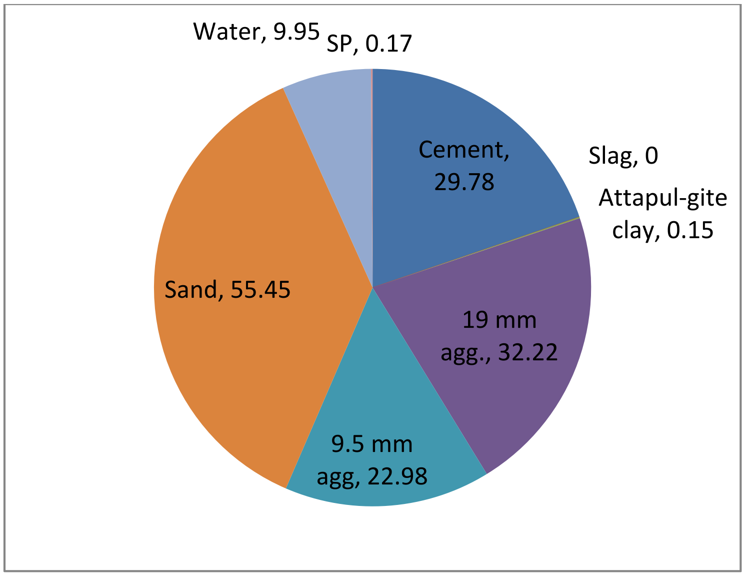


Figure 3. Mix design AC for 1 ft^3(Unit : Ib)

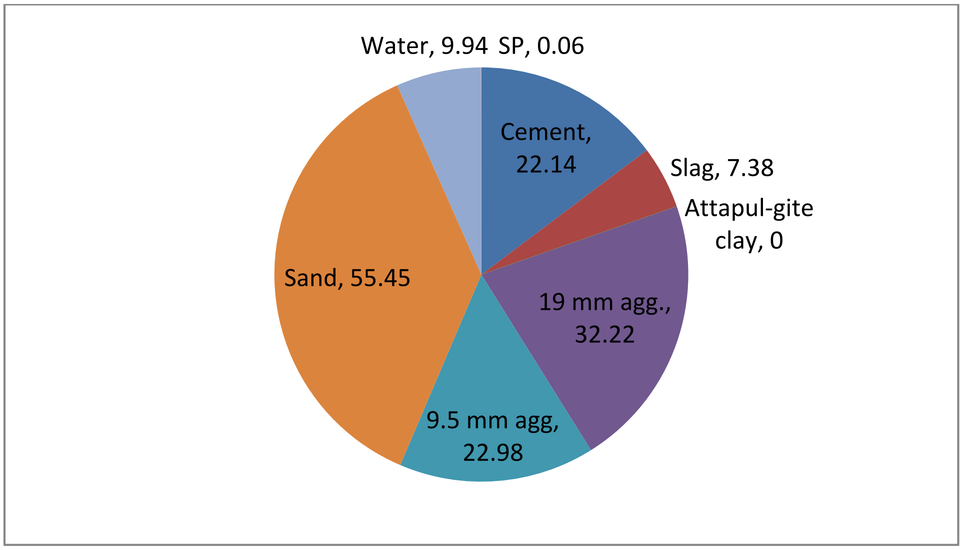


Figure 4. Mix design SL-B-1 for 1 ft^3(Unit : Ib)

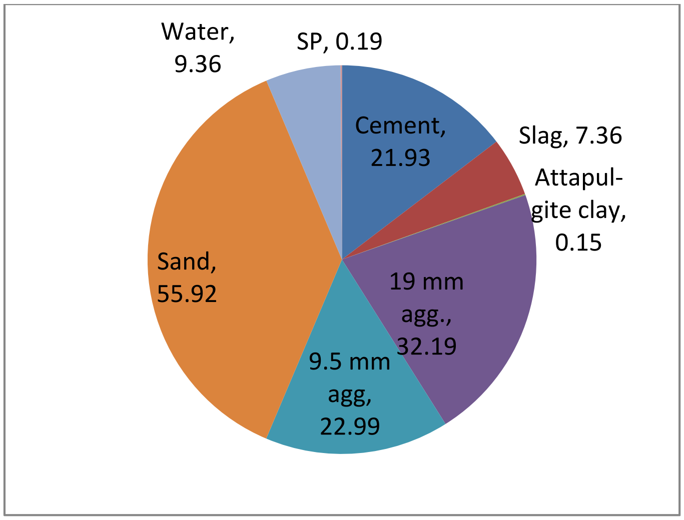


Figure 5. Mix design SL-B-AC for 1 ft^3(Unit : Ib)

a. Constituent materials of VFC

(1) Cement

The selection of the type of cement depends on the overall requirements for the concrete such as strength and durability. Ordinary Portland cement is most widely used to produce various types of VFC. It is used alone or in combination with cement replacement materials (CRM). Cement improves the flowing ability of VFC when used with water to lubricate the aggregates. Cement can also affect the segregation resistance of VFC by affecting the density of cement paste matrix of concrete [18].

(2) Water

The amount of water in VFC and conventional concrete is important for the properties at the fresh and hardened stages. However, VFC is more sensitive to the water content in the mix than traditional vibrated concrete. Adequate water is required for the hydration of cement, leading to the formation of paste to bind the aggregates. In addition, water is required in conjunction with Superplasticizer to achieve the self-compatibility of VFC by lubricating the fine and coarse aggregates in the mix. Typical range of water content in VFC (as per [18]) is 4.25-60 l/ft3 (150-2120 l/m^3).

(3) Aggregate

Aggregate (coarse or fine) characteristics such as size, gradation, shape, volume fraction, have a significant impact on self-compatibility of VFC [19]. With the reference to the coarse aggregate, it significantly affects the performance of VFC by influencing its flowing ability, passing ability and segregation resistance as well as its strength [18]. All standard sizes of coarse aggregate are generally suiTable to produce VFC. It should be selected in consideration of the performance need for fresh and hardened concrete [19]. Most VFC applications have used coarse aggregate with a maximum size in the range of 16~20 mm depending on local availability and particular application [20]. Nevertheless, sizes higher than 20 mm could possibly be used. However, VFC with higher volume fraction or maximum size of coarse aggregate relative to the gap will be more sensitive to segregation, and will likely need either higher powder content or a viscosity modifying agent (VMA) (see Figure 6).

(a) 9.5 mm aggregate **(b)** 19 mm aggregate

Figure 6 . Coarse Aggregates

The fine aggregates are also a key component of VFC, which plays a major role in its workability and stability. EFNARC [18] reports that the effect of fine aggregates on the fresh properties of VFC mixes is significantly higher than that of coarse aggregate. The fine aggregates addressed as sand/total aggregate (S/A) ratio is an important material parameter of VFC that influences its rheological properties.

(4) Supplementary Cementitious Materials (SCM)

CRM are used as a partial replacement of Portland cement in VFC mixes (see Figure 7). All CRMs have two common features; their particle size is smaller or the same as Portland cement particle and they become involved in the hydration reactions mainly because their ability to exhibit pozzolanic behavior. By themselves, pozzolans which contain silica (SiO2) in a reactive form have little or no cementations value. However, in a finely divided form and in the presence of moisture they will chemically react with calcium hydroxide at ordinary temperatures to form cementations compounds [21]. The most common CRMs used are ground granulated blast furnace slag (ggbs), silica fume (SF) and fly ash (FA).

Figure 7. Slag

(5) Superplasticizer (SP)

Superplasticizer (SP) is an essential component of VFC to provide the necessary workability [8]. The main purpose of using a Superplasticizer (SP) is to improve the flow-ability of concrete with low water to binder ratio by deflocculating the cement particles and freeing the trapped water through their dispersing action as illustrated in Figure 8:

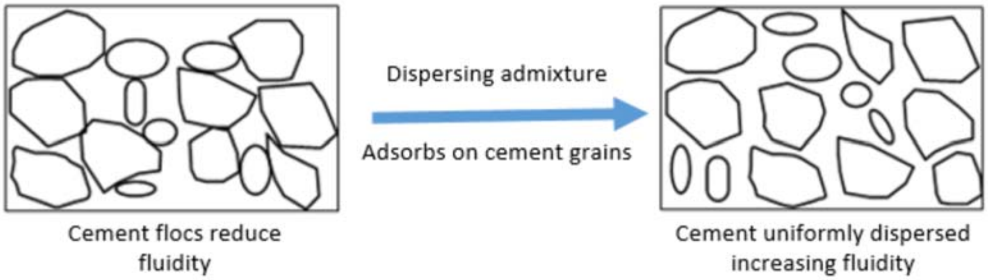


Figure 8. Superplasticizer Effect on concrete flow-ability

SP contributes to the achievement of denser packing and lower porosity in concrete by increasing the flow-ability, and thus assisting in producing VFCs of high strength and good durability. For achieving the VFC, an optimum combination of water and SP dosage can be derived for fixed w/c ratio in concrete (i.e., compressive strength). However, a high SP amount could cause segregation and bleeding.

b. Test Methods for VFC

The tests of the VFC defined in the ASTM standard and presented in Table 7:

Table 7. List of the ASTM test

Plastic Property Tests		
ASTM C1611	Slump flow ,T20,VSI	22”-26”
ASTM C1621	Slump flow w/J-Ring	Within 2” of slump
ASTM C1610	Column segregation	Less than 10% mass difference
ASTM C138	Unit weight, air-content	141-145 pcf,5-8%

All the plastic property tests were should be done immediately after the concrete mixing, the testing procedure are described as follows:

(1) Slump flow, Visual stability index and T_{50}

This test method provides a procedure to determine the slump flow of the VFC in the laboratory or at the field and also used to monitor the consistency of fresh concrete, and measures filling ability and stability for the VFC, the slump cone can be used in either the upright or inverted position resulting will be almost the same in both cases, It is difficult to produce VFC that is both flow able and non-segregating using coarse aggregates larger than 1 in, therefore this test method is consider applicable to VFC with max. coarse aggregate (1 in) in size. The slump flow Table was made of 1/2 in thick plexi-glass sheet attached to a stiff wood base plate to be free of standing water and had a min. diameter of 36 in, the cone mold is filled with VFC in one continuous motion to a height of (9±3 in) in two to four second, the concrete allowed to flow on to the slump board and two spread measurement to be taken horizontally at its largest diameter, the slump flow determined by averaging the two measured diameter (see Figure 9).

Figure 9. Slump test apparatus

The Visual stability index (VSI) is another test used to give an assessment of the slump flow of the VFC to evaluate the concrete parameters like the stability and the distribution of coarse aggregate. In this test the mixes of the VFC to be rated according to the guidelines provided by the PCI-2003, as per that guideline the mixes rated in 0.5 increments, where the value of 0 is related to the high stable mixes and value of 3 is related to high unstable (high segregation tendency). For the VFC, all the values of the VSI larger than 2 are not accepted due to the evidence of segregation and excessive bleeding, below is the VSI values classification as per the ASTM C1611 (Table 8):

Table 8. VSI values as per the ASTM C1611

VSI value	Criteria
0 = Highly stable	No evidence of segregation or bleeding
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass
2 = Unstable	Slight mortar halo, less than 0.5 in and / or aggregate pile in the center of the concrete mass.
3 = Highly unstable	Clearly segregating by evidence of a large mortar halo (greater than 0.5 in) and/or a large aggregate pile in the center of the concrete mass.

Note: Halo is an observed cement paste or mortar ring that has clearly separated from the coarse aggregate, around the outside circumference after flowing from the slump cone.

The T_{50} is defined as the time that the concrete takes to reach the 20 in diameter circle drawn on the slump board after starting to raise the slump cone vertically, which can be considered as a secondary indication of concrete flow and viscosity and can be used as a preliminary indicator of production uniformity of a given VFC mix as per the PCI-2003. The test procedure is carrying in the same time with the slump flow test, after filing the slump cone with the concrete and to be left in one time and the stopwatch started as soon as the cone is lifted over the flow board which the twenty inch diameter circle was outlined. The required time for the fresh concrete to expand into the twenty inch diameter circle recorded to the nearest 0.1 second.

(2) Slump flow w/J-Ring

This test measuring the passing ability for the VFC in combination with the slump cone mold, and this test applicable only for the VFC with maximum size of aggregate of 1 inch. This test consisting of a rigid ring frame support on sixteen 5/8 in diameter rods equally distributed on 12 in diameter circle 4 in above a flat surface (see Figure 10). The test procedure is to place the VFC in slump mold on inverted position and the concrete to be placed in one lift without vibration and the concrete to allow passing through J-Rings. After the diameter of the concrete to be measured in two directions approximately perpendicular to each other and the average to be obtain the slump flow, the difference between the J-Ring flow and the slump flow giving the passing ability of the concrete.

Figure 10. J-ring test apparatus

(3) U-box Test

Using this test to evaluate the self compatibility and filling ability of the VFC reinforced areas which is developed by the PCI-2003, this test consist of a vessel divided by middle wall to two equal parts with a sliding gate fitted between the two parts, beside the gate three bars 0.5 in diameter bars with 2 in center to center spacing (see Figure 11). The procedure of the test is to fill with concrete and after I minute the gate is opened allowing the concrete to pass into the other part, when the concrete flow stops, the height of the concrete in each side to be measured and the results are equal to the ratio of the concrete heights on two sides (h1/h2). The acceptable range of the (h1/h2) is between 0.8 and 1 in (JSCE-1998).

(4) Column segregation test

In this test we can determine the static segregation of the VFC by measuring the coarse aggregate content in the top portion and bottom portion of the cylinder tube, this test consist of an a 8 in diameter pipe with 26 in long schedule 40 PVC pipe divide into four equal portions each one (6.5 in) in height (see Figure 12). After filling the mold slightly in one lift and the top surface of the concrete leveled by means of lateral and horizontal motion, separate the pipe by thin plates (less than 1/16 in. in thickness) and put them in rest for

10 to 15 minutes, after that place the concrete of top and bottom parts in separate containers and weighted and the middle part to be thrown out. The concrete to be washed through a No. 4 sieve and keep the coarse aggregates on the sieve, then the aggregates for each sieve to be oven dried and weighted individually and compared to determine if there any segregated

Figure 11**.** U-Box test apparatus

Figure 12. Column segregation test

(5) L Box test

The L-box test is used to assess the filling and passing ability of VFC. The test is carried out in accordance with BS EN 12350-10 (2010) and EFNARC (2005). The times for the VFC to reach a distance of 7.87 in or 200 mm (t200) and 15.74 in or 400 mm (t400) along the horizontal part are measured. Also measured is the height of concrete at the two ends of the horizontal section of box (H1 and H2) after the concrete has stopped flowing (see Figure 13). The ratio H2/H1 represents the filling ability, and typically, this value should be between 0.8 and 1. The passing ability can be detected visually by inspecting the area around the re-bars.

Figure 13. L box test

7. FRESH AND HARDENED PROPERTIES OF VFC MIXES

a. Comparison of VFC mixes based on target plastic viscosity and compressive strength

We used three mixes design were tested in the fresh state using the slump cone, J- ring and L- box apparatus and in the hardened state using the compressive strength test. Dr. Dimitri Feys in Missouri University of S&T provided three VFC mixtures as shown in Table 9. To be able to compare between the VFC and the conventional concrete, we will use the conventional pavement concrete mix proportions data (C3) from the National Concrete Pavement Technology Center project- Iowa State University" Self-Consolidating Concrete Applications for Slip-Form Paving: Phase II" [16] as a reference only.

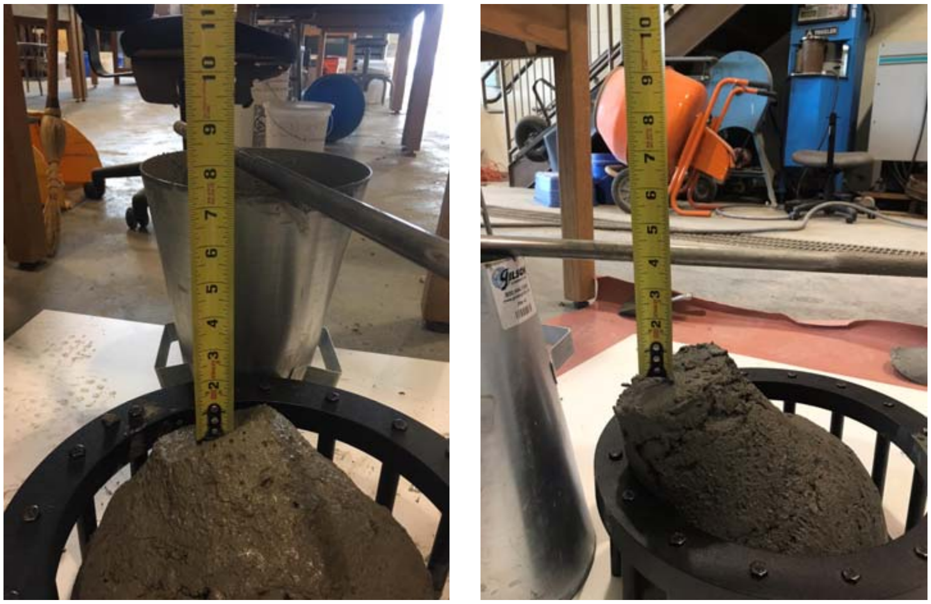
Table 9. Mix proportions of test VFC and conventional concrete mixes

Material	SL-B-1	AC	SL-B-AC	C3
Cement (Ib)	22.14	29.78	21.93	22.03
Slag (Ib)	7.38	0	7.36	0
Attapul-gite clay (Ib)	0	0.15	0.15	0
19 mm Aggregate (Ib)	32.22	32.22	32.19	62.44
9.5 mm Aggregate (Ib)	22.98	22.98	22.99	
Sand (Ib)	55.45	55.45	55.92	49.62
Water (Ib)	9.94	9.95	9.36	10.92
SP (Ib)	0.06	0.17	0.19	0
w/cm Ratio	0.34	0.33	0.32	0.5

- *material for 1 ft^3 in lb unit*

The verification of the proposed VFC mix design done by testing many mixes of different cylinders compressive strength and plastic viscosity.

All the mixes subjected to the slump flow as shown in Figure 14, the three tests shows different result depending on the water cement ratio, the slump test for mixing design SL-B-AC (a) was 8 in, mixing design AC (b) was 3.75 in and mixing design SL-B-1 was 0.5 in (See Table 10).



(a) SL-B-AC **(b) AC**

Figure 14. Slump test

J-ring and L-box tests in the fresh state to be sure that they meet the flow-abilty and passing ability criteria without segregation. For J-ring tests (See Figure 15), the mixing design SL-B-AC was 9 in and for mixing design AC was 8 in. (See Table 10).

Figure 15. J ring test (Mixing design AC)

For L- box tests (See Figure 16 and Figure 17), the mixing design SL-B-AC was 14 in and for mixing design AC was 8 in. (See Table 10).

Figure 16. L Box test (Mixing design SL-B-AC)

Figure 17. L Box test (Mixing design AC)

In order to test the ability of VFC mix to fill the formwork containing reinforcement under its own weight, the L–box apparatus with three adjustable steel rods (each of diameter 1/2 in) was used [18]. The times for the mix to reach 8 and 14 in were recorded. The results also showed that no large aggregate particles had segregated or been blocked by the rods. Therefore, from the flow and passing ability as shown in the Table 6 below, all the tests mixes satisfied the required criteria for viscosity.

The accuracy of the proposed design method has been validated through compressive strength tests performed on (4 x 8 in) cylinders (eight per mix).

Figure 18. 2 day strength of mix SL-B-AC

(a) 7 day (b) 28 day

Figure 19. Compressive Strength Test of mix AC

The results are presented in Table 10. The test was carried out at 2, 7 and 28 days of age. Figure 18 and Figure 19 shows the failure mode of concrete cylinders in 2, 7, and 28 days after casting concrete. The results confirm the well–known trends against the w/c ratio and confirmed the reliability of the proposed mix–design approach.

Table 10. Tests results

Test Name	SL-B-1	AC	SL-B-AC	C3
Slump test	0.5 in	3.75 in	8 in	-
L Box test / Travel time (sec.)	0	8 in	14 in / 3.06 sec	-
J-Ring Test	8 in	8 in	9 in	-
Compressive strength after 2 days	5,033 psi	6,524 psi	6,778 psi	2,850 psi
Compressive strength after 7 days	6,569 psi	8,105 psi	9,037 psi	3,450 psi
Compressive strength after 28 days	*	9,167 psi	9,620 psi	5,493 psi

* *Missed the test.*

Figure 20 showing the development of the compressive strength for the three mixtures and the C3, while mix SL-B-AC had strength more than mix AC due to the additive material (Slag).

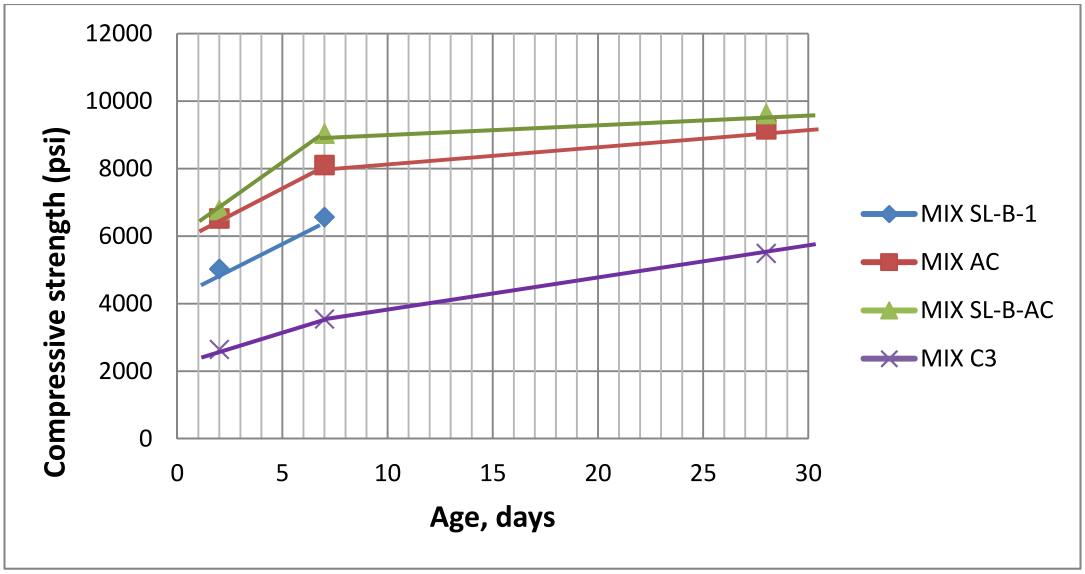


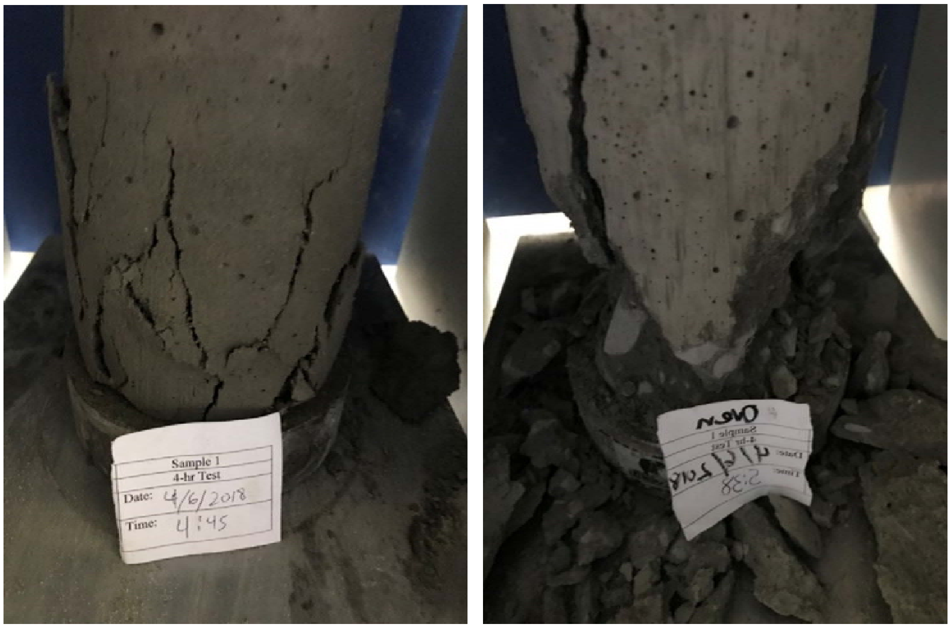
Figure 20. Compressive strength development of VFC and C3

b. Effects of Curing Conditions in VFC Mixtures

To confirm the previous findings on the different curing conditions in other RE-CAST proejct, SL-B-AC specimens were casted and cured in oven dry (100°F) and air dry (73°F) conditions. The specimens were tested in four and five hours after casting concrete as shown in Figure 21. The compressive strengths were compared with the air drying specimens as provided in Table 11. The oven dry specimen developed high early strength compared to air dry specimen, and the results confirms our findings in high early strength concrete. This finding should be further studied how we can make similar conditions in the field and assist to develop high early strength. Heating pad with electric supply would be considered by covering concrete surface, and will be tested in following studies.

Table 11. Compression test results of air dry and oven dry specimens

Test	Air Dry	Oven Dry
4-hour test	900 lbf	6,500 lbf
5-hour test	1,100 lbf	19,696.6 lbf (1,568.2 psi)



(a) Air dry (b) Oven dry

Figure 21. Cylinder specimens tested after air-dry and oven dry

8. MODIFICATION OF VFC MIXTURES TO ACHIEVE HIGH EARLY STRENGTH

a. Preliminary modification by decreasing w/c ratio and adding accelerator

The task to measure hardened concrete properties of VFC mixtures developed by Dr. Feys in Missouri University of Science and Technology was completed by measuring compressive strength of three VFC mixtures. At this stage, the VFC mixtures are modified to develop high early strength with low w/cm ratio and adding accelerator.

Based on the measured properties of the VFC mixtures provided by Dr. Feys, the AC mixture was chosen to further modify the mixture to develop high early strength. The AC mixture was modified by having half of type I cement and hale type III cement. The water was reduced from 9.95 lb to 8.955 lb, and accelerator was introduced by 16 oz as shown in Table 12.

Table 12. Mixtures with different aggregate and w/c ratio

Material	AC mixture (1 yd^3)	AC mixture (1 ft^3)	Modified AC mixture (1 ft^3)
Cement I	478.3	29.78	14.89
Cement III	-	-	14.89
Slag	-	-	-
Attapul-gite clay	2.4	0.15	0.15
19 mm agg.	517.5	32.22	32.22
9.5 mm agg	369.1	22.98	22.98
Sand	890.7	55.45	55.45
Water	159.8	9.95	8.955
SP	2.7	0.17	0.17
accelerator	-	-	16 oz

The measured compressive strengths are presented in Table 13. The early strength of the modified AC specimens had higher strength compared to original AC mixtures, but the 7 day strength was slightly reduced compared to original mixtures. Since the 7 day strength is still higher than target strength, the addition of accelerator is beneficial to increase early strength. The strength development is further measured in coming mix.

Table 13. Compressive strength of Modified AC mixture in Table 12.

Age	1st test (psi)	2nd test (psi)	Average (psi)
4 hour	166	166	166
6 hour	989	1,068	1,029
8 hour	2,072	2,260	2,166
10 hour	3,068	3,039	3,054
26.5 hour	5,488	5492	5,490
7 days	7,212	7490	7,351

b. Modification of AC Mixtures by adding accelerator

With the measured properties of the VFC mixtures provided by Dr. Feys, the AC mixtures were chosen to further modify the mixtures to develop high early strength. The AC mixture was modified by having half of type I cement and hale type III cement. The water was reduced from 9.95 lb to 8.955 lb, and accelerator was increased (up to 40 oz) in the mixtures as shown in Table 14.

Table 14. Mixtures with different aggregate and w/c ratio

Material	AC	AC-16	AC-24	AC-28	AC-32	AC-36	AC-40
Cement I	29.78	14.89	14.89	14.89	14.89	14.89	14.89
Cement III	-	14.89	14.89	14.89	14.89	14.89	14.89
Slag	-	-	-	-	-	-	-
Attapul-gite clay	0.15	0.15	0.15	0.15	0.15	0.15	0.15
19 mm agg.	32.22	32.22	32.22	32.22	32.22	32.22	32.22
9.5 mm agg	22.98	22.98	22.98	22.98	22.98	22.98	22.98
Sand	55.45	55.45	55.45	55.45	55.45	55.45	55.45
Water	9.95	8.955	8.955	8.955	8.955	8.955	8.955
SP	0.17	0.17	0.17	0.17	0.17	0.17	0.17
accelerator	**0**	**16 oz**	**24 oz**	**28 oz**	**32 oz**	**36 oz**	**40 oz**

The measured compressive strengths are presented in Table 15. The strength development of the the mixes is presented in the Figure 22. The strength development of concrete mixtures containing 24 oz accelerator achieved 2,983 psi in 8 hours, and over 10,000 psi in 168 hours (7 days). The 28 oz and 32 oz accelerator achieved similar 24 hour compressive strength, but the 4 hour and 6 hour strength is much higher with higher dosage of accelerator. Figure 23 presents 4-hour strength of different dosage of accelerator. It is clear the very early age strength increased with higher dosage of accelerator.

Table 15. Compressive strength of Modified AC mixture in Table 14.

Elapsed hour	AC-24	AC-28	AC-32	AC-36	AC-40	AC-40a
4	258	543	1,373	1,545	1,998	565
6	1,695	1,557	2,385	-	-	1,477
8	2,983	2,735	3,106	4,103	3,365	1,969
10	3,336	-	-	-	-	-
24	5,622	5,131	5,687	5,488	6,707	5,152
72	9,267	-	-	-	-	-
168	10,299	-	-	-	-	-
672	-	-	-	10,778	11,426	11,102

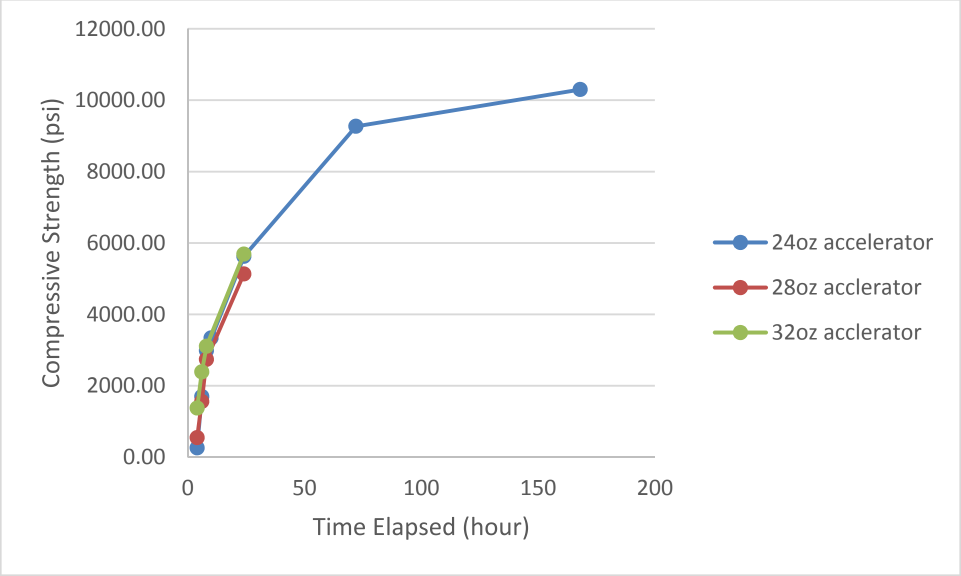


Figure 22. Strength Development of Concrete mixtures containing 24 oz, 28 oz, and 32 oz Accelerator

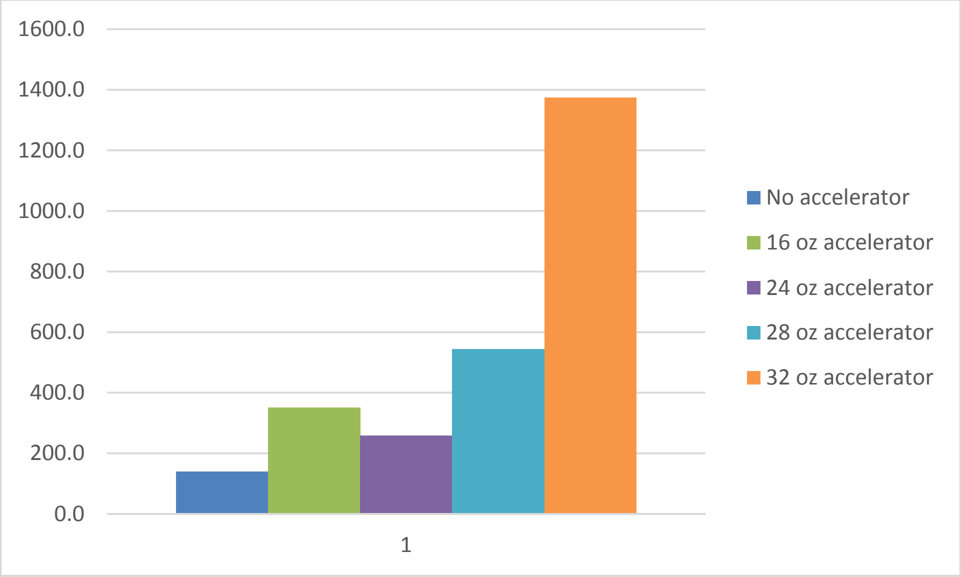


Figure 23. 4-hour Strength of Concrete mixtures with Different Dosage of Accelerator

For the high dosage of accelerator (AC-40 and 40a), however, the strength is decreased compared to AC-36 mixtures. It can be attributed as the strength degradation with too much accelerator or mistakes in the mixing materials and/or proportion. With the mixing difficulties and sensitivity of mixing proportion and short placing time, it is considered that 40 oz. accelerator is considered as the maximum dosage in the mix. The strength development at 4 hour, 8 hour and 24 hour are presented from the 16 oz. to 40 oz. in the Figure 24. The strength development of concrete mixtures containing 40 oz accelerator achieved 1,998 psi in 4 hours, and 6,707 psi in 24 hours. The mixture with 36 oz. accelerator developed 4,103 psi in 8 hours. Based on the comparison and observation, the mixture (AC-36) containing 36 oz. of accelerator is considered as the candidate for further study on the shrinkage, and thermal changes.

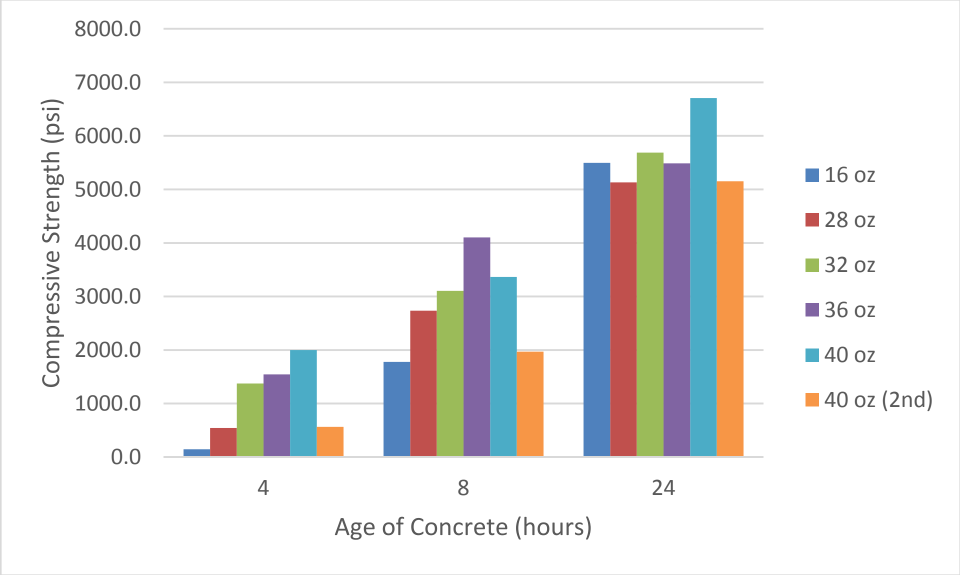


Figure 24. Strength Development of Concrete Mixtures Containing Various Dosage of Accelerator

The temperature of two mixtures containing 16 oz and 20 oz accelerator was measured with a cup test. The concrete sample was put in 6 oz. styrofoam cup and a thermocouple was inserted in the middle of concrete mix. The cup was sealed with aluminum foil and measured the temperature development of the concrete as shown in Figure 25. The Figure 26 shows the temperature changes with time for the mixtures. The figure shows that the increase dosage of accelerator shorten the time to make the peak temperature and increase the peak temperature, and it would help to expedite the development of compressive strength.

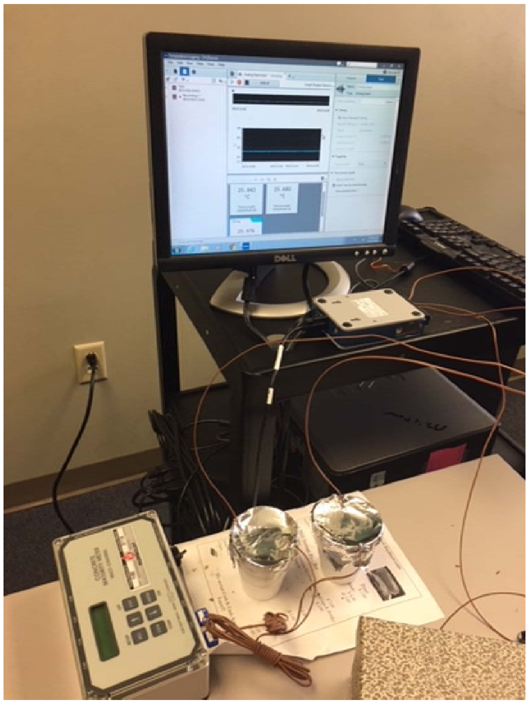


Figure 25. Temperature measurement of AC mixtures

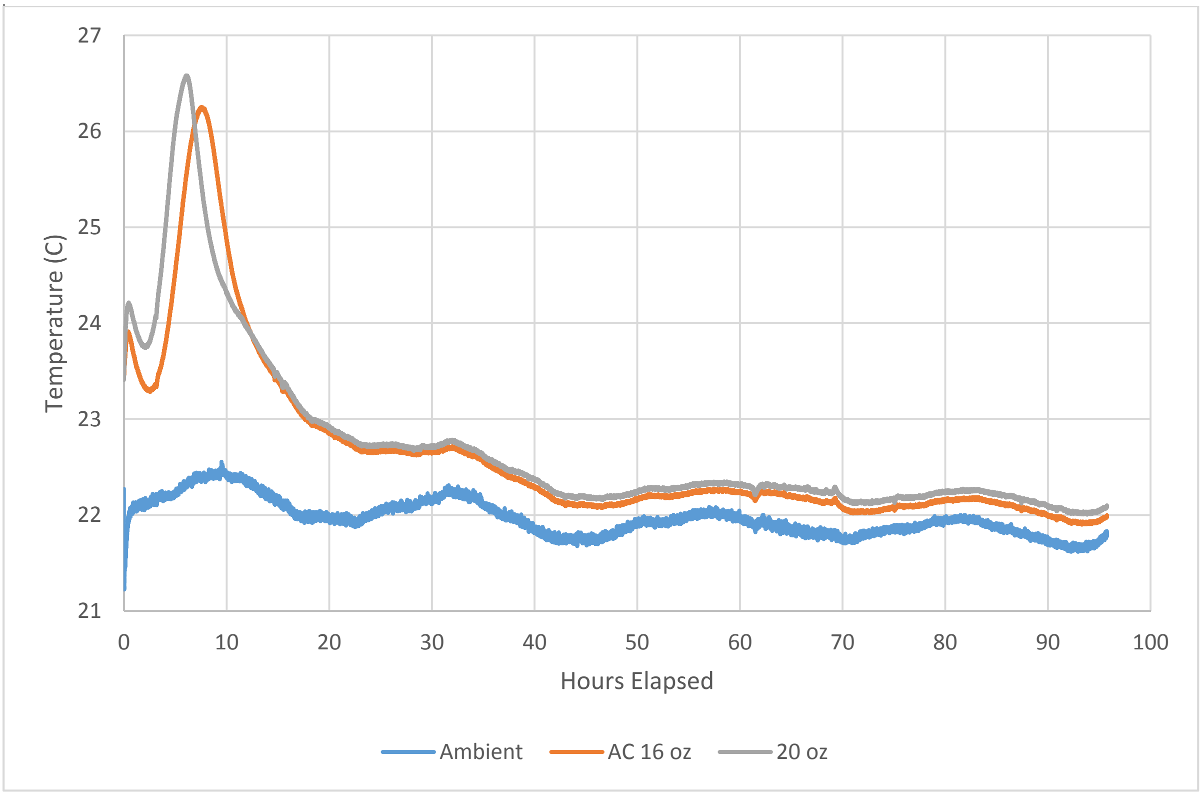


Figure 26. Temperature development of AC mixtures containing accelerator of 16 oz and 20 oz.

The temperature evolution of the AC 40 mixture was measured and presented in Figure 27 with the ambient temperature as a comparison. From the temperature measurement of the AC-16 and AC-20 mixture, it was found that the increase dosage of accelerator shorten the time to make the peak temperature and increase the peak temperature. In the mixtures, the peak temperature was measured in 7 hours and 5.5 hours. For the current mixture with 40 oz. accelerator, the time for the peak temperature is 2.8 hours. So the observation from the previous mixture is still valid, and it explains the early strength (4 and 8 hour) development of 40 oz is much higher than 16 or 20 oz. mixture. It is also noted that the peak temperature (24.2 °C) of the 40 oz. accelerator is lower than the temperatures (26.2 and 26.5 °C) of previous two mixtures containing 16 and 20 oz. accelerator. The difference of the peak temperature is attributed to the ambient temperature difference of two measurements (20.7°C vs. 22 °C).

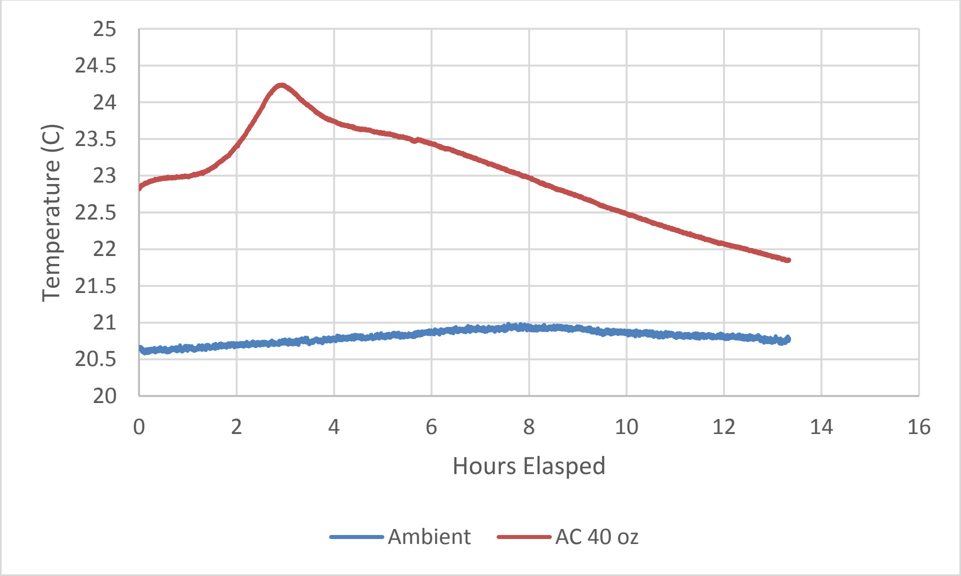


Figure 27. Temperature development of AC mixtures containing accelerator of 40 oz.

c. Effects of Curing Conditions in AC-36 Mixture

With the concrete mixture of AC-36, 13 specimens were cased cured in three different curing conditions (ambient curing, heated blanket, and oven dry). Figure 28 shows some pictures taken during the casting. Two specimens were wrapped in the electric blanket, and turn on with the Level 2 temperature for 2 hours, and off the power as explained in the previous report. Four cylinders were placed in an oven and set the temperature of 100°F. Other specimens were placed in room temperature (65°F) until tests at the designated time. Figure 29 presents failure shape of concrete cylinders at 6 hour. As see in the pictures, the concrete cylinder in air-dry was still wet (darker color) while the oven-dry cylinder was dry at the surface. The inside of the oven-dry specimen is still wet, but it was drier than air-dry as we expected. Figure 30 shows failure shape of the concrete cylinder after compression tests at 14 days.

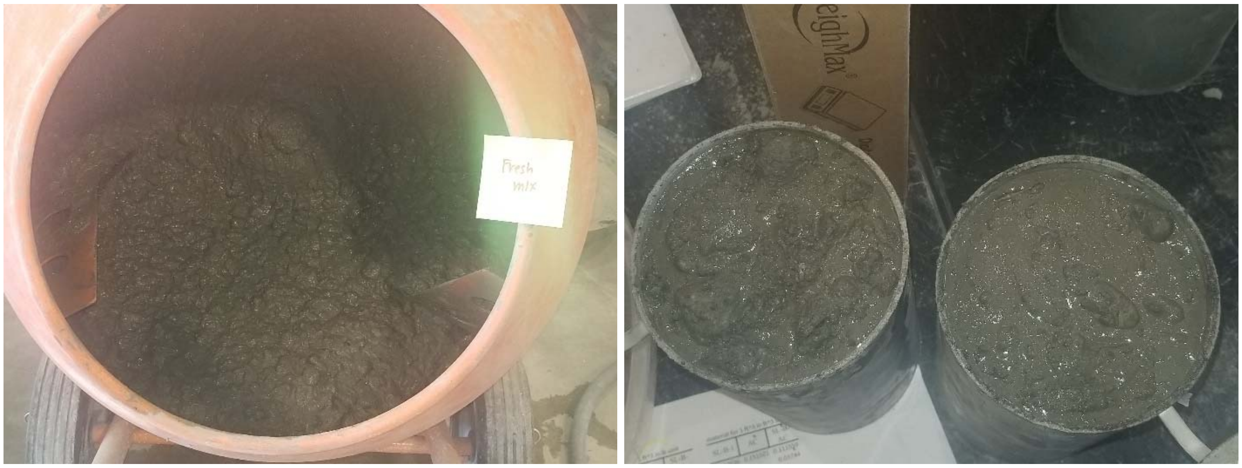


Figure 28. Fresh Concrete

Air-Dry

Oven-Dry

Figure 29. Failure of Concrete Cylinders at 6-hour Compressive Strength Test

Figure 30. Failure of Concrete Cylinders at 14-day Compressive Strength Test

The measured compressive strengths of three curing conditions are presented in Table 16. Figure 31 shows the strength development for the different curing conditions. The development of compressive strength is clearly affected by having heated blanket or oven dry. At 14 days, however, the effects of curing condition is not much compared to early age. It was plan to have 8-hour compression test of heated blanket and oven-dry specimens, and was not accessible to the laboratory in the evening Friday and weekend.

Table 16. Compressive strength (psi) of Modified AC mixture in Table 12

Time elapsed (hr)	**Ambient condition**			**Heated blanket**	**Oven dry**		
	1st specimen	2nd specimen	average		1st specimen	2nd specimen	average
4	340.37	246.82	**293.59**	**2179.43**	2,358.28	2,490.98	**2,424.63**
6	1,223.49	1,239.82	**1,231.65**	**-**	3,553.84	-	**3,553.84**
336	8,578.74	6,029.69	**7,304.22**	**8,244.98**	7,293.23	-	**7,293.23**
672	8,706.69	-	**8,706.69**	**-**	-	-	**-**

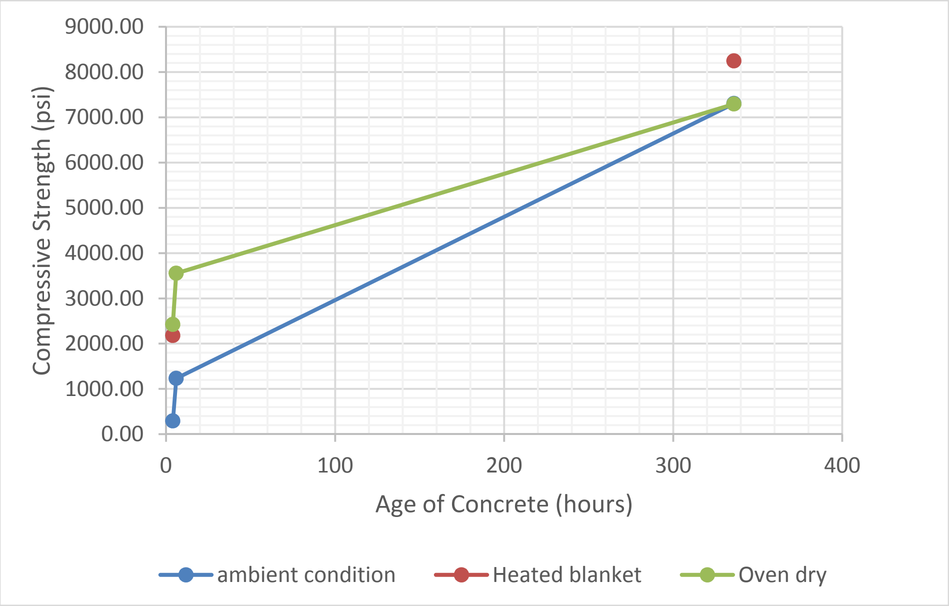


Figure 31. Strength Development of Concrete Mixture with Different Curing Conditions

To focus on the strength development at early age, 2nd mix was made on March 22. At this time, the same mixture was used and cast 14 cylinders. Table 17 shows the results of compressive strength, and Figure 32 presents the strength development of three different curing conditions. It is clear that oven dry has high impact on the strength development, and heated blanket has some impact as seen in previous mixes. The difference between oven dry and heated blanket is blowing air, and the blowing air might help to take moisture from the surface of concrete, and it might help drying and consequently early strength development.

Table 17. Compressive strength (psi) of Modified AC mixture in Table 16

Time elapsed (hr)	Ambient condition			Heated blanket	Oven dry		
	1st specimen	2nd specimen	average		1st specimen	2nd specimen	average
4	199.04	167.20	**183.12**	**979.30**	1,971.34	2,024.04	**1,997.69**
6	1,042.32	949.55	**995.93**	**-**	4,205.80	-	**4,205.80**
8	2,216.58	2,100.95	**2,158.76**	**2,929.69**	5,016.67	-	**5,016.67**
24	5,830.04	6,129.79	**5,979.91**	**-**	-	-	**-**

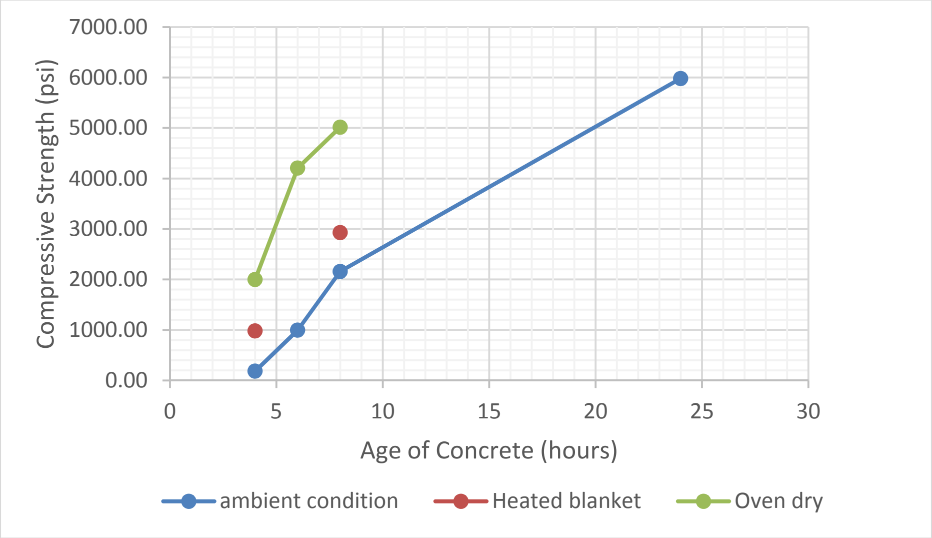


Figure 32. Strength Development of Concrete Mixture with Different Curing Conditions

In the previous tests, it was found that oven dry has great impact on the strength development, and heated blanket has some impact compared to ambient drying condition. The difference between oven dry and heated blanket is blowing air, and the blowing air might help to take moisture from the surface of concrete, and it might help drying and consequently early strength development. To be practical on curing in the field, it is now planning to place concrete cylinders in the temperature controlled pan and see the effects.

The AC-36 mixture was used to produce high early strength concrete based on the previous trial mixtures. Four different curing conditions were used to compare their effects. The first curing condition is to put in an oven with the inside temperature of 95°F. The oven has a fan in the back so that air is blow out from inside to outside. Figure 33 shows the temperature setup of oven used in the curing. A couple of specimens were cured in heated blanket which is also set up to 95°F as explained in the previous report. (Figure 34) Few specimens were cured in front of heating fan which is blowing warm air (95°F) throughout the curing period. (Figure 35) For a reference, the ambient curing (air dry) was also used for some specimens.

Table 18 shows compressive strength tested in 4-hour, 6-hour, 8-hour, and 24-hour after casting concrete cured in four different conditions. It is clear that heating the concrete help to develop the compressive strength at early age. The oven curing is the most effective method to others. Figure 36 shows strength development with time. Figure 37 shows failure mode of concrete specimens tested in 8-hour cured in air-dry and fan-dry samples.

Table 18. Comparison of Compressive Strength for Different Curing Conditions

Hour	Oven	Fan	Air	Blanket
4	834.39	380.57	130.57	372.77
6	2,473.14	1,053.51	719.43	-
8	4,518.98	2,078.26	1,703.82	2,286.78
24	7,314.87	-	5,891.72	-

Figure 33. Oven setup with 95°F

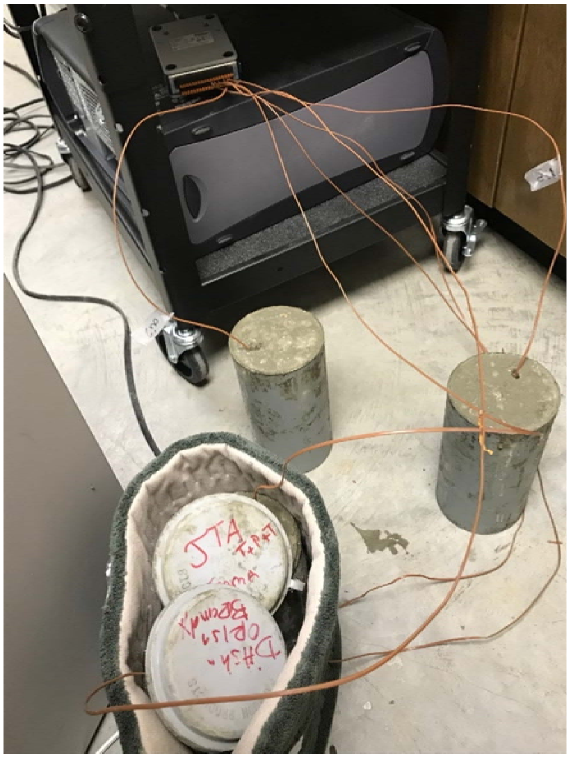


Figure 34. Specimens in heated blanket and ambient temperature

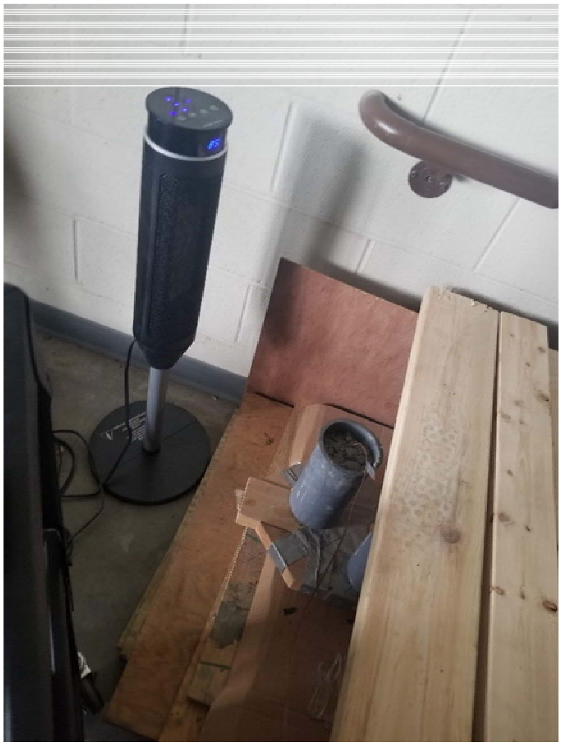


Figure 35. Specimens placed in front of heating fan with 95°F setting temperature

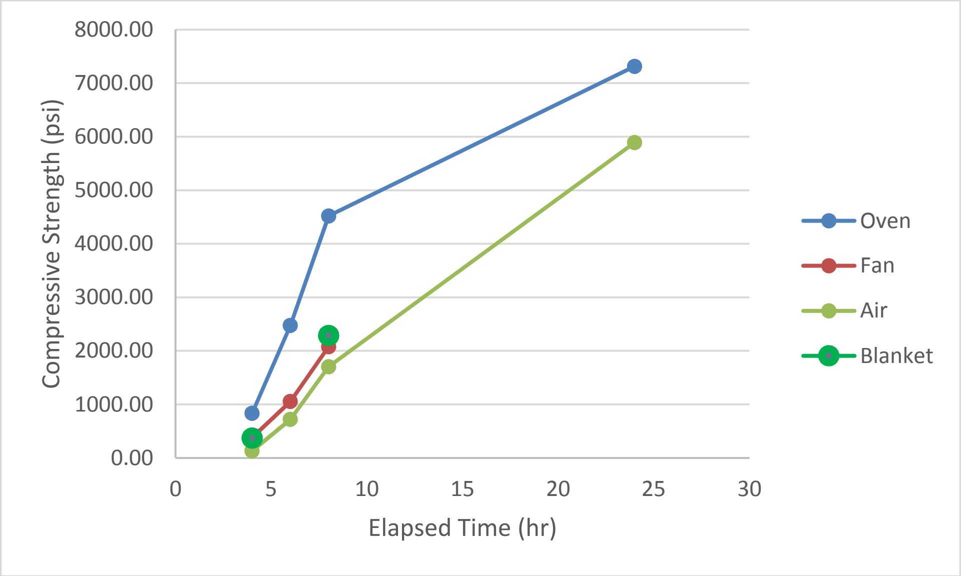


Figure 36. Strength development with time for four different curing conditions. (w/c = 0.3)

Air-Dry

Fan-Dry

Figure 37. Failure of Concrete Cylinders at 8-hour Compressive Strength Test

During the adjustment of mixing water, a mixture with high water content (12.56 lb) was used with the same mix. The four different curing conditions were also used as previously, and the effects of curing condition is not much dramatically increasing for oven dry. In 24 hours, the oven dry, fan dry, and air dry having the similar strength as shown in Table 19. This observation is very interesting since we studied early age strength (4-8 hours), and the heating effect is more clearly shows in the strength development for low w/c concrete. Figure 38 shows the strength development for the four different curing conditions.

Table 19. Comparison of Compressive Strength for Different Curing Conditions

Hour	Oven	Fan	Air	Blanket
4	493.36	151.83	159.15	270.55
6	1,220.88	588.14	582.33	-
8	2,008.30	1,225.45	1,129.96	1,312.98
24.75	3,947.32	3,798.98	3,528.79	-

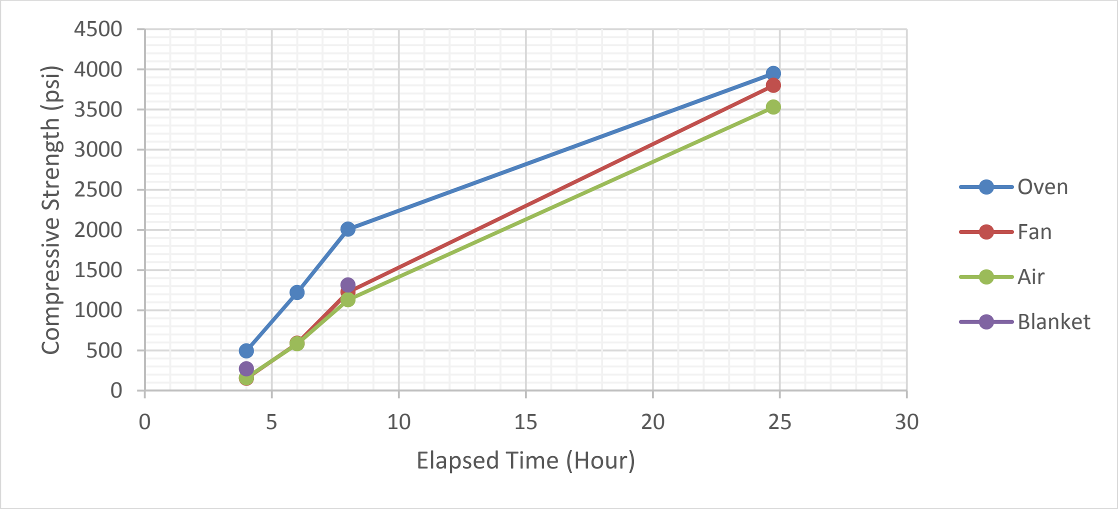


Figure 38. Strength development with time for four different curing conditions (w/c = 0.42).

9. COST ANALYSIS

To study the cost of the production and construction of the VFC and the conventional concrete pavement we need to focus on five parameters which are the concrete materials, concrete mixing and transportation, formwork for convectional pavement concrete, concrete casting and finishing, and also we need to assume the cost of the concrete mixing, transportation and the finishing are the same for the VFC and the conventional concrete.

The unit costs of materials used in the analysis for the VFC and the conventional concrete are as shown in Table 20:

Table 20. Unit cost of concrete materials ($)

Material	Cost ($)
Cement (per ton)	105
Slag (per ton)	95
Attapul-gite clay (per ton)	8
19 mm agg. (per ton)	16
9.5 mm agg (per ton)	16
Sand (per ton)	11.5

Based on the given unit costs, the total material costs of the VFC were calculated and are given in Table 21.

Table 21. Material cost of VFC and conventional concrete ($/yd^3)

	SL-B-1	AC	SL-B-AC	C3
Material cost of VFC ($/ yd^3)	61.38	62.76	61.13	52.82

And as per the mix design for the VFC and the conventional concrete we can see that the material cost for the VFC is equal or more than the cost of the conventional concrete due to use more of cementations materials, admixtures, and fiber and not in the conventional concrete type.

In estimating the cost of placing the concrete, we assume the costs of mixing, transportation, finishing and curing are the same for both of the VFC and conventional concrete. The conventional concrete requires vibration, formwork, and additional labor for the spreading of the concrete in forms. The VFC requires a paver and operators, but it requires less labor for finishing. Based on these assumptions, the unit costs for the VFC and conventional concrete were derived in Table 22.

Table 22. Construction process unit cost for the VFC and conventional concrete ($/yd^3)

Construction process	Cost ($)
Concrete Vibration with operator	10
Formwork with labor	12
Labor for handling and spreading	11
Paver with operator	16

Table 23 provides a comparison of the breakdown costs of these two different construction methods, and it shows that the material cost of the VFC higher than the conventional concrete but the cost of the construction is less The present cost analysis does not include the cost saving that resulted from accelerated construction provided by the SCC slip-form paving method.

Table 23. Estimated construction cost of VFC and conventional concrete ($/yd^3)

Item	**SL-B-1**	**AC**	**SL-B-AC**	**C3**
Material cost of VFC ($/ yd^3)	61.38	62.76	61.13	52.82
Concrete Vibration with operator	0	0	0	10
Formwork with labor	0	0	0	12
Labor for handling and spreading	0	0	0	11
Paver with operator	16	16	16	0
Total	77.38	78.76	77.13	85.82

10. CONCLUSIONS

The experimental work attesting the validity of the proposed mix design procedure was performed in both fresh and hardened states via a series of VFC (Vibration Free Concrete) mixes provided by other researcher in separate project. The test mixes were found to meet the necessary self-compacting and the compressive strength criteria, thus fully validating the proposed mix proportioning method. Therefore, this method reduces considerably the extent of laboratory work, the testing time and the materials used.

Experimental study showed that the VFC has a lower viscosity comparing with conventional concrete due to the mix design criteria for the VFC which have smaller volume of coarse aggregates. The required force for VFC to flow is shown to be inversely proportional to its slump, and also the fines materials (slag) has significant effects on flow ability and shape-holding ability of VFC as shown clearly in results of the mixing design of SL-B-AC and AC, the results of SL-B-AC shows high compressive strength and slump comparing with AC mix design due to the slag material. "Increasing the filing material (slag) content of a cement-based material considerably increases its yield stress and viscosity".

The SL-B-1 mix design need to be redesign because of its result of the slump tests. Two different samples were made for this mix and in both cases the slump tests were 0 and 0.5 in. From this it was found the clay is has significant effects on flow ability.

The compressive strength and rate of the strength development of VFC tend to be higher than those of conventional concrete due to the lower water-to-binder ratio. The elastic modulus of VFC is lower due to its low coarse aggregate content. The porosity and rapid chloride ion permeability of VFC are noticeably higher than those of conventional pavement concrete at 28 days, but they become comparable at the later ages, probably due to the extensive use of supplementary materials. The heat of cementations material hydration of VFC is comparable to or lowers than that of conventional pavement concrete. The freeze-thaw durability of VFC is also comparable to that of conventional concrete, which is primarily dependent upon durability of the aggregates used. Scaling resistance to deicing chemicals varies with VFC mixes, and addition of filling material generally provides VFC with a better scaling resistance to deicing chemicals.

The AC mix was further modified to achieve high early strength by adding accelerator in the mixture and having different curing conditions. The optimum content of the accelerator to develop high early strength was to be 36 oz. Among the four different curing conditions with the AC mixtures having 36oz accelerator, oven dry condition is the best to achieve high early strength.

A comparison analysis shows that the material cost of VFC is equal to or greater than that of conventional pavement concrete. The main contributors to the higher cost in VFC are the use of more cementations materials and admixtures/additives. The total costs, the sum of material and construction costs, of VFC mixes are comparable to those of conventional concrete.

11. RECOMMENDATIONS FOR FURTHER STUDY

- It would be interesting if other inert fine materials may be proposed to be used as a replacement to cementations material. This may lead to reduction in VFC cost and cracking potential due to drying shrinkage.
- Also shrinkage-reducing admixture and other mitigation measures such as self-curing may be studied.
- More admixtures may be studied for VFC applications. The admixtures should maintain or increase yield stress to promote shape-holding ability.
- The curing method in lieu of oven dry should be considered since oven dry is not practical curing method in the pavement construction. High capacity blanket or heating fan is suggested to achieve high early strength in rapid pavement repair and/or construction.
- Pre-field construction of VFC slab and field test should be conducted to verify the findings in the laboratory tests.

12. REFERENCES

[1] Tymkowicz, S., and Steffes, R. F. 1996. “VIBRATION Study for Consolidation of Portland Cement Concrete.” *Proc., Semisesquicentennial Transportation Conf.*, Iowa State Univ., Ames, Iowa.

[2] Ardani, A., Hussain, S., and LaForce, R., 2003. “Evaluation of Premature PCC Pavement Longitudinal Cracking in Colorado.” *Proc., 2003 Mid-Continent Transportation Research Symp.*, Iowa State Univ., Ames, Iowa.

[3] Wang K., S.P. Shah, D.J. White, J. Gray, T. Voigt, L. Gang, J. Hu, C. Halverson, and B.Y. Pekmezci. 2005. “Self-Consolidating Concrete—Applications for Slip-Form Paving: Phase I (Feasibility Study)”, TPF-5(098). Ames, IA: Center for Portland Cement Concrete Pavement Technology.

[4] Wang K., S.P. Shah, D.J. White, J. Gray, T. Voigt, L. Gang, J. Hu, C. Halverson, and B.Y. Pekmezci. 2011. Self-Consolidating Concrete—Applications for Slip-Form Paving: Phase II. TPF-5(098). Ames, IA: Center for Portland Cement Concrete Pavement Technology.

[5] Pekmezci, B.Y., Voigt, T., Wang, K., and Shah, S.P. 2007. “Low Compaction Energy Concrete for Improved Slip Form Casting of Concrete Pavements.” *ACI Mater. J.*, 3 104, 251–258.

[6] Voigt. T., Mbele. J., Wang. K., and Surendra P. Shah. S. P. “Using Fly Ash, Clay, and Fibers for Simultaneous Improvement of Concrete Green Strength and Consolidability for Slip-Form Pavement”, 2010, Journal of Materials in Civil Engineering, 22, 196-206.

[7] Lomboy. G., Wang. k., and Ouyang. C., 2011, “Shrinkage and Fracture Properties of Semiflowable Self-Consolidating Concrete”, Journal of Materials in Civil Engineering, 23, 1514-1524.

[8] H. Okamura and M. Ouchi, “Self-Compacting Concrete,” Journal of Advanced Concrete Technology, vol. 1, no. 1, pp. 5-15, April 2003.

[9] Bertil, P., 2001, A Comparison between Mechanical Properties of Self-Compacting Concrete and Corresponding Properties of Normal Concrete”, Cement and Concrete Research, 31, 193-198. https://doi.org/10.1016/S0008-8846(00)00497-X

[10] Philippe, T., Ahmed, L., Khalil, H., Gilles, P.C. and Abdeldjelil, B., 2006, “Cracking Tendency of Self-Compacting Concrete Subjected to Restrained Shrinkage: Experimental Study and Modeling”, Journal of Materials in Civil Engineering, 18, 46-54. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:1(46)

[11] Jin-Kenn, K., Sang, H.H., Yon, D.P. and Jae, H.N., 1998, “Material Properties of Self-Flowing Concrete”, Journal of Materials in Civil Engineering, 10, 244-249. https://doi.org/10.1061/(ASCE)0899-1561(1998)10:4(244)

[12] Roziere, E., Granger, S., Turcry, P. and Loukili, A, 2007, “Influence of Paste Volume on Shrinkage Cracking and Fracture Properties of Self-Compacting Concrete”, Cement and Concrete Composites, 29, 626-636. https://doi.org/10.1016/j.cemconcomp.2007.03.010

[13] Aijaz Ahmad Zende ,Dr R. B. Khadirnaikar, “An Overview of the Properties of Self Compacting Concrete “IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE).

[14] Mohammed Shamil Mohammed Abo Dhaheer, “Design and Properties of Self-Compacting Concrete Mixes and Their Simulation in the J-Ring Test”, November 2016.

[15] Center for Portland Cement Concrete Pavement Technology Iowa State University, “Self-Consolidating Concrete—Applications for Slip-Form Paving: Phase I”.

[16] National Concrete Pavement Technology Center Iowa State University, “Self-Consolidating Concrete Applications for Slip-Form Paving: Phase II”.

[17] Assaad, J., Khayat, K., Mesbah, H., 2003, “Assessment of the thixotropy of flowable and self-consolidating concrete”, ACI Materials Journal, 100(2), pp. 99–107.

[18] EFNARC Guidelines, 2005, “The European Guidelines for Self-Compacting Concrete; Specification, Production and Use”, p. 63.

[19] Koehler, E.P. and Fowler, D.W., 2007, “Aggregates in self- consolidating concrete. International Center for Aggregates Research (ICAR)”, The University of Texas, Austin, USA.

[20] Domone, P.L., 2006, “Self-compacting concrete: An analysis of 11 years of case studies. Cement and Concrete Composites”, 28(2), pp. 197–208.

[21] Domone, P.L. and Illston, J., 2010, “Construction materials: Their nature and behavior”, New York, USA: Spon Press.

APPENDIX

Progress Report for RE-CAST Project 2B:

Enhancing Thixotropy of Cement-Paste

Dr. Dimitri Feys

Missouri University of Science and Technology

RE-CAST PROJECT 2B:
APPLICATION OF VIBRATION-FREE CONCRETE MIXTURES IN RAPID PAVEMENT CONSTRUCTION

PROGRESS REPORT:
ENHANCING THIXOTROPY OF CEMENT-PASTE
(JUNE, 2017)

By
Dimitri Feys, Assistant Professor
Piyush Rajendra Lunkad, Graduate Assistant

Table of Contents

1 Introduction

This report describes the progress on the development of vibration-free concrete (VFC) to be used for slipform paving. This concrete type must be close to self-consolidating to ensure a proper compaction and to minimize the entrapped air content. On the other hand, as shape stability is required, the concrete mixture must develop a sufficiently high yield stress shortly after placement, to ensure it can withstand its own weight. Sufficient fluidity and high thixotropy are thus simultaneously required. To minimize material use, and as the origin of thixotropy is in the cement paste, the first task of this research is performed on paste level. The second task, currently ongoing, focuses on the development of the concrete mixtures, based on the results of the paste study, while the third task investigates the mechanical properties and durability of the developed mixtures. This report describes the results and conclusions of the first task.

2 Materials and Methods

2.1 Materials

2.1.1 Cement

A commercially available type I/II ordinary Portland cement has been used throughout this research work. The cement has an estimated Bogue composition of 61% C_3S, 8% C_2S, 6% C_3A, 9% C_4AF, and 3.4% of gypsum. The density is 3170 kg/m^3. Measurements are currently ongoing to determine the particle size distribution and surface area of the cement.

2.1.2 Supplementary cementitious materials and mineral fillers

The following supplementary cementitious materials (SCMs) and mineral fillers were employed to investigate their suitability for VFC for slipforming. The grain size distribution and surface area of these materials is currently being determined.

- Class C fly ash, at 25% replacement[1]
- Slag cement, at 25% replacement, density 2910 kg/m^3
- Limestone filler, at 10% replacement, density 2730 kg/m^3
- Silica fume, at 5% replacement, density 2390 kg/m^3
- Metakaolin, at 25% replacement, 2680 kg/m^3
- Kaolin, at 1% replacement, 2940 kg/m^3
- Nano silica, at 1% replacement, 2670 kg/m^3
- Attapulgite clay, at 0.5% replacement, delivered at a 20% solid concentration. The density of the particles is 2290 kg/m^3.

These SCMs were first employed as binary systems, after which the best performing materials were combined in ternary mixtures.

2.1.3 Dispersing admixtures

Two commercially available dispersing admixtures (SP) were employed: one polycarboxylate-based (PCE) and one polynaftalene-based (PNS) superplasticizer. The dosage of the admixture was varied to assure a mini-slump flow diameter of 300 ± 10 mm.

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[1] *Measurements on fly ash delivered erroneous results. The research team is figuring out the issues with the density determination.*

2.2 Mix design and mixing procedure

The investigation on the cement pastes was divided into two subtasks. For both dispersing admixtures, the influence of w/c was evaluated, in absence of any SCM or filler. Consecutively, the PCE dispersant and a w/cm = 0.35 was retained for the investigation on the SCMs and fillers.

2.2.1 Mix design

Table 1 represents the mix designs evaluated. All cement pastes were prepared in a small Hobart mixer. The volume of cement paste produced is 750 ml for each mixture.

Table 1. Mix designs of investigated cement pastes (in grams for 750 ml of paste)

	CEMENT	**WATER**	**SCM**	**DISPERSANT**	**W/CM**
PCE 0.30	1218	365		PCE: 4.4	0.30
PCE 0.35	1126	394		PCE: 3.0	0.35
PCE 0.40	1048	419		PCE: 2.0	0.40
PCE 0.45	979	441		PCE: 1.5	0.45
PNS 0.30	1218	365		PNS: 12.2	0.30
PNS 0.35	1126	394		PNS: 8.8	0.35
PNS 0.40	1048	419		PNS: 4.1	0.40
PNS 0.45	979	441		PNS: 2.2	0.45
FA-C 25	845	394	Fly ash: 282	PCE: 3.8	0.35
SLAG 25	845	394	Slag: 282	PCE: 2.6	0.35
LF 10	1014	394	Limestone: 113	PCE: 2.8	0.35
SF 5	1070	394	Silica fume: 56	PCE: 4.9	0.35
MK 25	845	394	Metakaolin: 282	PCE: 11.2	0.35
KA 1	1115	394	Kaolin: 11	PCE: 3.6	0.35
NS 1	1115	394	Nanosilica: 11	PCE: 6.1	0.35
AC 0.5	1121	394	Attapulgite clay*[2]: 6	PCE: 10.7	0.35
SL 25 – SF 5	789	394	Slag: 282 Silica fume: 56	PCE: 4.0	0.35
SL 25 – AC 0.5	839	394	Slag: 282 Attapulgite clay: 6	PCE: 9.8	0.35
SF 5 – AC 0.5	1064	394	Silica fume: 56	PCE: 23.3	0.35

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[2] *It should be noted that the Attapulgite clay is delivered in slurry form. The reported values are the mass of active ingredient. The added water of the mixture has been compensated for the water in the slurry. The amount of water reported is the total amount of water in the cement paste.*

			Attapulgite clay: 6		
SL 25 – SF 5 – AC 0.5	783	394	Slag: 282 Silica fume: 56 Attapulgite clay: 6	PCE: 14.9	0.35

2.2.2 *Mixing procedure*

All mixtures were prepared in a small Hobart mixer. Table 2 shows the different steps in the procedure, in which mixing and scraping are altered to ensure the homogeneity of the sample. The contact time between cement and water is taken as the reference time. The starting time of the rheological measurements is relative to this reference time. The dispersing admixture (SP) is added in delayed fashion. The desired quantity is determined through preliminary tests, evaluating the mini-slump flow for different dosages.

Table 2. Mixing procedure.

TIME	DURATION	ACTION	ADDITION
-0.5 min	30 s	Mixing	Dry materials
0 min	60 s	Mixing	Water
1 min	60 s	Scraping	
2 min	30 s	Mixing	
2.5 min	120 s	Mixing	SP
4.5 min	30 s	Scraping	
5 min	60 s	Mixing	

2.3 Rheology

2.3.1 *Measurement procedure*

The rheological properties of the mixtures were evaluated with the Anton Paar MCR 302, in parallel plate configuration. The plates are 50 mm in diameter and are sandblasted to minimize slip between the plates and the sample. The gap was maintained at 1 mm, and temperature was kept constant at 20°C. The temperature-controlling hood was placed on top of the system in an attempt to minimize the evaporation of water from the sample.

Immediately after mixing and the evaluation of the mini-slump flow, a small sample of cement paste is placed on the bottom plate. The lowering of the upper plate squeezes the sample in between both plates, filling up all space in between the plates. The edges of the plates were trimmed to avoid the edge effects.

The sample was evaluated using two different procedures: a flow curve, and static yield stress measurements at rest. The flow curve is measured by imposing a linearly decreasing shear rate with time, ranging from 100 s^{-1} to 5 s^{-1} in a 30 s timeframe (interval 2 in Figure 1). The flow curve is preceded by a 90 s pre-shear period, during which the shear rate is kept constant at 100 s^{-1} (interval 1 in Figure 1). This pre-shear is imposed to bring all samples to the same reference state (corresponding to this shear rate), in an attempt to eliminate the shear history (mixing, placing and rest) from the sample prior to the measurements. The flow curve is used to determine the dynamic yield stress and plastic viscosity (if the material obeys the Bingham model), or the modified Bingham model was imposed in case the sample was severely shear-thickening.

To determine the thixotropic properties, the sample was subjected to a constant shear rate of 0.005 s^{-1} (exaggerated in Figure 1). The corresponding shear stress evolution of the sample is monitored over a 60 s time period. When the thixotropic properties were evaluated immediately after obtaining the flow curve (interval 3 in Figure 1), a steady increase in shear stress is monitored. This increase in shear stress is a reflection of the thixotropic properties, immediately after mixing. This thixotropic measurement is then repeated four times at 5 minute intervals, each time giving the sample 4 min rest, while measuring the shear stress response in the 5th minute (intervals 5, 7, 9 and 11 in Figure 1). For these profiles, as a larger static yield stress is developed, the shear stress shows, potentially, a steep slope with time, reaches a peak, followed by a descending curve. The first part of the curve corresponds to the elastic deformation, while the peak corresponds to the static yield stress: the stress needed to initiate flow after rest.

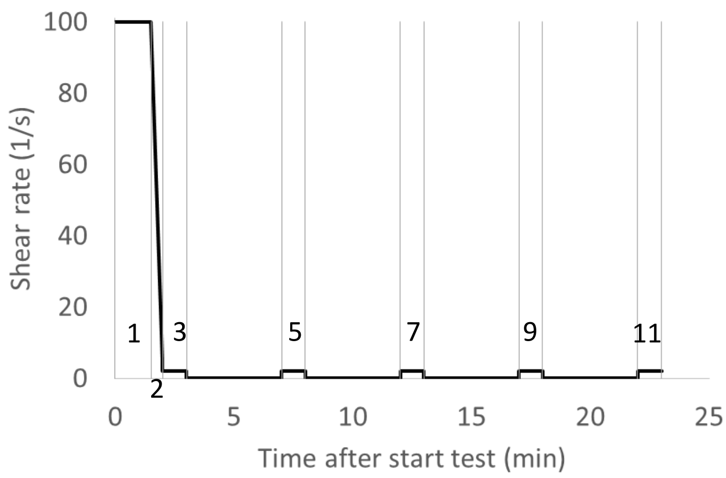

Figure 1. Shear rate profile. Interval 1 is the pre-shear, interval 2 represents the flow curve. During intervals 3, 5, 7, 9 and 11, the sample is sheared at 0.005 s^{-1} during 1 minute (the figure is exaggerated to enhance visibility). In between intervals 3, 5, 7, 9 and 11, the sample is at rest.

The pre-shear prior to the flow curve tests starts at 15 min after contact between water and cement. The first flow curve is determined between 16.5 and 17 min, and in the 17th, 22nd, 27th, 32nd and 37th minute, the stress response to a very small shear rate is determined. The entire procedure: pre-shear, flow curve and 5 thixotropy tests, is repeated on the same sample, 45 min after contact between cement and water. By comparing both flow curves at 15 and 45 min, an indication is given on the contribution of workability loss (mainly caused by strong C-S-H connections between the particles) to the stress development. For practical applications, the workability loss is less favorable in case of prolonged transportation times.

2.3.2 Determination of rheological properties

Figure 2 shows a typical result of the flow curve measurement. The measured torque (T) is expressed as a function of the angular velocity (Ω). By means of a Reiner-Riwlin type of equation for parallel plate rheometers, the intercept of the T-Ω curve is transformed into the yield stress, and the slope of the curve can be used to calculate the viscosity. For the shown example, the yield stress is 5.1 Pa, and the plastic viscosity is 0.72 Pa s at 15 min. The evolution of the obtained (dynamic) yield stress from 15 to 45 min is used to evaluate the workability loss of the mixture.

Figure 3 shows the typical stress response at a constant shear rate of 0.005 s^{-1}, immediately measured after the flow curve. In total, 100 data points are determined in 60 s. The shear stress profile shows a continuously increasing shear stress with time, attributed to the restructuring of the material under very small shear. The average of the last 20 data points is taken as one of the parameters studied: it indicates how much yield stress the sample can develop immediately after shearing.

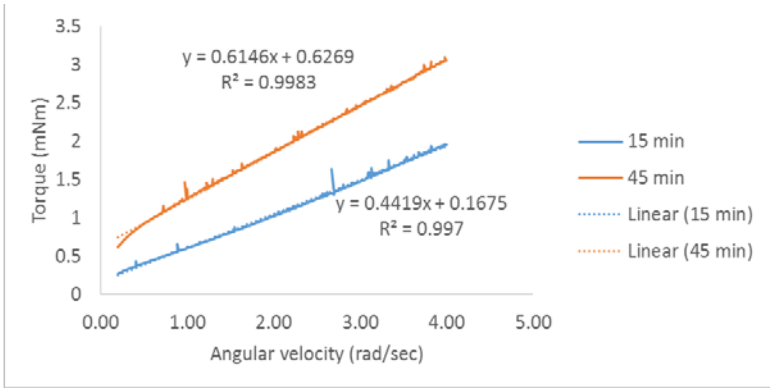

Figure 2. Flow curves at 15 and 45 min for the PCE 0.35 mixture.

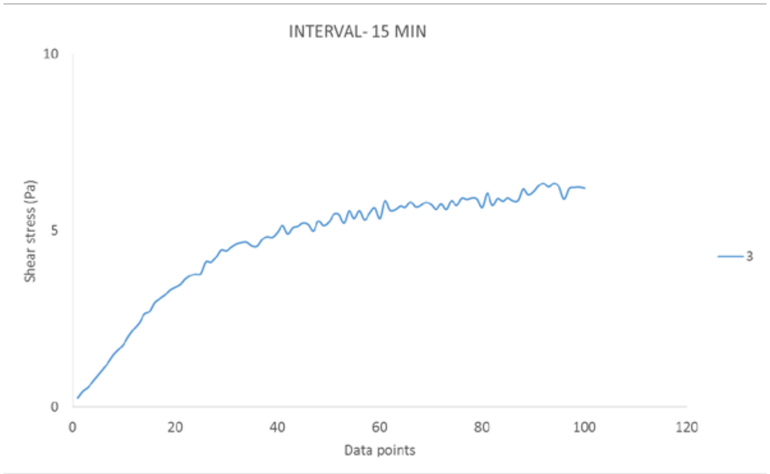

Figure 3. Typical result of the increase in shear stress at a constant shear rate of 0.005 s^{-1}, immediately after obtaining the flow curve. Result shown is for the PCE 0.35 mixture at 17 min.

Figure 4 shows the remaining static yield stress responses. The legend indicates the measurement intervals in the rheometer. For intervals 5, 7, 9 and 11, the maximum values are considered the static yield stress. The thixotropy is further evaluated by the average increase in static yield stress with time ($\Delta\tau_{0,s}$: static yield stress minus shear stress at end of interval 3 / elapsed time since the end of the flow curve), as well as the individual value of the 5th interval, corresponding to a 5 min rest (in fact, 1 min at 0.005 s^{-1}: interval 3, and 4 min rest).

$$\Delta\tau_{0,s} = \frac{\tau_{0,s,x} - \tau_{0,s,3}}{t_x - t_3}$$

Where: $\Delta\tau_{0,s}$ = the increase of static yield stress (Pa/min)
$\tau_{0,s,x}$ = the static yield stress measured in interval x (Pa) (x = 5, 7, 9, or 11)
t_x = time at which $\tau_{0,s,x}$ is measured

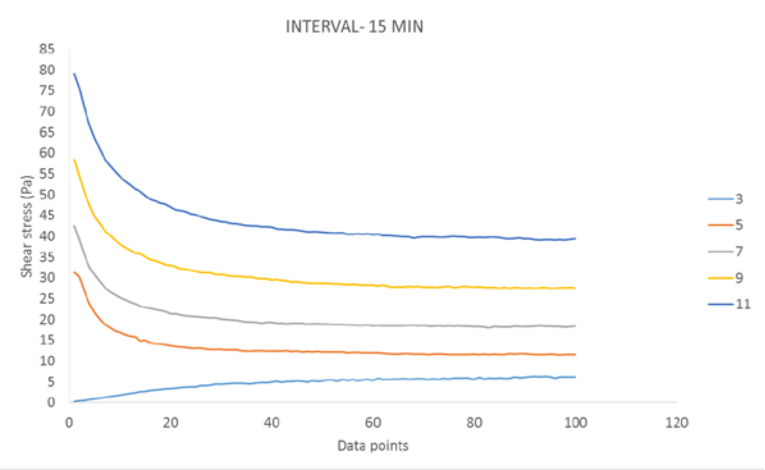

Figure 4. Static yield stress measurements. The colors represent the measurement intervals in the rheometer. Results for the PCE 0.35 mixture at 15 min.

To summarize: the following parameters are used for the evaluation of the rheological properties:

- Increase in dynamic yield stress, obtained from the flow curves between 15 and 45 min, to determine the workability loss
- The average shear stress at the end of the third interval, just after the flow curve, which corresponds to the immediate development of internal structure.
- The increase in static yield stress over 5 min of rest, taken as the maximum shear stress value at interval 5 minus the value at the end of interval 3.
- The average increase in static yield stress with time, taken as the average of the maximum shear stress (minus shear stress at the end of interval 3) divided by the elapsed time since the end of the flow curve, for intervals 5, 7, 9 and 11.

3 Results

3.1 Influence of water-to-cement ratio and dispersant type

The influence of w/c and the dispersant type on the rheology, and in particular thixotropic build-up, has been investigated based on the first eight mixtures mentioned in Table 1. Table 3 shows the detailed results of all measurements. The first three columns represent the flow curve results, in terms of (dynamic) yield stress and viscosity, both at 15 and 45 min. The change in dynamic yield stress is an indication of the workability loss of the sample. The last three columns are reflecting the thixotropic build-up of the pastes. The static yield stress in interval 3 is measured 1 min after the determination of the flow curve. The static yield stress increase with time in the following intervals is calculated by means of the $\Delta\tau_{0,s}$ equation above.

The results in Table 3 and in Figure 4 to Figure 7 clearly show, as expected, that all rheological properties are directly dependent on w/c, regardless of the dispersant type. The lower w/c, the more thixotropic the mixtures are. An efficient way to increase thixotropy of cement pastes is to decrease w/c, especially for values of w/c below 0.40. In fact, at w/c = 0.40, no significant thixotropy in the pastes has been noticed. Regarding the dispersant type, the PNS superplasticizer delivers the largest increase in static yield stress in the first minute (Figure 6), but in the longer term, the increase in static yield stress for the PNS is lower than that for the PCE (Table 3, Figure 7).

Furthermore, the mixtures with PNS show a larger workability loss, based on the dynamic yield stress obtained from the flow curves (Figure 5). This is also reflected in a larger static yield stress values for the second measurement (starting at 45 min), compared to the first measurement (starting at 15 min). In case a long workability retention is desired (e.g. in case of long transportation times), this workability loss is disadvantageous. To reduce the workability loss, the PCE dispersing agent is selected for the next series of experiments.

Table 3. Rheological results for the pastes with different w/c and different dispersant type. Note that YS stands for the yield stress, visco is the viscosity, ΔYS is the change in dynamic yield stress between the 15 and 45 min flow curve measurements. The static yield stress in interval 3 is the increase in shear stress (at 0.005 s^{-1}*) during 1 minute immediately after determining the flow curve. The static yield stress in interval 5 stands for the increase in yield stress since interval 3, divided by the elapsed time. The average static yield stress increase stands for the evolution of static yield stress over intervals 5, 7, 9, and 11 (i.e. average static yield stress increase over 20 min).*

	DYNAMIC YS (PA)	**VISCO (PA S)**	**ΔYS (PA/MIN)**	**STATIC YS INTERVAL 3 (PA/MIN)**	**STATIC YS INTERVAL 5 (PA/MIN)**	**AVERAGE STATIC YS (PA/MIN)**
PCE 0.30	*15’*: 8.1 *45’*: 30.7	*15’*: 1.01 *45’*: 1.40	0.76	*15’*: 20.0 *45’*: 53.0	*15’*: 11.6 *45’*: 15.2	*15’*: 6.4 *45’*: 8.7
PCE 0.35	*15’*: 5.1 *45’*: 19.2	*15’*: 0.72 *45’*: 1.00	0.47	*15’*: 6.2 *45’*: 22.4	*15’*: 5.0 *45’*: 12.0	*15’*: 3.9 *45’*: 7.2
PCE 0.40	*15’*: 2.4 *45’*: 7.4	*15’*: 0.25 *45’*: 0.38	0.17	*15’*: 0.5 *45’*: 3.6	*15’*: 0.7 *45’*: 3.1	*15’*: 1.2 *45’*: 2.9
PCE 0.45	*15’*: 2.9 *45’*: 6.5	*15’*: 0.13 *45’*: 0.20	0.12	*15’*: 0.9 *45’*: 2.5	*15’*: 1.1 *45’*: 1.7	*15’*: 1.0 *45’*: 1.5
PNS 0.30	*15’*: 12.3 *45’*: 40.7	*15’*: 0.90 *45’*: 1.14	0.95	*15’*: 20.4 *45’*: 60.4	*15’*: 7.2 *45’*: 13.5	*15’*: 4.1 *45’*: 8.2
PNS 0.35	*15’*: 13.3 *45’*: 37.0	*15’*: 0.25 *45’*: 0.36	0.79	*15’*: 10.7 *45’*: 42.7	*15’*: 2.1 *45’*: 11.6	*15’*: 2.2 *45’*: 7.5
PNS 0.40	*15’*: 6.3 *45’*: 14.5	*15’*: 0.17 *45’*: 0.26	0.27	*15’*: 0.3 *45’*: 4.8	*15’*: 0.1 *45’*: -	*15’*: 0.2 *45’*: 0.9
PNS 0.45	*15’*: 0.3 *45’*: 0.8	*15’*: 0.05 *45’*: 0.06	0.02	*15’*: 0.1 *45’*: 0.0	*15’*: 0.1 *45’*: 0.0	*15’*: 0.1 *45’*: 0.0

As thixotropy is largely dependent on w/c, the most logical choice to maximize thixotropy would be w/c = 0.30. However, detailed analysis of the static yield stress curves learns that the static yield stress does not substantially increase beyond 5 min of rest for the mixtures with w/c = 0.30. It appears that the static yield stress plateaus and any subsequent increase, especially for the measurements after 45 min, could be attributed to the hydration mechanism. This reduction in static yield stress can be clearly observed when comparing the last three columns in Table 3. The average increase in static yield stress over 20 min is approximately 65% smaller compared to the increase in the first minute for the PCE 0.30 system. The difference between the average increase in static yield stress and the increase in static yield stress in the first minute is less than 50% for the PCE 0.35 mixture, indicating a more prolonged increase in thixotropic properties (and hydration). The mixture with w/c = 0.35 also has a lower workability loss, and therefore, the PCE 0.35 mixture is selected as reference for the remaining part of the work on cement-pastes.

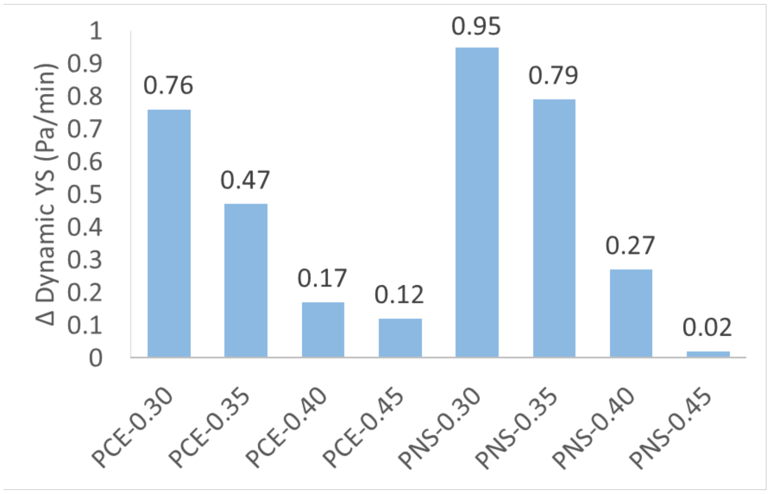

Figure 5. Increase in dynamic yield stress.

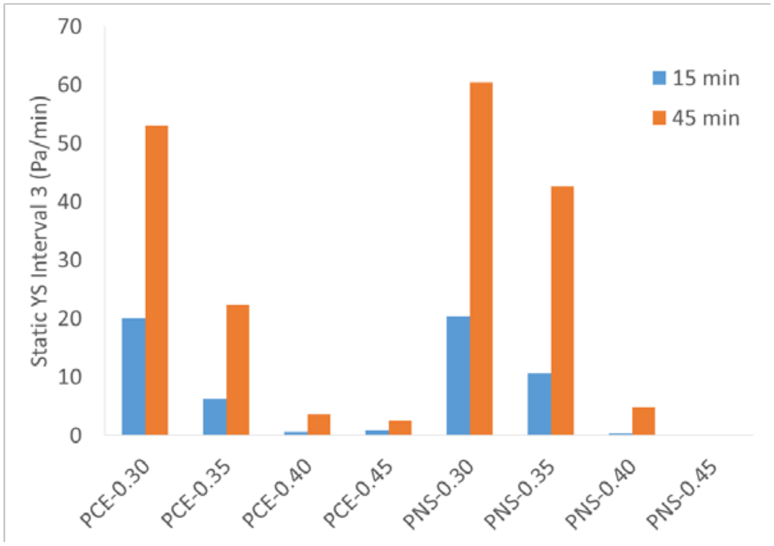

Figure 6. Static yield stress for interval 3.

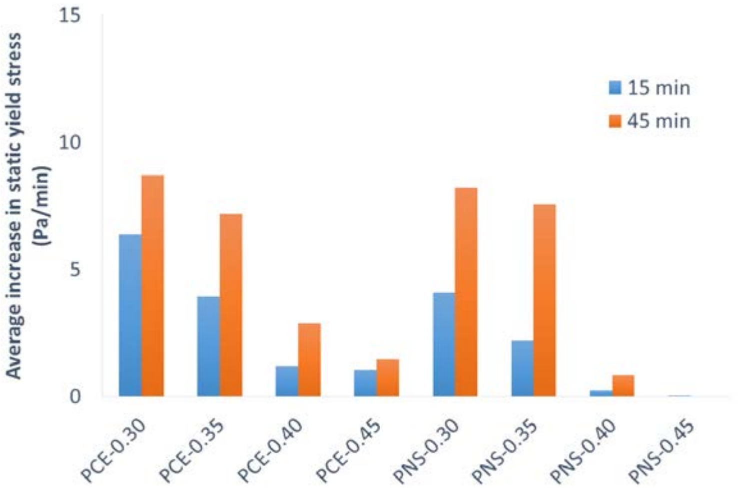

Figure 7. Average increase in static yield stress.

3.2 Influence of supplementary cementitious materials and mineral fillers

3.2.1 Binary binder systems

After the selection of the PCE dispersant and the 0.35 water-to-cement ratio, a number of different supplementary cementitious materials (SCMs) and mineral fillers were evaluated. Detailed results are presented in Table 4, and in Figure 8 to Figure 10. Figure 11 shows the SP consumption to reach the desired mini-slump flow (as reported in Table 1). From Figure 8, it can be seen that nearly all added SCMs or fillers cause a less important increase in dynamic yield stress compared to the reference mixture, except for the mixture with slag. It is also noteworthy to state that the mixture with 0.5% attapulgite clay showed no increase in dynamic yield stress and a slight increase in plastic viscosity. Comparing the increase in static yield stress during the 1st minute for the 15 min test, the reference mixture with plain OPC showed the largest increase, while the mixtures with attapulgite clay, silica fume and slag showed similar behavior (Figure 9). Limestone filler and metakaolin, at the used dosages, significantly reduce the thixotropic build-up.

However, the difference between the static yield stress at 15 min and the one at 45 min is largely influenced by the workability loss, as for the highly restructuring mixtures (REF, SL 25, SF 5 and AC 0.5), a direct relationship between the increase in dynamic yields stress from 15 to 45 min, and the static yield stress at 45 min can be found. From the average increase in static yield stress (Figure 10), for the test started at 15 min, the silica fume mixture shows the most important increase in static yield stress (considering that the results on the slag mixture were deemed erroneous). The mixtures with metakaolin, fly ash and nanosilica also show a substantial increase in static yield stress, but the speed of development in the first minute was lower than the other mixtures. The attapulgite clay mixture shows a large increase in static yield stress in the first minute, but the increase in yield stress slows down over time.

Based on the above observations, silica fume, slag and attapulgite clay are retained for further analysis. Silica fume is a performance-enhancing SCM, it can reduce viscosity at a low dose, it increases the thixotropic response of the mixture and reduces the workability loss, potentially due to the larger SP amount. The attapulgite clay is mostly beneficial for the immediate development of yield stress, but it requires a significant addition of dispersant, potentially causing the negligible workability loss. Slag shows a quick increase in static yield stress, but causes a large workability loss, rendering the cement-slag combination on its own less favorable for potential extended transportation of the mixture.

Table 4. Rheological properties of cement pastes with binary composition (cement + 1 SCM or filler)

	DYNAMIC YS (PA)	VISCO (PA S)	ΔYS (PA/MIN)	STATIC YS INTERVAL 3 (PA/MIN)	STATIC YS INTERVAL 5 (PA/MIN)	AVERAGE STATIC YS (PA/MIN)
REF	*15'*: 5.1 *45'*: 19.2	*15'*: 0.72 *45'*: 1.00	0.47	*15'*: 6.2 *45'*: 22.4	*15'*: 5.0 *45'*: 12.0	*15'*: 3.9 *45'*: 7.2
FA 25	*15'*: 4.0 *45'*: 15.5	*15'*: 0.60 *45'*: 0.89	0.38	*15'*: 3.3 *45'*: 15.1	*15'*: 2.8 *45'*: 8.0	*15'*: 2.9 *45'*: 6.1
LF 10	*15'*: 1.9 *45'*: 8.6	*15'*: 0.40 *45'*: 0.58	0.22	*15'*: 0.9 *45'*: 4.7	*15'*: 0.9 *45'*: 3.6	*15'*: 1.2 *45'*: 3.5
SL 25	*15'*: 6.2 *45'*: 22.4	*15'*: 0.46 *45'*: 0.78	0.54	*15'*: 4.8 *45'*: 24.6	*15'*: 5.3 *45'*: 13.5	*15'*: - *45'*: 9.2
SF 5	*15'*: 1.7 *45'*: 5.5	*15'*: 0.43 *45'*: 0.57	0.13	*15'*: 5.0 *45'*: 10.8	*15'*: 4.5 *45'*: 8.4	*15'*: 4.8 *45'*: 7.8
MK 25	*15'*: 2.2 *45'*: 3.8	*15'*: 0.59[3] *45'*: 0.77[3]	0.07	*15'*: 2.5 *45'*: 6.3	*15'*: - *45'*: 6.2	*15'*: 3.0 *45'*: 12.4
K 1	*15'*: 3.9 *45'*: 11.8	*15'*: 0.32 *45'*: 0.46	0.26	*15'*: 3.3 *45'*: 12.0	*15'*: - *45'*: 6.7	*15'*: 1.7 *45'*: 5.9
NS 1	*15'*: 1.3 *45'*: 7.0	*15'*: 0.39 *45'*: 0.61	0.19	*15'*: 3.9 *45'*: 12.9	*15'*: 2.6 *45'*: 8.9	*15'*: 3.2 *45'*: 8.1
AC 0.5	*15'*: 1.5 *45'*: 1.6	*15'*: 0.27 *45'*: 0.38	0.00	*15'*: 5.3 *45'*: 6.2	*15'*: 2.2 *45'*: 2.4	*15'*: 1.5 *45'*: 2.4

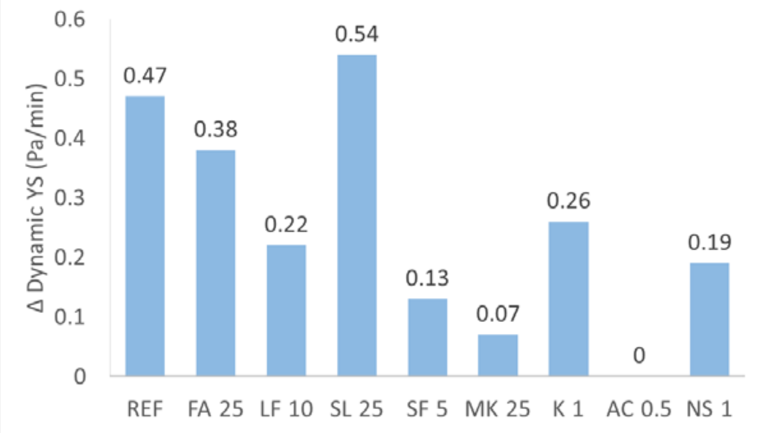

Figure 8. Increase in dynamic yield stress of binary systems.

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[3] *The metakaolin mixture showed severe shear-thickening behavior, and the viscosity was approximated as the differential viscosity at 50* s^{-1}.

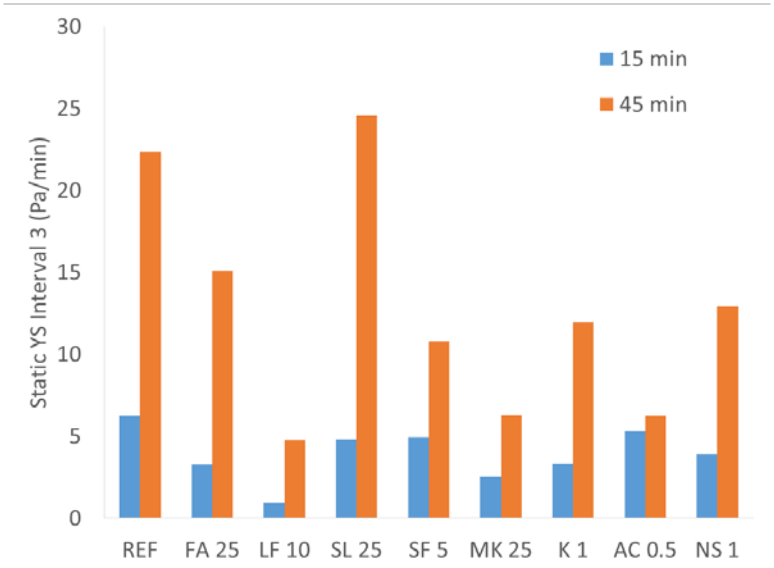

Figure 9. Static yield stress in interval 3 for binary systems.

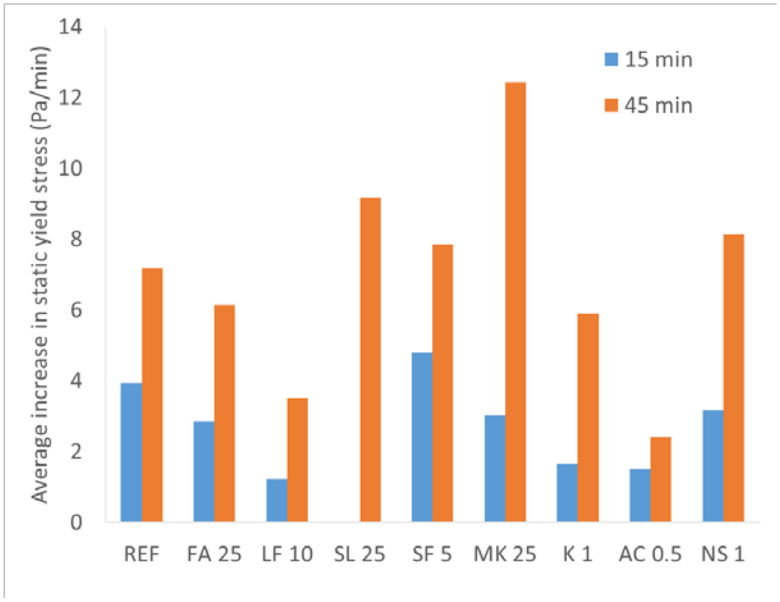

Figure 10. Average increase in static yield stress for binary systems.

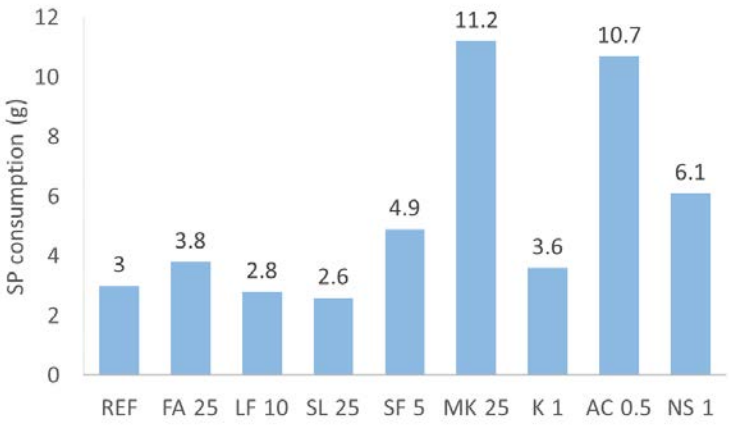

Figure 11. SP consumption of binary mixtures.

3.2.2 Ternary and quaternary binder systems

When starting the subtask on ternary binder systems, a new delivery of cement was made to the laboratory. Although the cement is the same type, produced by the same producer as the previous delivery, some changes in physical properties and chemical composition may affect the rheological response of the mixtures. Therefore, the reference mixture with no SCMs or binders, a w/c = 0.35 and the PCE dispersing admixture, was reproduced and the new values of the rheological properties are reported in Table 5. It should also be noted that the SP quantity necessary to achieve a mini-slump flow of 300 ± 15 mm was slightly lower: 2.9 g for the new cement relative to 3.0 g for the old delivery.

The results for the ternary and quaternary mixtures are summarized in Table 5. In Figure 12 to Figure 14, the rheological properties of the ternary and quaternary mixtures are shown. The new reference cement mixture and the binary systems with slag, silica fume and attapulgite clay are also included in the figures to enhance visual assessment. Figure 15 shows the SP demand of the studied binder systems. The increase in dynamic yield stress from 15 to 45 min is substantially lower for all mixtures containing attapulgite clay, despite the inclusion of slag in some of the mixtures. This can most likely be attributed to the increased SP dosage, as the dosage is at least of the same magnitude as the binary mixture with attapulgite clay. The ternary mixture with slag and silica fume shows a workability loss in between that of the binary mixtures with slag and silica fume separately.

The increase in static yield stress within the first minute (interval 3), is for all ternary and quaternary mixtures higher than for the reference and binary mixtures. However, the benefit of combining attapulgite clay and silica fume is only minor and a significant increase in SP consumption is noted, making these mixtures less favorable. The mixture with slag and attapulgite clay shows a significant increase in thixotropic capacity, without showing a significant loss in workability. Combining slag and silica fume also delivers a significant increase in static yield stress development, but the workability loss may affect the results. The average increase in static yield stress shows similar behavior: combining silica fume and attapulgite clay, with or without slag, results in inferior rheological response compared to only employing silica fume.

Based on all data shown, the following mixtures are deemed optimal for the further development of VFC for slipform applications:

- A ternary mixture combining 25% slag and 0.5% attapulgite clay, intended for extended transportation times, as the thixotropic build-up is significant and the workability loss is minor.
- A ternary mixture containing 25% slag and 5% silica fume, as an alternative if attapulgite clay is not available. This mixture also show substantial thixotropic build-up, but the workability loss can be significant. Hence, this mixture could be suitable for on-site or nearby concrete production and

placement. A mixture with only 5% silica fume could work as alternative. A binary mixture with only 25% slag is not recommended, as the workability loss is deemed to be the main mechanism for the static yield stress development. Non-reversible build-up of yield stress could limit self-consolidation if the waiting time is too elevated.

Table 5. Rheological properties of ternary and quaternary systems.

	DYNAMIC YS (PA)	**VISCO (PA S)**	**ΔYS (PA/MIN)**	**STATIC YS INTERVAL 3 (PA/MIN)**	**STATIC YS INTERVAL 5 (PA/MIN)**	**AVERAGE STATIC YS (PA/MIN)**
REF-NEW	*15’*: 11.0 *45’*: 27.9	*15’*: 0.34 *45’*: 0.53	0.56	*15’*: 5.3 *45’*: 23.3	*15’*: 0.6 *45’*: 7.8	*15’*: 3.9 *45’*: 7.2
SL 25 – AC 0.5	*15’*: 6.7 *45’*: 7.7	*15’*: 0.33 *45’*: 0.44	0.03	*15’*: 18.9 *45’*: 22.4	*15’*: 8.3 *45’*: 8.6	*15’*: 7.8 *45’*: 7.7
SF 5 – AC 0.5	*15’*: 10.5 *45’*: 10.7	*15’*: 0.47 *45’*: 0.53	0.01	*15’*: 6.9 *45’*: 7.7	*15’*: 1.8 *45’*: 1.8	*15’*: 1.2 *45’*: 1.3
SL 25 – SF 5 – AC 0.5	*15’*: 3.6 *45’*: 4.0	*15’*: 0.29 *45’*: 0.36	0.02	*15’*: 6.7 *45’*: 7.4	*15’*: 3.5 *45’*: 3.4	*15’*: 2.7 *45’*: 2.8
SL 25 – SF 5	*15’*: 7.8 *45’*: 16.8	*15’*: 0.37 *45’*: 0.50	0.30	*15’*: 12.5 *45’*: 23.3	*15’*: 4.2 *45’*: 10.9	*15’*: 4.1 *45’*: 8.6

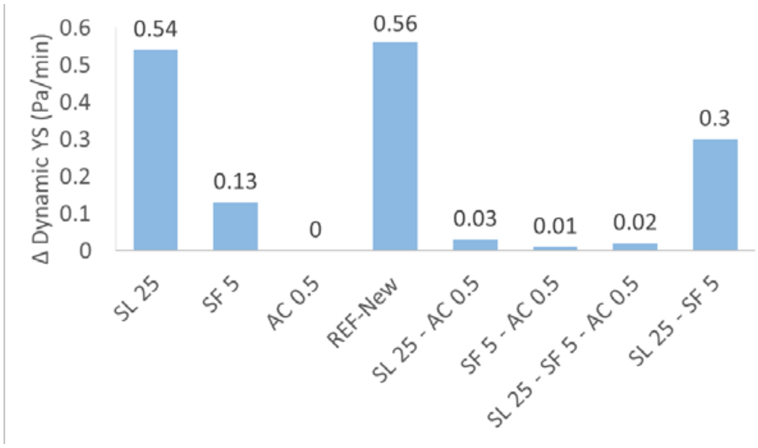

Figure 12. Increase in dynamic yield stress for ternary and quaternary systems.

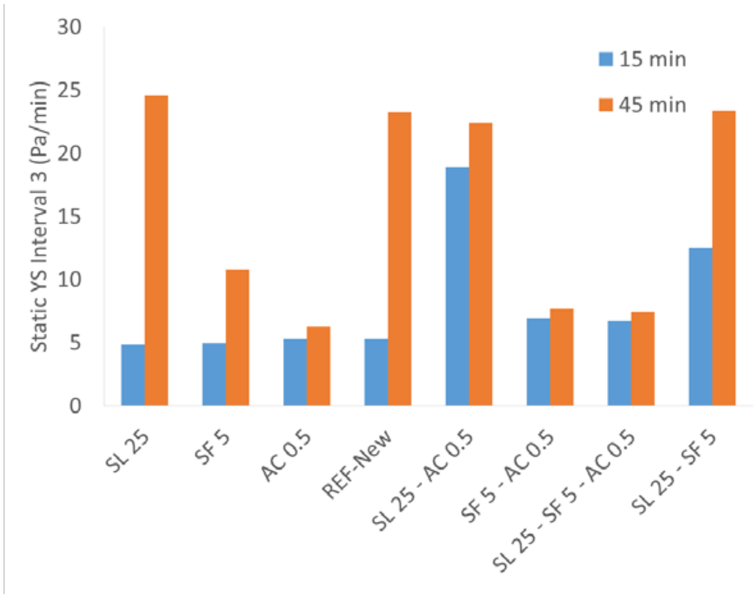

Figure 13. Static yield stress at the end of the 3rd measurement interval for ternary and quaternary systems.

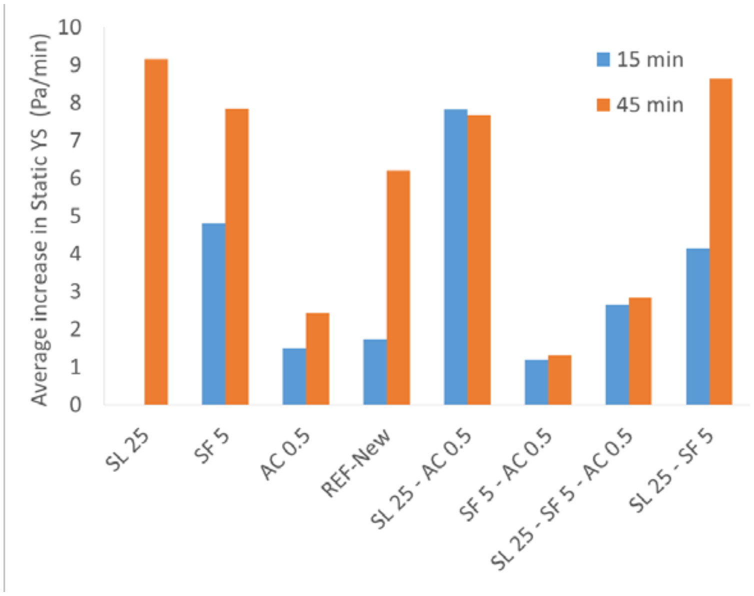

Figure 14. Average increase in static yield stress for ternary and quaternary systems.

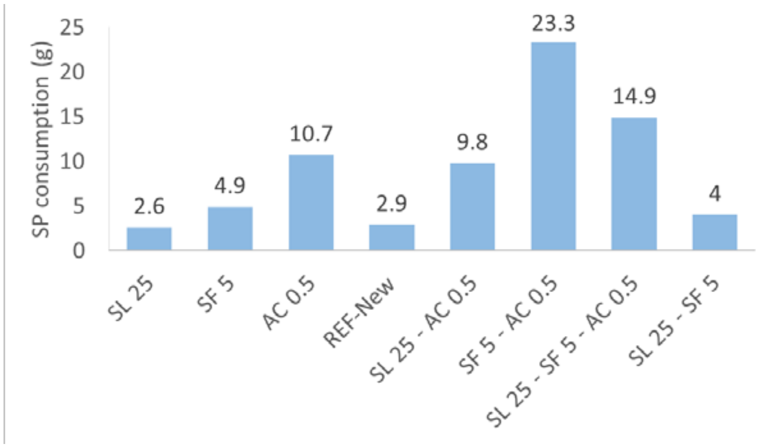

Figure 15. SP demand for ternary and quaternary systems.

4 Future work

4.1 Concrete development based on excess-paste layer concept.

The paste component of this research work has allowed for the selection of two binder systems which show strong thixotropic build-up and low workability loss. These binder systems will be used to develop flowable VFC, with a target slump flow of 500 mm (20 in.). The development of the concrete is based on the excess-paste layer concept. In this method, a part of the paste is trapped in between the voids of the aggregates. This part is equivalent to the empty space in between the aggregates at maximum packing density. For example, if the maximum packing density of the used aggregates is 0.75, it means that 250 l of paste in 1 m^3 of concrete will not participate to the flow of the material. Any paste in excess of this amount is assumed to form a layer with constant thickness around all aggregates. The larger this excess paste layer, the easier the concrete can flow. However, aggregates amplify the rheological behavior of the paste, and the closer the aggregate volume fraction is to its maximum packing density (or the threshold causing friction), the larger the amplification of the paste properties. Hence, maximizing thixotropic build-up in the concrete and assuring sufficient fluidity are contradicting requirements.

4.2 Evaluation of fresh concrete properties

At this stage, the best combination of three sources of aggregates delivering the best packing density is selected, and concrete mixtures will be produced with one of the binder combinations and three excess paste layer thicknesses. The concrete mixtures will be evaluated for:

- Slump flow, which is the criterion for fluidity
- Dynamic rheological properties with the ConTec Viscometer 5
- Static yield stress determination by means of the ICAR rheometer
- Density and air content
- Green strength development on freshly cast 100 x 200 mm cylinders (4 x 8 in.), which will be demolded after different resting times. In case the cylinder does not collapse under its own weight, it will be loaded with small weights until failure.
- Cylinders will be produced for compressive strength testing at 28 days. The density of the cylinder will give an indication on the degree of compaction and the suitability of the mixture.

Once the excess paste layer thickness is established, the other binder combination will also be evaluated. For the mixture containing attapulgite, an immediate addition of the attapulgite and SP, and a delayed addition after a 45 min simulated transportation time will be compared. In the final stage, the feasibility to add synthetic fibers and the addition of air-entraining agents will be investigated.

4.3 Hardened concrete testing and field implementation

Based on the concrete mix designs developed, the hardened concrete properties, including compressive and tensile strength, freeze-thaw durability and total shrinkage will be evaluated by the partners at Southern University in Baton Rouge, LA. After final validation, slipformed concrete slabs will be produced and evaluated at Baton Rouge, LA.