TECHNICAL REPORT STANDARD PAGE

1. Report No. 338	2. Government Accession No.
3. Recipient's Catalog No.	
4. Title and Subtitle **Self-Compacting Concrete Demonstration Project**	5. Report Date **December 22, 1998**
	6. Performing Organization Code
7. Author(s) **David J. Mukai and John Q. Ehrgott**	8. Performing Organization Report No. 338
9. Performing Organization Name and Address **Louisiana State University** **Civil and Environmental Engineering** **Baton Rouge, LA 70803-6405**	10. Work Unit No.
	11. Contract or Grant No. 98-4TIRE
12. Sponsoring Agency Name and Address **Louisiana Transportation Research Center**	13. Type of Report and Period Covered **Final Report** **7/1/97 to 6/31/98**
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Self-compacting concrete is a type of concrete currently being developed that does not need vibration to be placed, even in very congested areas. The primary objective of this study was to compare the rheology, or flowing characteristics, of three different self-compacting concrete mixes to a high performance concrete mix and a flowing concrete mix proportioned in accordance with ASTM C-1017-92. To this end, five simple tests were used to evaluate the rheology of the different mixes. While all five mixes exhibited high slumps, the high performance and flowing concrete mixes could not achieve the same flowability as the self-compacting concrete mixes. A full size Type-I girder model was used to determine which mixes qualified as self-compacting, and only the mixes specifically proportioned to be self-compacting filled the girder without voids. Two different tests, a U-Test and a modified Khayat Horizontal flow test, clearly differentiated between the self-compacting mixes and the non-self-compacting mixes. The U-Test measured the ability of the concrete to flow through a vertical gate of reinforcing steel in a U-shaped apparatus. The Horizontal flow test measured the ability of the concrete to flow horizontally through repeated grids of vertical and horizontal reinforcing steel. Also, the different self-compacting concrete mixes are compared and contrasted with each other, a high performance concrete mix ,and a flowable concrete mix. It was found that three characteristics of self-compacting concrete are: a high cementitious material content, a low coarse aggregate content, and a high dosage of high range water reducer.

17. Key Words concrete, self-compacting, self-placing, rheology, mix design		18. Distribution Statement **Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.**	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price

SELF-COMPACTING CONCRETE DEMONSTRATION PROJECT

by

David J. Mukai

John Q. Ehrgott

College of Engineering
Department of Civil and Environmental Engineering
Louisiana State University
Baton Rouge, Louisiana 70803

conducted for

LTRC Project No. 98-4TIRE
State Project No. 736-99-0574

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

June 1998

ABSTRACT

Self-compacting concrete is a type of concrete currently being developed that does not need vibration to be placed, even in very congested areas. The primary objective of this study was to compare the rheology, or flowing characteristics, of three different self-compacting concrete mixes to a high performance concrete mix and a flowing concrete mix proportioned in accordance with ASTM C-1017-92. To this end, five simple tests were used to evaluate the rheology of the different mixes. While all five mixes exhibited high slumps, the high performance and flowing concrete mixes could not achieve the same flowability as the self-compacting concrete mixes. A full size Type-I girder model was used to determine which mixes qualified as self-compacting, and only the mixes specifically proportioned to be self-compacting filled the girder without voids. Two different tests, a U-Test and a modified Khayat Horizontal flow test, clearly differentiated between the self-compacting mixes and the non-self-compacting mixes. The U-Test measured the ability of the concrete to flow through a vertical gate of reinforcing steel in a U-shaped apparatus. The Horizontal flow test measured the ability of the concrete to flow horizontally through repeated grids of vertical and horizontal reinforcing steel. Also, the different self-compacting concrete mixes are compared and contrasted with each other, a high performance concrete mix, and a flowable concrete mix. It was found that three characteristics of self-compacting concrete are: a high cementitious material content, a low coarse aggregate content, and a high dosage of high range water reducer.

ACKNOWLEDGEMENTS

The authors wish to thank the Louisiana Transportation Research Center for their support of this work through LTRC Project No. 98-4TIRE (State Project No. 736-99-0574). The authors also wish to thank Dr. Kamal Khayat for his help and guidance. The authors also appreciate the support and direction of Curtis Fletcher, the Project Review Committee, and Art Rogers, all of LTRC.

IMPLEMENTATION STATEMENT

This project was a demonstration project meant only to show the feasibility of Self-Compacting Concrete (SCC). By nature, TIRE projects are exploratory in nature, hence there are no immediate implementations for this project. However, the authors recommend that a suite of tests be carried out to qualify SCC as an acceptable structural concrete for DOTD.

TABLE OF CONTENTS

Abstract iii

Acknowledgements v

Implementation Statement vii

Table of Contents ix

List of Figures xi

Introduction 1

Objective 7

Scope 9

Methodology 11

Discussion of Results 19

Conclusions 27

Recommendations 29

List of Acronyms, Abbreviations, and Symbols 31

References 33

LIST OF FIGURES

Figure 1. Mix compositions by percent weight.. 13
Figure 2. Cementitious material composition by percent weight 14
Figure 3. Model Type I Girder form 16
Figure 4. U-test apparatus.. 17
Figure 5. Modified Khayat horizontal flow box test apparatus 18
Figure 6. Type I girder results 21
Figure 7. U-test results.. 22
Figure 8. Modified Khayat horizontal flow box test results.. 23

INTRODUCTION

The present immense challenge of maintaining our aging infrastructure clearly illustrates the importance of building durable structures. To meet this challenge, the concrete research community has developed and promoted high performance concrete (HPC) as the material of choice for future reinforced and prestressed concrete infrastructure projects. The advantages of HPC are well documented, and HPC is finding its way into many projects, most notably high rise structures and bridges. One area of HPC performance that has not been completely investigated is rheology, or flowing characteristics. The current state of the art of SCC can be summarized by the works of Okamura, Miura, Khayat, and others.

Okamura

Beginning in the early 1980's, Japan faced a major shortage of skilled workers in the construction industry which led to a similar reduction in construction quality. This shortage sparked a lot of research interest. Okamura decided to pursue a self-compacting concrete which would guarantee durable concrete with less skilled labor during construction [*1*]. Okamura focused his initial effort on antiwashout underwater concrete which contained viscosity modifying agents. He knew that a viscous mix was required to counter the segregation effects of a highly flowable concrete. But Okamura found that the highly viscous agent used in this type of concrete caused a high level of entrapped air and a poor ability to compact in confined areas. From here, he focused his efforts on the workability of concrete. Hashimoto of Gumma University showed through experimentation that Okamura was on the right track and low or moderate viscosity was a vital key in flowable concrete [*1*]. Hashimoto showed as the concrete paste flowed through obstacles, such as reinforcing bars, the coarse aggregate would come in contact with other aggregate. This contact between the aggregate caused a shear stress to develop. Okamura took this one step further by running experiments that simulated the shear forces in the concrete particles flowing through obstacles. He found by varying the water/cement ratio he could reduce the shear stress between the aggregate, thus improving the flowability of the concrete. The down side to the change in water/cement ratio was a loss in viscosity which led to segregation in the mix. With the addition of superplasticizers, Okamura was able to achieve the flowability without the loss in viscosity. He expanded his experiments to include a "U" test that tested the flowability of freshly mixed concretes as it flowed through tight obstacles. Although the viscosity was reduced in the cement paste, Okamura found that if the aggregate content became too high it would lead to reduced flow. His experiments led to aggregate limitations in a mix design in order to minimize contact between the aggregate as it flowed through tight areas. The limitation on course aggregate was about 50 percent of the solid volume. The same principal of aggregate limitation applied to fine aggregate. As the amount of fine aggregate increased, the contact between the aggregate increased and caused shear stresses and thus reduced flow. Okamura found the limitation on fine aggregate was about 40 percent of mortar volume.

In the summer of 1988 Ozawa was credited for producing the first successful self-compacting concrete. In the years to follow, research increased by both the universities and industries. By the 1990's, self-compacting concrete entered the construction industry and was used for such things as suspension bridge anchors in the Akashi Straits Bridge, and for natural gas tanks. Both projects had positive results which included reduced labor cost and reduced construction time. The concrete produced was a high quality concrete. Self-compacting concrete has also been used in very thin walled structures in which concrete was used to fill a steel shell. This thin walled structure could not be poured with traditional concrete due to limiting spacing [*1*].

Researchers in Japan have continued to improve self-compacting concrete since its development. In September of 1995, the Self-Compacting Concrete Committee was formed in Japan for research and development in hopes to further the use of self-compacting concrete.

Miura

In Japan, research has been done on many aspects of self-compacting concrete. An article by Miura, Takeda, Chikamatsu, and Sogo discussed results from several mix tests that evaluated different material proportions in self-compacting concrete [*2*]. The authors' focus was on the flowability and the viscosity or segregation resistance of self-compacting concrete. They used the slump test to establish the flowability. Since there was no definitive way to test the viscosity of a mix, Miura, Takeda, Chikamatsu, and Sogo developed a testing method to evaluate the viscosity of concrete. They simply timed the flow through a funnel type apparatus. They were able to correlate the testing results to the general viscosity or the segregation resistance of each mix. When the viscosity was high enough to produce a stable flow, the flow out rate or time was faster which indicated better segregation resistance. When viscosity was too low, segregation occurred, and the flow rate was slower and fluctuated. In the research it was found that the viscosity in the mortar and the coarse aggregate volume affected the segregation resistance of the concrete. However, high segregation resistance reduced the smooth flow of the concrete. This seemed to reinforce Okamura's findings from studying the underwater concrete with high viscosity.

Miura, Takeda, Chikamatsu, and Sogo knew that the use of superplasticizers and excess water had adverse effects on concrete such as low durability and low early strength [*2*]. Therefore, they studied the effect of using different mineral admixtures such as fly ash and slag powder to help counter these effects. By holding all other parameters constant, they found an increase in the flowability by replacing the ordinary cement material with varying percentages of these cementitious admixtures. They took it one step further and found that a combination of the different cementitious admixtures had a greater effect on flowability than using only one cementitious admixture. The studies indicated that a replacement of 80 percent of portland cement with 30 percent of fly ash and 50 percent of slag had the highest flowability. It was also found that the powder/water ratio seemed to have the greatest effect on the segregation resistance.

Miura, Takeda, Chikamatsu, and Sogo continued there studies on large scale construction projects [*2*]. They evaluated the use of self-compacting concrete in such projects as natural gas storage tanks and thin/tall walls placed from high points. After some discussion and investigation, they found that self-compacting concrete was suitable for heavily reinforced structures or rapid non-vibrated pours in large structures.

Khayat

Research on SCC is spreading closer to the United States. In October 1997, an article was published in *ACI Materials Journal* by Khayat and Guizani of the University of Sherbrooke in Canada [*3*]. Khayat and Guizani carried the definition of self-compacting concrete a step further. They defined it as having high slump (minimum of 23 inches) and the ability to cast without excess bleeding, settlement, and segregation. They argued that in order to get high slumps, a mix would tend to segregate. This was due to the low viscosities in a highly flowable concrete mix. Khayat and Guizani described how the settlement of heavy solids caused free water to move upward in a mix which leads to bleeding and sedimentation of cement material as well as surface settlements, all of which has an adverse effect on the durability, permeability, and strength of a concrete mix. They also found with highly fluid concrete, an increase in water/cement ratio leads to a decrease in concrete stability. Like other researchers on self-compacting concrete, Khayat and Guizani used superplasticizer as a means of reducing the water/cement ratio without reducing the flowability of the concrete mix. They did find, however, that superplasticizer does have its limit, and excessive amounts can lead to segregation due to loss in viscosity. Khayat's and Guizani's research focused on the use of viscosity-modifying admixtures along with superplasticizer as a means of increasing flowability without decreasing the stability of the concrete. They found that viscosity modifying admixture increased the ability of the mix to suspend the solid particles and reduce sedimentation. They also found that by using the viscosity admixture together with superplasticizer, self-compacting concrete remained stable during pumping, casting, and consolidation. Khayat and Guizani also studied the use of different cementitious admixtures and the different effects each had on self-compacting concrete. Like Miura, Takeda, Chikamatsu, and Sogo, Khayat and Guizani showed that when compared to normal fluid concrete, self-compacting concrete stability can be improved by using mineral admixtures such as fly ash, blast furnace slag, and limestone filler. They attributed this to better grain size distribution in the mix. Khayat and Guizani concluded that using viscosity admixtures and superplasticizer can significantly reduce bleeding, segregation, and settlement of flowable concrete.

In a second article, Khayat, Manai, and Trudel studied the uniformity of different self-compacting concrete mixes cast in deep experimental walls without consolidation [*4*]. They also used a normal medium fluid concrete mix as a control; however, this mix was vibrated in the wall. They found that the self-compacting concrete mixes performed similar to the control mix in compression strength and modulus of elasticity in relation to the height of the wall. This seems to reinforce the theory that a concrete can be proportioned to be self-compacting without segregation and stability problems, even in a deep structural member.

Related Literature

Literature on this subject is new and limited, with the majority of the work being performed in Japan. Several articles, translated to English, give an insight to the growth of self-compacting concrete in the Japan's construction industry. One article, "New Construction Materials Proliferate in Japan", described how self-compacting concrete aims to reduce site labor and shorten construction time. The author explained how self-compacting concrete can also improve the quality of concrete by reducing placement defects. Starting in 1993, the author cited several examples where self-compacting concrete was being used on construction projects . One example was the Kiba-Park Large Bridge, a cable-stayed prestressed concrete bridge. In this project, two workers were able to pour over 650 m^3 in nine months. Another example was the Landmark tower , the tallest high-rise building in Japan. In this project, 885 m^3 was pumped into steel tubular columns. The author stated that the cost of the self-compacting concrete was about 20 percent higher than normal concrete, but the labor productivity more than overcame the material cost for these cases. In Japan, there is a core group of construction companies that the author called the big five. All of these construction companies along with the help of universities have developed their own version of self-compacting concrete. The viscosity agents seemed to be the main difference between the different concrete mixes.

As pointed out by Okamura, highly flowable concrete that does not need vibration ensures quality concrete pours and thereby increases durability [*1*]. This type of concrete is referred to as self-compacting concrete (SCC), and also sometimes is referred to as self-placing, self-consolidating, flowable, and non-vibration concrete.

In an example of SCC being used in industry, Miura et. al. have evaluated several different mixes, investigating different material proportions [*2*]. They have also investigated the effect of fly ash and slag cement on SCC and developed a test for SCC flow characteristics in which they timed the flow of the SCC through a funnel. Finally, they have carried out studies on large-scale construction projects.

More recently, attention has been given to the effect of viscosity modifying admixtures (VMA). Khayat has investigated using VMA to improve the stability of SCC and has looked at the effect of VMA on segregation and surface bleeding at various water/cement ratios [*3*].

OBJECTIVE

The objectives of this project are:

1. To demonstrate that it is possible to proportion concrete mixes with high strengths that do not need vibration to be placed in congested areas.
2. To identify the salient characteristics of SCC mixes.
3. To compare SCC mixes with high performance concrete and flowable concrete mixes.
4. To construct test apparatus that can evaluate the rheology properties of SCC.

SCOPE

This project is an exploratory project and is meant to be a demonstration project. Hence the scope of this project is limited. There will be no attempt to make this study a comprehensive, rigorous study. Rather, only representative SCC, HPC, and FC mixes will be evaluated.

METHODOLOGY

Mix Designs

This project focused on five different mixes: three self-compacting mixes, one high performance concrete mix, and one flowable concrete mix. All three SCC mixes have a lower coarse aggregate content and a relatively large dosage of high range water reducer. The first self-compacting mix (designated Mix O) was based on the guidelines for proportioning SCC given by Okamura [*1*]. The second SCC mix (Mix M) was based on the work of Miura and features a high cementitious material factor [*2*] . Also, in this mix 45 percent of the cement (by weight) was replaced with slag cement and 20 percent with fly ash. The final SCC mix (Mix K) was based on Khayat's work and features a high cement factor, 21 percent replacement of cement with fly ash, three percent replacement of cement with silica fume, and a VMA [*3*]. The first non-SCC mix (Mix H) is based on information obtained from a FHWA HPC Showcase in Louisiana and features a 22 percent replacement of cement with fly ash [*5*]. The mix is modeled after the mix used by Texas DOT in their Louetta bridge project. Unfortunately, because of inferior fly ash and aggregate quality, only moderate strengths were obtained (45.2 MPa [6.55 ksi] at 28 days). Since the focus of this study is on the rheology of the mixes, this was not considered a fatal drawback to the study. The flowable concrete mix (Mix F) was designed according to ASTM guidelines [*6*]. The mix proportions per cubic meter for all these mixes are listed in Table 1. Figure 1 shows the mix components by percent weight. The cementitious material breakdown by percent weight for these mixes is shown in Figure 2. The coarse aggregate had a maximum size of 25 mm (1 in) and a nominal maximum size of 19 mm (0.75 in). The coarse aggregate had a specific gravity of 2.60, a moisture content of 1.75 percent and an absorption rate of 1.18 percent. The fine aggregate had a moisture content of 2.6 percent. Based on data of other similar aggregate, the specific gravity was assumed to be 2.6 and the absorption rate was assumed to be 1.0 percent. The gradations of both the coarse and fine aggregates fell within the recommended ranges in ASTM C33.

Table 1.
Mix Proportions per Cubic Meter

	SCC			non-SCC	
	Mix O	Mix M	Mix K	Mix H	Mix F
Water (kg)	202	206	29	169	163
Portland Cement (kg)	524	174	424	325	334
Fly Ash (kg)	0	99	120	94	0
Slag Cement (kg)	0	226	0	0	0
Silica Fume (kg)	0	0	18	0	0
Fine Aggregate (kg)	606	730	702	640	785
Coarse Aggregate (kg)	1039	920	829	1143	1040
HRWR (ml)	3998	5036	3590	4117	1796
VMA (ml)	0	0	359	0	0
Total Wt (kg)	2371	2355	2323	2371	2323

1 m^3 = 1.308 yd^3
1 kg = 2.205 lbm
1ml = 0.03381 fl. oz.

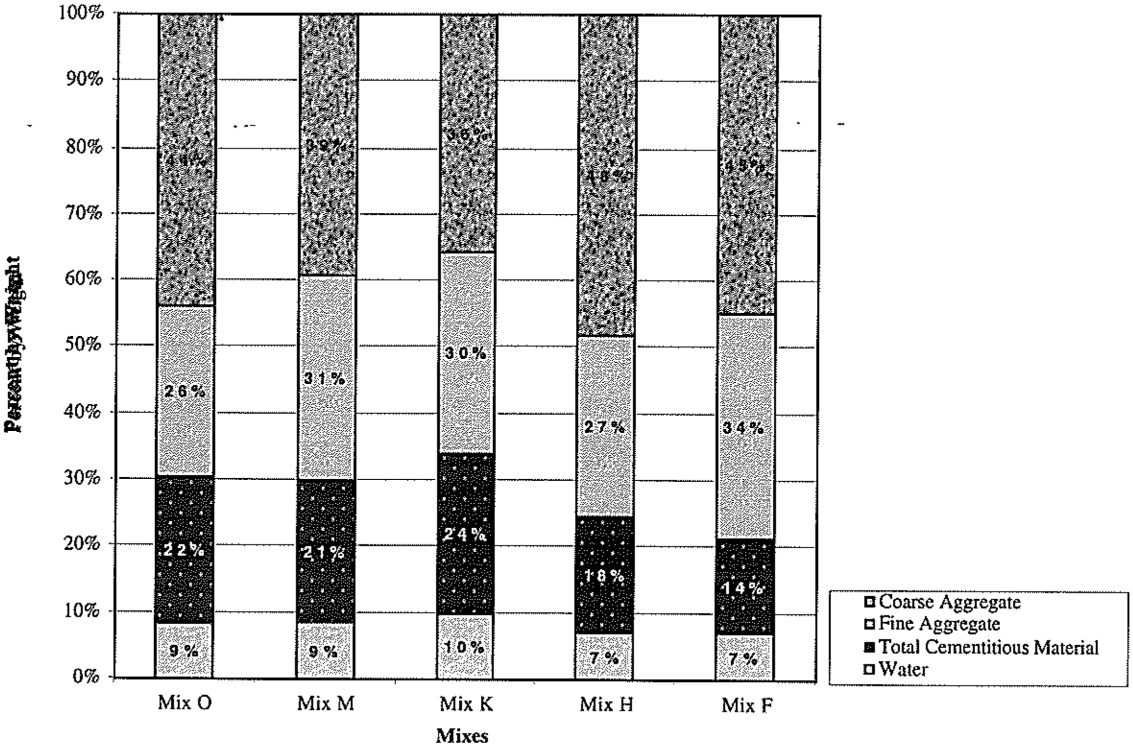


Figure 1
Mix compositions by percent weight

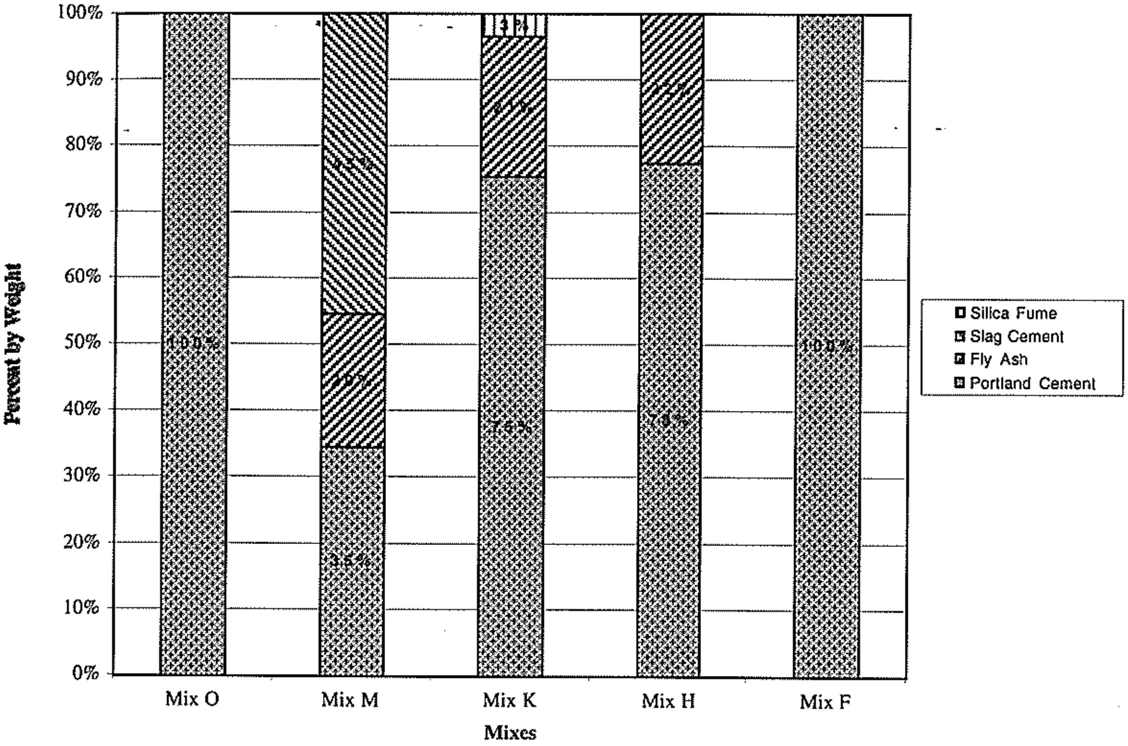


Figure 2
Cementitious material composition by percent weight

Batching Process

The mixes were prepared in small batches, approximately 0.03 m^3 (1 cubic foot). In mixes using a high range water reducer (HRWR), when the slump without the HRWR was specified, the water content was adjusted to achieve the targeted slump, and then the HRWR was added to the mix. After mixing, another slump test was taken and the concrete was poured through the various test apparatus. In cases where the various tests took more than 30 minutes and the effect of the HRWR was beginning to diminish, a small amount of HRWR was added to the mix to bring it back to the original consistency. The final test in all cases was to fill a full scale model Type I girder form. The concrete was then transferred to cylinder molds. To keep a record of the batching process and the performance of the various mixes in the different rheology tests, the entire process was captured on video. The cylinders were then cured in a temperature controlled water bath until testing.

Rheology Test Apparatus

Five different tests were evaluated for determining the flow characteristics of the different concrete mixes. The simplest test conducted was a timed slump test. In most cases, the SCC mixes flowed out into a large diameter pancake with a height equal to the aggregate size. Thus, traditional slump measurements were meaningless. In lieu of the traditional slump measurement, twenty seconds after the slump cone was removed the average diameter of the pancake was measured.

The test apparatus used to determine if a mix was considered self-compacting was a model Type I AASHTO girder. The model consisted of a 305 mm (12 in) long segment of the bulb section of a Type I girder with a Plexiglas front. The form contained several horizontal pieces of smooth conduit meant to model prestressing strands. The conduit diameter was 19 mm (0.75 in), which is significantly larger than a 15 mm (0.6 in) diameter strand. The strands were located on a 51 mm (2 in) grid and thus, the clear space between the simulated strands was 32 mm (1.25 in). In all cases, the mix was put into the model a scoop at a time from a consistent height until either the form filled up or the concrete clogged and backed up out of the form. A schematic drawing of the test apparatus is shown in Figure 3.

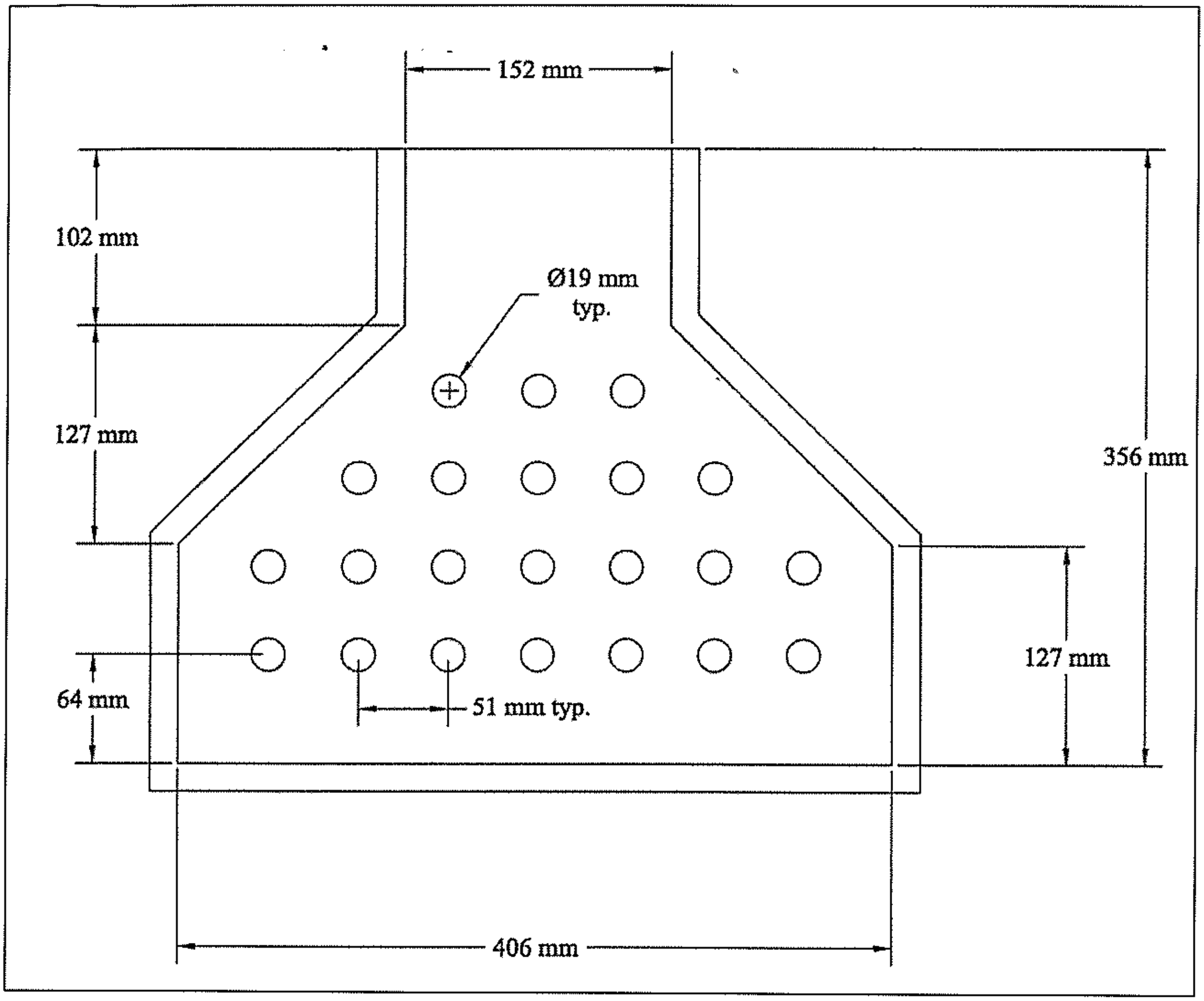


Figure 3
Model Type I Girder form

A variation of the U-Tester developed by Shindo was used to evaluate flow characteristics [*8*]. A schematic drawing of the U-Test apparatus is shown in Figure 4. Initially, the reinforcing steel gate contained three deformed bars with a clear spacing of 38 mm (1.5 in). This spacing proved too narrow for all the mixes and the outer bars were removed, leaving a clear space of 95 mm (3.75 in). In the U-Test, one side of the apparatus was filled to a height of 610 mm (24 in). A gate separating the two sides of the tester was then removed and the resulting concrete heights on both sides of the tester were measured and used to calculate a differential height between the two sides.

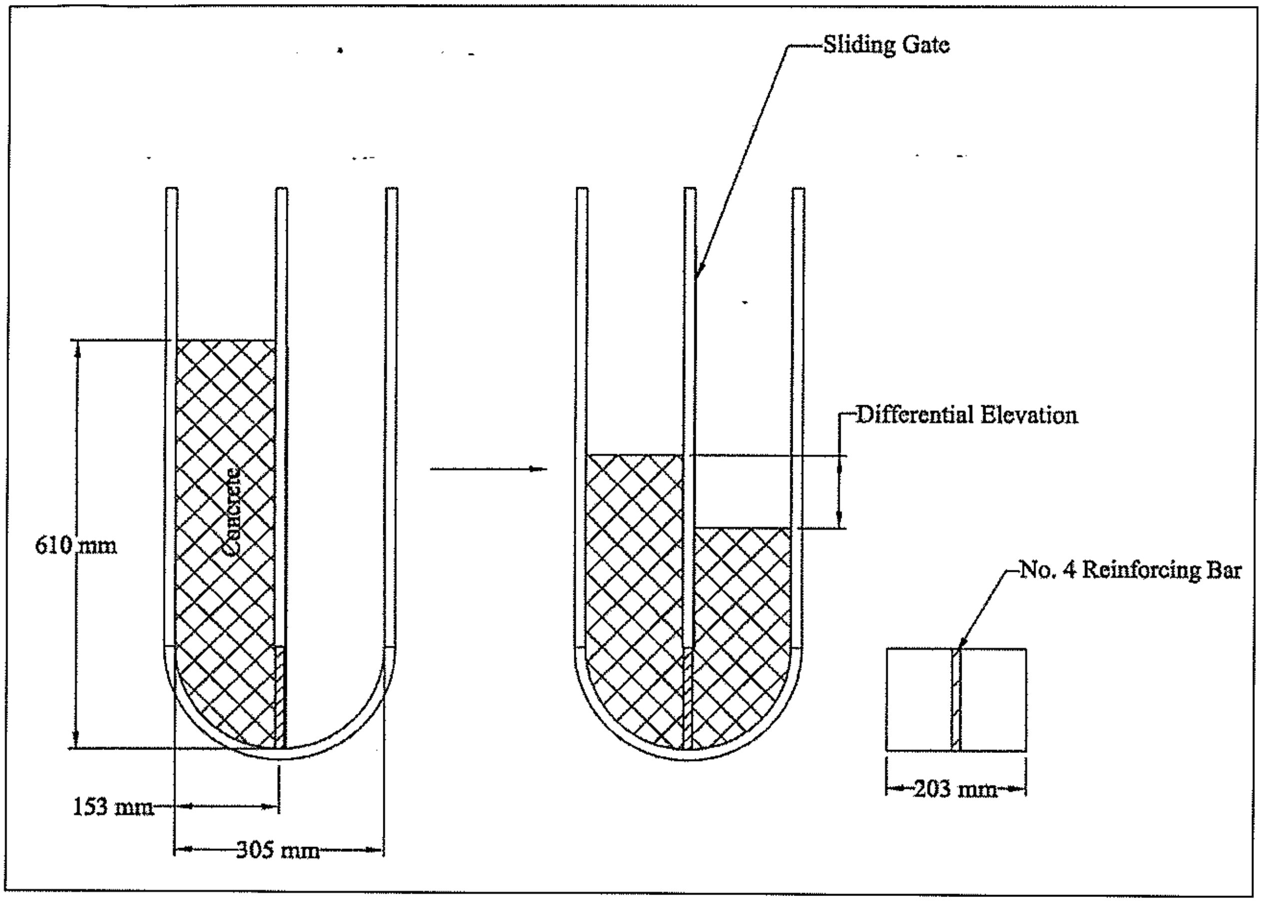


Figure 4
U-test apparatus

A horizontal flow box similar to one used by Khayat was also used to evaluate the flow characteristics of the mixes and is shown in Figure 5 [*3*]. In this test, the concrete was poured a scoop at a time into the opening from a fixed height and the mix then flowed horizontally through the grid. When the concrete backed up and reached a specified height, the profile of the concrete surface was measured and the percentage of the horizontal chamber filled with concrete was calculated.

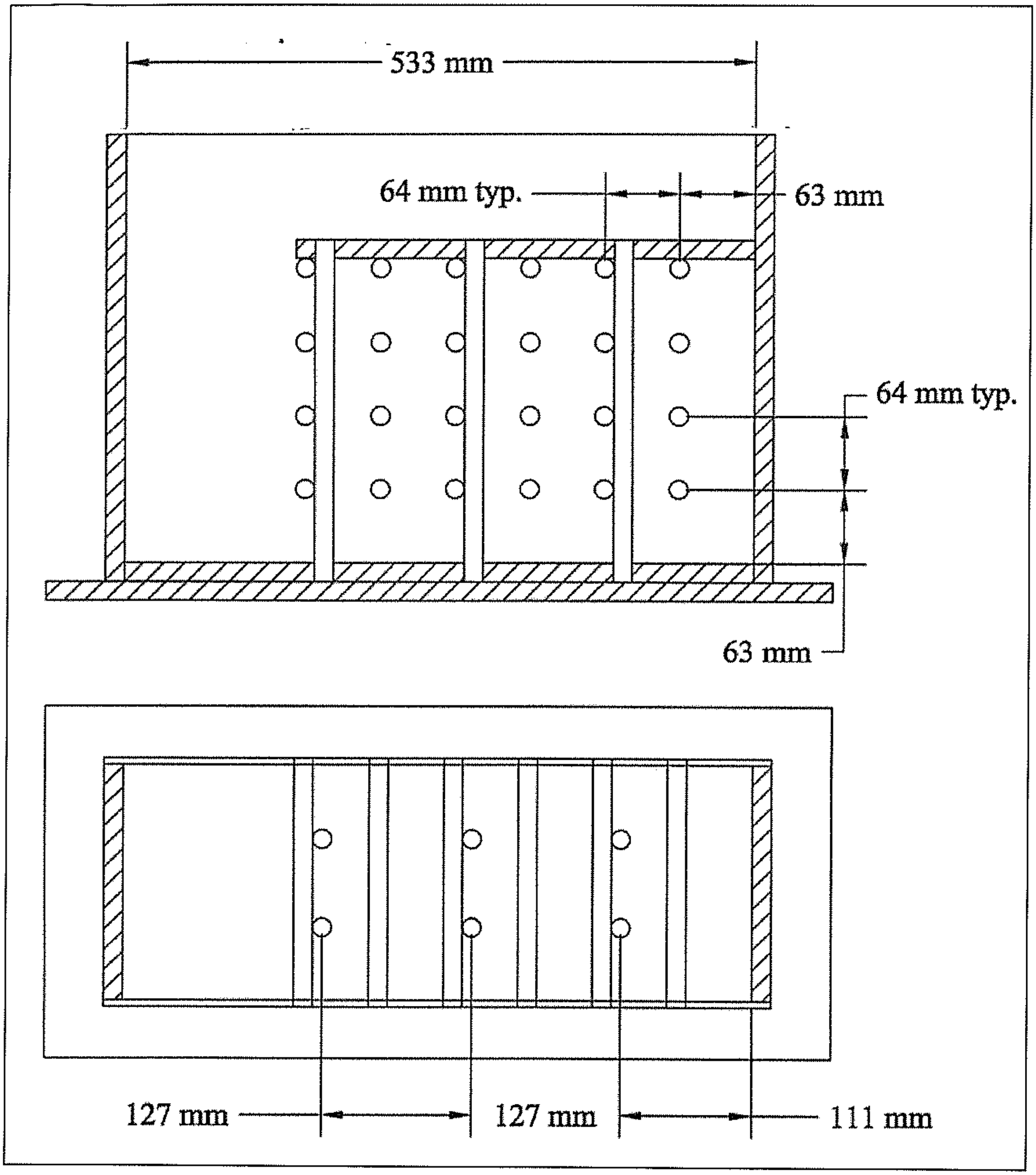


Figure 5
Modified Khayat horizontal flow box test apparatus

Strength Tests

Although incidental to the primary objectives of this project, three cylinders per mix design were tested at a controlled strain rate of 66.7 µstrains/second.

DISCUSSION OF RESULTS

Results

Timed slump tests. The timed slump tests were carried out on all the mixes, and the results along with all the other flow characteristic test results are listed in Table 2. Mix O achieved a pancake diameter of 762 m (30 in) while the other two SCC mixes, mixes M and K, achieved diameters of 597 and 635 mm (23.5 and 25 in) respectively. Mix H achieved a similar pancake diameter of 648 mm (25.5 in) while the flowable concrete mix did not form a pancake but had a vertical slump of 210 mm (8.25 in).

Table 2.
Rheology and Strength Test Results

	SCC			non-SCC	
	Mix O	Mix M	Mix K	Mix H	Mix F
Slump Diameter (cm)	76	60	61	65	a
U Test Differential Elevation (cm)	0	5	0	30	36
Horizontal Flow Test (percent filled)	60	79	91	35	2
28 Day Strength (MPa)	50.6	41.3	41.2	45.2	b

[a]Did not slump enough to form a pancake. Had a vertical slump of 21.0 cm.
[b]Results not available.
1 cm = 0.3937 in
1 MPa = 145.0 psi

Model Type I girder. The Type I Girder results clearly illustrate the difference in flow characteristics between the SCC and non-SCC mixes. Figure 6 shows how the different mixes flowed into the congested girder. In all cases, the SCC mixes flowed through the simulated strands and filled the form with no voids. Also, mix O showed very slight visual signs of segregation while mixes M and K showed no signs of segregation. Both mix H and mix F produced voids when poured into the test girder. In both these cases, the concrete was vibrated to remove the voids and the difference in volume before vibration and after vibration was taken as the percentage of voids. Mixes H and F had eight percent and 40 percent voids respectively.

U-Test and horizontal flow box. The U-Test results, shown in Figure 7 and listed in Table 2, clearly differentiated between the SCC and non-SCC mixes. Mixes H and F had differential elevations of 305 mm (12 in) and 356 mm (14 in) respectively. In contrast to this, SCC mixes O and K had no differential elevation and SCC mix M had a 51 mm (2 in) differential elevation.

The Horizontal Flow Box test results are shown in Figure 8 and listed in Table 2. There is a wide range of results with the non-SCC mixes filling up smaller percentages of the chamber than the SCC mixes. Of the non-SCC mixes, mix F clearly has inferior flow characteristics compared to mix H (2 percent filled vs. 35 percent filled). SCC mixes K, M, and O had results of 91 percent, 79 percent, and 57 percent filled respectively. It is interesting to note that the M mix performed better than the O mix in this test but did not do as well as the O mix in the U-Test.

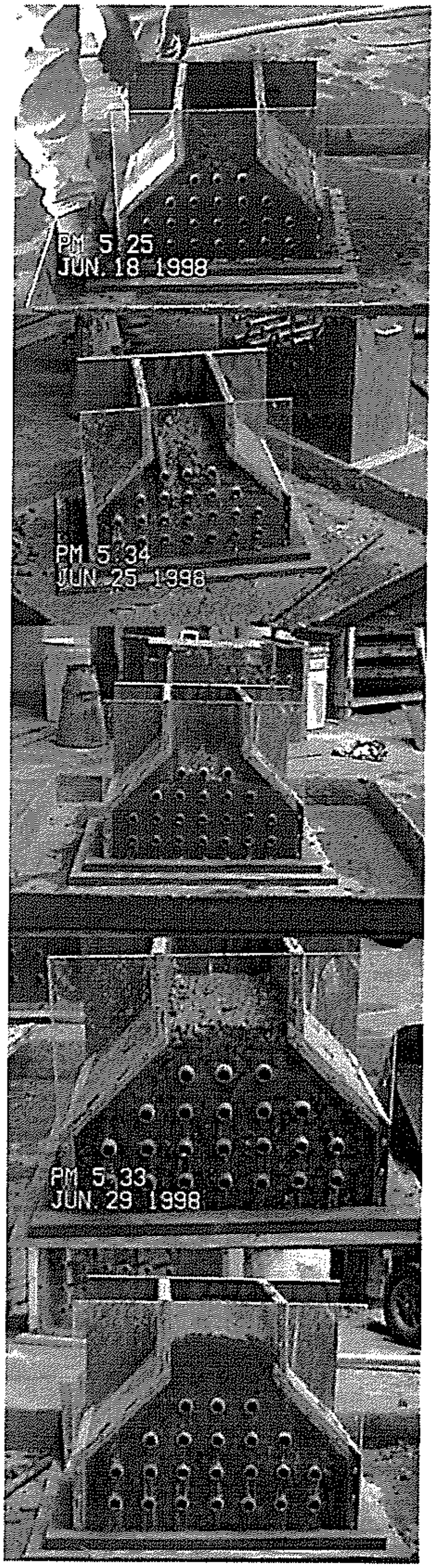


Figure 6
Type I girder results

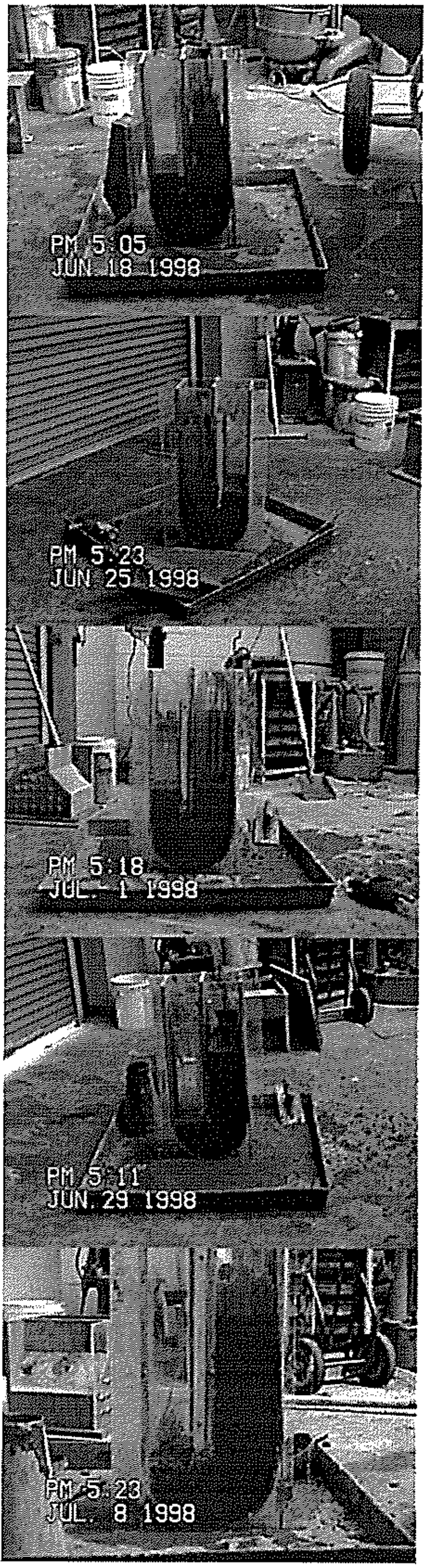
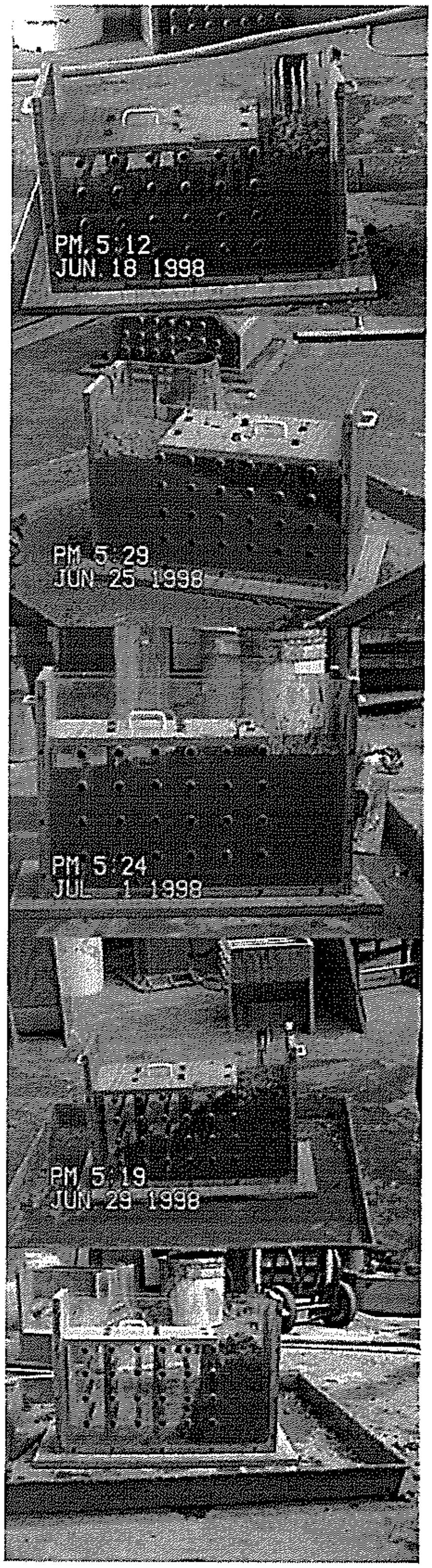


Figure 7
U-test results



Mix O

Mix M

Mix K

Mix H

Mix F

Figure 8
Modified Khayat horizontal flow box test results

Strength test results. These results are incidental to this study and are included in Table 2 for completeness sake and to illustrate that SCC can have normal to high 28 day compressive strengths. The O, M, and K SCC mixes had 28 day strengths of 50.6, 41.3 and 41.2 MPa (7.34, 5.99, and 5.98 ksi) respectively.

Discussion

The model Type I girder was used as the crucible for determining if a mix was self-compacting or not. Only the mixes that were specifically designed to be self-compacting (mixes O, M, and K) were able to fill the model girder with no vibration. Mix F, which was proportioned according to ASTM specifications for flowable concrete was not able to fill the girder form. Mix H, which was proportioned to be a high performance concrete, performed better than the flowable mix. This mix was able to flow into the girder form, but had many voids. The improved flow characteristics of the mix are likely due to the high fly ash content.

While the model girder clearly showed which mixes were self-compacting, the timed slump test was not able to effectively differentiate between SCC and non-SCC mixes in all cases. For example, SCC mixes M and K had pancake diameters of 597 and 635 mm (23.5 and 25 in), respectively, and the non-SCC H mix had a larger diameter of 648 mm (25.5 in). Thus, though slump tests are useful to give a feel for the consistency of a mix, they can not be relied on to determine if a mix is self-compacting.

In the U-test, both non-SCC mixes had differential elevations over 305 mm (12 in) and the SCC mixes had differential elevations less than 51 mm (2 in). Thus, the U-Test was able to differentiate between SCC and non-SCC mixes but was not able to quantify the flow characteristics of the different SCC mixes.

The horizontal flow test was able to differentiate between SCC and non-SCC mixes and quantify the flow characteristics of the different SCC mixes. The worst SCC mix filled 60 percent of the chamber while the best non-SCC mix filled 35 percent of the chamber; the SCC mix filled 1.71 times the non-SCC mix. In addition to this, the test showed that the H mix flowed much better than the F mix (35 percent vs. 2 percent). Also, the test quantified the difference in flow characteristics among the SCC mixes. While the K, M, and O mixes had almost identical U-test results, they had distinct results in the horizontal flow test: the K, M, and O mixes filled 91 percent, 79 percent, and 60 percent of the chamber, respectively.

With tests that can differentiate between non-SCC and SCC mixes, it is now possible to begin to determine what makes a mix self-compacting. While more data is needed to make definitive conclusions, the results here along with what is available in the literature are enough to begin to identify the salient features of self-compacting concrete mixes.

From examining the composition of mixes O, M, and K, it seems that there are three common characteristics among these mixes:

- a high cementitious material content
- a low coarse aggregate content
- a high HRWR dosage

Also, the M and K mixes make use of large percentage replacement of portland cement with fly ash and/or slag cement. The non-SCC mixes have some of these characteristics but not all three. For example, the H mix has a large replacement percentage of fly ash, a high HRWR dosage, and has a moderately high cementitious material content. However, it does not have a low coarse aggregate content. The F mix has a moderately low coarse aggregate content, but does not have as high a cementitious material content or HRWR dosage as the SCC mixes. Further illustrating the importance of the coarse aggregate content, mix O, which had the worst performance of the SCC mixes on the horizontal flow box test has the highest coarse aggregate content of the SCC mixes.

The mix with the best flow characteristics, mix K, was able to achieve the highest flowability of the SCC mixes even with a lower HRWR dosage because it has a higher cementitious material content and a lower coarse aggregate content. Also, this mix exhibited the least amount of segregation, likely due to the VMA in the mix.

CONCLUSIONS

The following conclusions can be drawn from this study:

It has independently been verified that it is possible to proportion concrete mixes with high strengths that do not need vibration to be placed in congested areas.

SCC mixes typically have the following characteristics:

- a high cementitious material content
- a low coarse aggregate content
- a high HRWR dosage
- a high percentage replacement of cement with fly ash, slag cement, or both

Concrete proportioned according to ASTM C-1017-92, *Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete* is not equivalent to self compacting concrete.

Slump tests alone can not predict if a concrete mixture will be self-compacting.

The U-Test and modified horizontal flow box test are able to distinguish between SCC and non-SCC mixes.

The modified Khayat horizontal flow box test is able to quantify the flow characteristics of different SCC mixes.

RECOMMENDATIONS

The authors recommend that DOTD seriously consider conducting a suite of experiments to qualify self-compacting concrete as a structural concrete. However, since the study of self-compacting concrete is so undeveloped, the authors recommend two options:

Option 1. If DOTD desires to become a national leader in the use of SCC, the authors recommend that DOTD immediately fund research projects looking into the fundamental properties of SCC then fund research projects to qualify SCC as an acceptable structural material for Louisiana.

Option 2. If DOTD does not desire to become a national leader in the use of SCC, but is only interested in qualifying SCC as an acceptable structural material for Louisiana, then the authors recommend that DOTD wait until other researchers conduct projects looking into the fundamental properties of SCC then fund research projects to qualify SCC as an acceptable structural material for Louisiana.

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

SCC	Self Compacting Concrete
HPC	High Performance Concrete
FC	Flowable Concrete
GGBFS	Ground Granulated Blast Furnace Slag

REFERENCES

1. Okamura, Hajime. "Ferguson Lecture for 1996: Self-Compacting High-Performance Concrete", *Concrete International* vol. 19, no. 7, July 1997, pp. 50-54.

2. Miura, N.; Takeda, N.; Chikamatsu, R.; and Sogo, S., "Application of Super Workable Concrete to Reinforced Concrete Structures with Difficult Construction Conditions", *High Performance Concrete in Severe Environments, ACI SP 140-8*, pp. 163-186.

3. Khayat and Guizani "Use of Viscosity - Modifying Admixture to Enhance Stability of Fluid Concrete," *ACI Materials Journal*, Vol. 94, No. 4, pp. 332-340.

4. Khayat, K.H., Manai, K., and Trudel, A., "In-Situ Mechanical Properties of Wall Elements Cast Using Self-Consolidating Concrete", *ACI Materials Journal*, Vol. 94, No. 6, 1997, pp. 491-500.

5. High-Performance Concrete Showcase LTRC Technology Exchange Program Feb 26-27, 1997, Baton Rouge, LA.

6. ASTM C-1017-92, Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete.